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Mechanical behaviour of an experimental embankment dam during initial impoundment

Comportement mécanique d'un barrage en remblai expérimental lors de la mise en eau initiale

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ABSTRACT: Sweden's largest dam owner, Vattenfall AB, together with several teams of researchers, built an experimental embankment dam. The purpose was to study the mechanical behaviour as well as to detect built-in damages. The dam is a small scale conventional earth- and rockfill dam. In this paper, the mechanical behaviour of the dam in terms of development of saturation and pore pressure, deformations and strains during impoundment is presented. Pore pressure measurements have shown a slightly slower development of the pore pressure than what was expected from numerical predictions. The horizontal deformations are increasing in magnitude from the upstream side to downstream side, with quite well agreement with the locations of higher strains in the dam.

RÉSUMÉ : Un barrage en remblai expérimental a été construit par le plus grand exploitant de barrage suédois, Vattenfall AB, en coopération avec plusieurs équipes de chercheurs. Le but était d'étudier le comportement mécanique ainsi que de détecter d'éventuels dommages inclus. Le barrage est un barrage conventionnel en terre et en enrochement à petite échelle. Dans cet article, le comportement mécanique du barrage en termes de pression interstitielle, de déformations et de contraintes lors de la mise en eau est présenté. Les résultats ont montré un développement légèrement plus lent de la pression interstitielle que ce que prévu par le modèle numérique. Les déformations horizontales augmentent en amplitude du côté amont au côté aval, avec un assez bon accord sur les emplacements des contraintes les plus élevées dans le barrage.

KEYWORDS: embankment dam, impoundment, pore pressure, deformation, strain

Mots clés: barrage en remblai, mise en eau, pression interstitielle, déformation, contrainte

1 INTRODUCTION

In 2019 an experimental embankment dam was built as a collaboration between Sweden's largest dam owner Vattenfall AB and research groups from Luleå University of Technology, Uppsala University, Lund University of Technology and HydroResearch AB. There are two main purposes of the research on the experimental dam. One part is to study the mechanical behaviour of the embankment dam during its first impoundment as well as throughout the continued operation. Another part is to test that capability of a range of geophysical methods, like resistivity and tomography, to detect several embedded defects damages that were built into the embankment dam, see Johansson et al. (2021), Nooroz et al. (2021) and Salas-Romero et al. (2021). Geotechnical monitoring is performed using pore pressure transducers, inclinometers and strain measurements close to the interface at the bottom of the embankment dam before and during reservoir filling as well as during the operational phase. Vattenfall AB is funding the construction of the experimental dam at the site of its research and development laboratory facilities in Älvkarleby, Sweden.

In this contribution, the field data from the initial impoundment of the dam is reviewed.

2 THE EMBANKMENT DAM

The experimental dam was built in a surrounding box made of concrete. The dimensions of the box are 20 m x 16 m, with the foundation level 4 m under the ground surface. In order to achieve a controlled environment, a tent was raised after finalizing the construction of the embankment dam, to protect it from precipitation. The closely located river Dalälven is supplying the dam with water.

The constructed embankment dam, showed in Figure 1, is four metres high. The dam is zoned, consisting of a central glacial till core which is surrounded by fine- and coarse filters. Outside the filter zones, the shoulder material is placed. The embankment dam is designed according to the Swedish dam safety guidelines, RIDAS (Swedenergy, 2021). The design is based on the core material and the fractions of the filter materials are designed in order to prevent internal erosion. For details on the particle size distribution of the material, see Toromanovic et al. (2020a). It took four weeks to complete the construction. The embankment dam was constructed in 20 cm thick horizontal layers. A detailed description of the construction work can be found in Toromanovic et al. (2020a). Some values of material parameters in the dam zones are presented in Table 1, retrieved from field, laboratory tests and RIDAS, when the particle size prevented testing of the conditions (Bernstone et al., 2021).

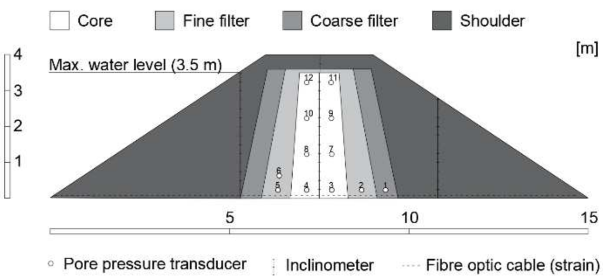

Figure 1. Cross-section of the embankment dam.

Table 1. Values of material parameters in the embankment dam.

Zone	Unit weight[1] kN/m³	Friction angle[2] °	Hydraulic conductivity m/s
Core	22.8 (23.5)	44	$5.3\cdot10^{-8}$
Fine filter	20.3 (21.0)	36*	$5.6\cdot10^{-5}$
Coarse filter	17 (19)	40*	$1.8\cdot10^{-2}$
Shoulder	18* (20*)	41*	$2.8\cdot10^{-1}$

Note: [1]Unsaturated unit weight is given first, the saturated one in parenthesis. [1,2] Values with asterisks are from RIDAS (Swedenergy, 2021).

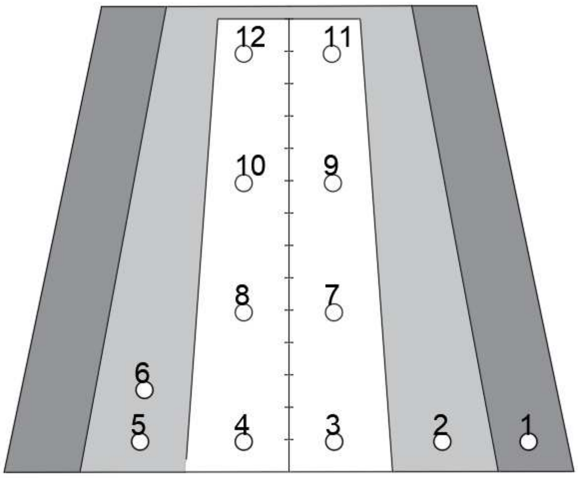

Figure 2. Zoomed view of the filter zones and the core.

3 IMPOUNDMENT PROCEDURE

The water level in the experimental dam is continuously logged on the upstream side. In Figure 3, the measured water levels during the impoundment are shown. The impoundment was started on the 13th of March 2020. When the water level reached 2 metres, after 21 days, the impoundment was interrupted due to a need to improve the pumping capacity of the seepage water that was collected downstream. Over 39 days, between the 8th May 2020 and the 6th June 2020, the embankment dam was impounded to the maximum operation level at almost 3.5 metres, just below the top surface of the core. This corresponds to the stair-looking part of the graph. Thereafter, the water level was slightly lowered to 3.3 metres and kept constant.

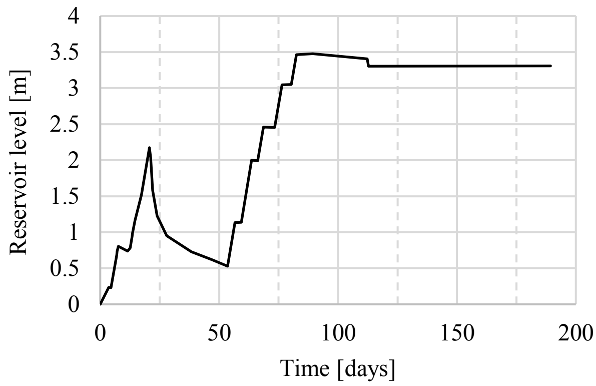

Figure 3. Water level in the reservoir.

4 GEOTECHNICAL INSTRUMENTATION

The geotechnical instrumentation in the embankment dam consists of pore pressure transducers, inclinometer measurements involving MEMS technology, see Danisch et al. (2007), and fibre optics for gathering strains developing at the interface. All measurements are performed continuously. The sensors are concentrated to one section, as exemplified by the cross-section in Figure 1.

4.1 *Pore pressure*

Pore pressures are measured by vibrating wire piezometers in the core and in the filters of the embankment dam. The piezometers were installed during construction and placed directly on a compacted layer. The pore pressure transducers are 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 react to the pressure changes outside the transducer. This also means that the measurements are affected by the atmospheric pressure which needs to be corrected for. All pore pressure readings presented in this paper have been corrected for the prevailing air pressure.

4.2 *Deformation*

The deformations in the embankment dam are monitored by shape accelerometer arrays (SAA), of type Measurand SAAV250. The system allows for deformation monitoring in x-, y- and z-directions. There is one sensor in each segment of 0.25 m, these were specially manufactured in order to fit the scale of the experimental dam. Three inclinometers were installed, with position given in Figure 1 and with the following length; 3.5 m upstream, 4.0 m in the centre and 3.0 m downstream. The x-direction is from upstream to downstream. The y-direction is defined along the axis of the embankment dam, in the longitudinal direction from the right abutment to the left abutment, and the z-direction vertical. When installing the SAA's, they were guided down into plastic tubes that were built into the embankment dam during construction. These were not as straight as shown in Figure 1, caused by the construction process. The plastic tubes were glued to the concrete bottom. As this is not fully guaranteeing the fixation over time, the top points of the inclinometers are used as reference points. Continuous measurements of the deformations are on-going. The data is available online, providing the possibility to follow the development in real-time.

4.3 *Strain*

Strain measurements with fibre optics are performed in the bottom of the embankment dam. The measurements are done perpendicularly to the axis of the dam in four sections.

Two fibre optic cables were installed; one for measuring strain and one for temperature compensation. The cables have been installed in a shielded bed of sand. The cables are placed perpendicularly to the axis of the embankment dam, the cables have to cross all material zones. The material is varying from the fine-grained till in the core to a more boulder-sized material in the shoulder of the embankment dam. In the area of the shoulder and filter zones, geotextile was placed under the cables and thereafter sand was filled around the cables which created protective "tubes". Bentonite was used to seal the cables in the core. The cables were pre-tensioned when installed, and loosened after the construction was finalized.

The fibre optic cables were installed in a loop, consisting of four sections through the embankment dam, see Figure 4. After construction, the clamps providing the pre-tension were loosened, as the cables were already fixed in the material and thereby "locked" in place.

The zero-measurement in end of November 2019 using was successful. Measurements have been performed continuously during the impoundment of the embankment dam. Further ahead, measurements will be performed at certain times, when the loading scenarios are changing in the embankment dam. Details about the measuring procedure can be found in Iten (2011).

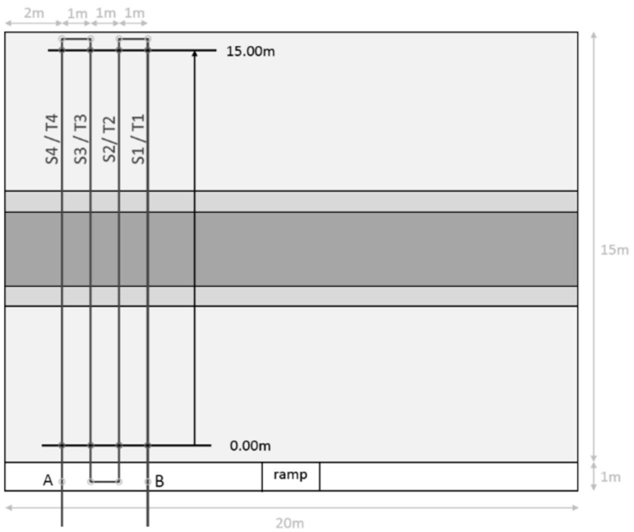

Figure 4. Field set up of the strain cables.

5 RESULTS FROM MONITORING

5.1 *Pore pressure*

The results of the pore pressure readings during impoundment are presented in Figures 5-7. The numbers of the transducers used in the graphs correspond to the positions of the transducers shown in Figure 2.

Some fluctuations were noticed in the pore pressure readings before the impoundment, this can be attributed to moisture in the material and melting snow built in during construction. All values are zeroed on the 13th of March 2020 to avoid influences during construction.

Figure 5 is showing the pore pressure in the coarser parts of the embankment dam; P1 in the coarse filter downstream, P2 in the fine filter downstream as well as P5 and P6 in the fine filter upstream.

When the impoundment starts, the transducers in the coarser filter zones upstream have an immediate reaction. This is to be expected, since the material is highly permeable. The pressure in P6 is lower than in P5, this is also expected due to their installation levels. P2 has a minor indication of pressure changing prior to the peak of the first impoundment. P1 did not indicate changes under the same period.

During the second part of impoundment, P5 and P6 are quickly following the rise of the water level in the reservoir. For the transducers in the downstream side of the embankment dam, it takes until 23rd of March until there is any significant pressure change observed. The values of the pressure are negative indicating that suction is occurring in these zones. P2 is expected be subjected to show higher negative pore pressure than P1 because of the higher fine content. Nevertheless, the pressure measured in P1 is slightly higher than expected.

In Figure 6, the pore pressures in the upstream part of the core are shown, this corresponds to transducers P4, P8, P10 and P12. During the first interrupted impoundment, all transducers, except P12, the one at the top, are reacting to the increased water level. It is expected that the highest pressures are recorded in P4, followed by P8, P10 and P12.

During the resumed impoundment, 5th of May 2020, the pressure is increasing in P4, P8 and P10. For the topmost transducer, P12, a decreased pressure is observed. This can be explained by suction developing in that area as there is more access to water from the impoundment. The saturation front is developing. At the maximum level, the pressure in P12 is very close to zero, which indicates that the phreatic line is very close to the position of the transducer. As the water level is stabilizing, the pressure is also stabilizing. Given positive pressure in P4, P8 and P10, the phreatic line is located above these. The pressure in P12 is negative, the phreatic line is under and this part of the embankment dam might not be fully saturated.

In Figure 7, the results of the monitoring of the pore pressures in the downstream part of the core are shown. That corresponds to transducers P3, P7, P9 and P11. During the interrupted impoundment the transducer P3 is reacting quickly. This is indicating that the saturation front has reached through the core. If compared to P4, there is a slight delay in the pressure, this is to be expected since it takes some time for the saturation to progress throughout the core. The pressure in P7 is increasing and slightly in P9. The topmost transducer, P11, has very little reaction. As the water level in the reservoir is lowered, there is negative pore pressure in P9, which corresponds to suction and that the degree of saturation is increasing.

During the impoundment to the retention level, P3 is showing very low pressure. This is interpreted as this part of the core is not fully saturated, perhaps that the water around P3 is finding an "easier path". For the transducer P7, the pressure is building up. In theory, the pressure in P3 should be at all times higher than P7. The transducers P9 and P11 are showing negative pressure, which is indicating that the phreatic line is located below these transducers.

In Toromanovic et al. (2021), the phreatic line was numerically predicted for what can be expected in the embankment dam after 90 days. The solid line in Figure 8 is representing the predicted phreatic line in the core along with the interpretation of the levels from the monitoring (indicated by two lines). It seems like the saturation of the core, and steady-state conditions had not been reached after 90 days of operation. The pressure in P3 has built up to levels according to predictions during further operation.

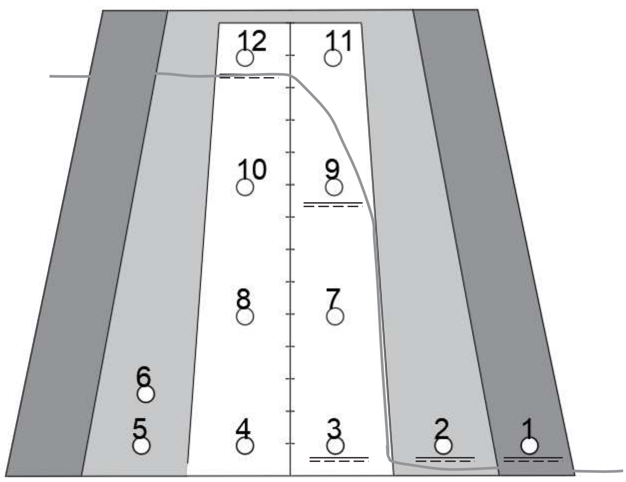

Figure 8. Interpretations of the phreatic line, along with the expected phreatic line.

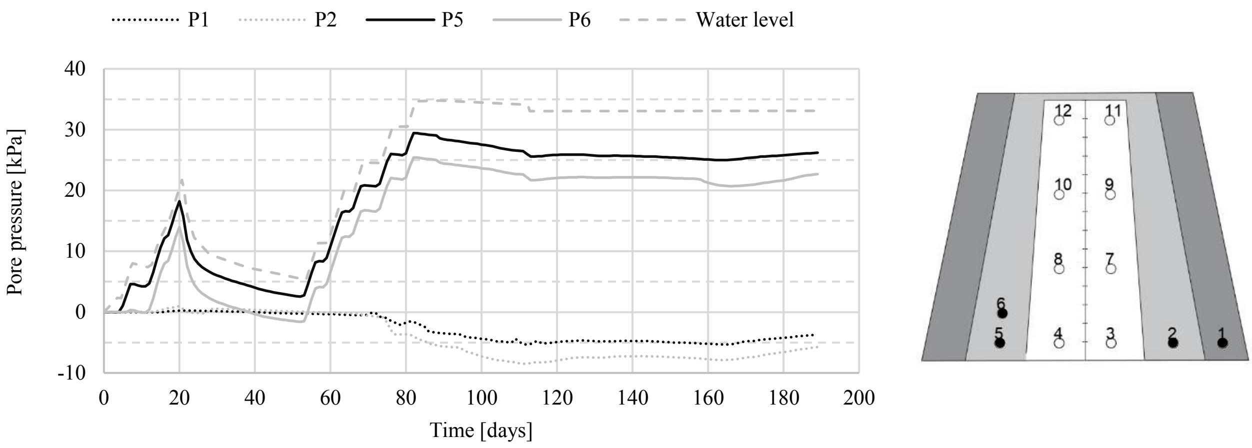

Figure 5. Pore pressure measurements in the dam during impoundment, P1-P2 and P5-P6.

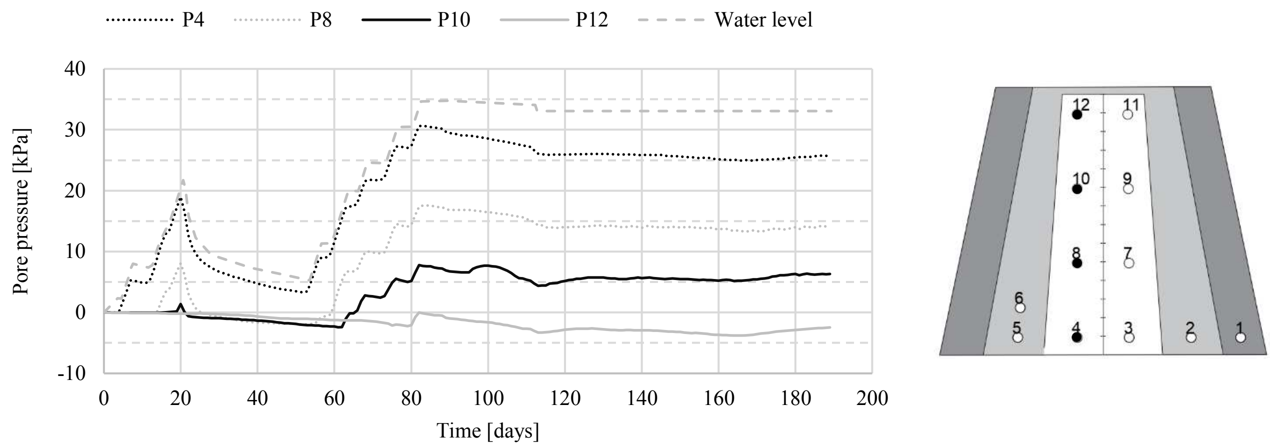

Figure 6. Pore pressure measurements in the dam during impoundment, P4-P8-P10-P12.

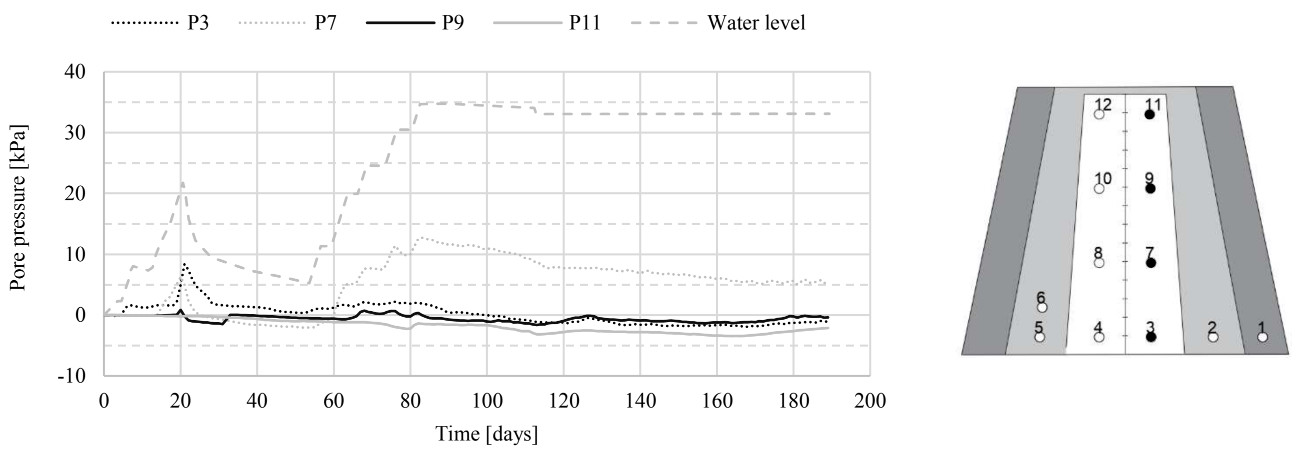

Figure 7. Pore pressure measurements in the dam during impoundment, P3-P7-P9-P11.

5.2 *Deformation*

Since the bottom points of the inclinometers were not fully fixed to the concrete slab during construction the top point of the device is used as a reference point. The tops of the inclinometers were measured after finalized construction in November 2019 and next time in November 2020. The deformations of the dam presented in Figure 9 are over a period of one year, including impoundment. Only the horizontal components of the deformations are presented, being positive in the downstream direction.

As the deformations are overall positive in Figure 9 for each inclinometer, there is an indication of movement in the downstream direction. The deformations are increasing in magnitude from the upstream side of the dam to downstream side of the dam.

The upstream inclinometer is showing almost 3 mm horizontal deformation in the bottom. At the height of 1 m, there is a slight bulge. This is also noticed on the downstream side, this could be related to the material at this level was not completely compacted. The material is slightly looser there. Above this level, the deformations decrease with height.

For the middle inclinometer, there is an indication of 20 mm movement in the bottom, the deformations are at the same magnitude up until the middle of the dam. Here the "bulge" deformation is larger than in the upstream part. From the field data, there is an indication of a slightly lower density of the till material of the core around this level. Further up, the deformations are lower. The field data is indicating lower densities, and thereby lower stiffnessess, in this part of the dam. A lower stiffness could be an explanation for the uneven deformations caused by the water load. Deformations at the very top in the middle inclinomter could also be affected by activity on the dam (i.e.).

In the downstream part, there are indications of almost 44 mm of deformations in the bottom. Further up, the "bulge" is visible as discussed above. The deformations in the dam are quite constant up to the very top of the downstream inclinometer. The deviating deformation of the upper 30 cm of support fill is very likely to be caused when measuring the reference point of the inclinometer.

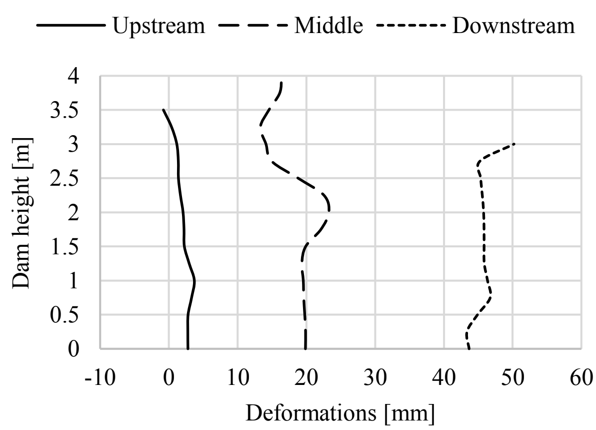

Figure 9. Horizontal deformations in the dam.

5.3 *Strain*

The results of the strain measurements are presented in Figure 10, at the end of this paper. The results are presented for the side S1, which is found in a top view in Figure 4. In Figure 10, the upstream side is to the right and the downstream side to the left. Positive values are tension and negative values are compression. The strains are presented as average values for 1 metre of cable. The strains have been corrected for the influence of temperature. These measurements are zeroed at the 9th of March, before the impoundment started.

In Figure 10, the solid line representing 25 days of impoundment shows the strains. The strains are overall quite even, but there are larger strains towards the end of the downstream side. At the 5th of May, represented by the broken curve, at the start of the second part of impoundment, no significant changes in strain have occurred on the upstream side. On the downstream side, more compression strains have developed.

The line representing 89 days of impoundment in Figure 10, shows the strains in the dam after the second time of impoundment. There are more strains at the core in the middle of the dam. Considering the upstream side of the core, the strains are approximately in the same range in that side. On the downstream side of the dam there are some significantly larger strains, which are partially caused by the cables being exposed to air. In general, more strains are occurring in the downstream side than in the upstream side.

There are deformations towards the bottom of the dam, according to the inclinometer measurements. This observation is supported by the measurements from the strains. The higher strains are found in the core and on the downstream side.

6 CONCLUDING REMARKS

During the impoundment, the behaviour of the experimental embankment dam has been monitored in terms of pore pressures, deformations and strains.

The pore pressure develops as expected, except some delays in development in the downstream part of the core. This might be caused by an unexpected flow path.

The dam has shown minor deformation in the upstream part caused by the impoundment. Deformations are increasing from the upstream side of the dam to the downstream side of the dam. There are indications of movement at the bottom.

The strains in the dam are presented for one section of the dam. These measurements are showing the largest strains in the core and in the downstream part of the dam. This corresponds to the deformations observed from the inclinometer measurements.

In on-going work at Luleå University of Technology, the measurements from impoundment as well as from the operational phase are analysed. The results will further be utilised in inverse analysis for parameter identification of the material in the embankment dam. The values of the material parameters are retrieved by calibrating measurement values from field against corresponding results obtained in finite element simulations.. This is a continuation of the work reported by Toromanovic at al. (2020b). The calibrated finite element models can further be used for predicting future behaviour of dams, acting as digital twins for dams. The technique can be useful as support in dam safety work, if applied to existing dams.

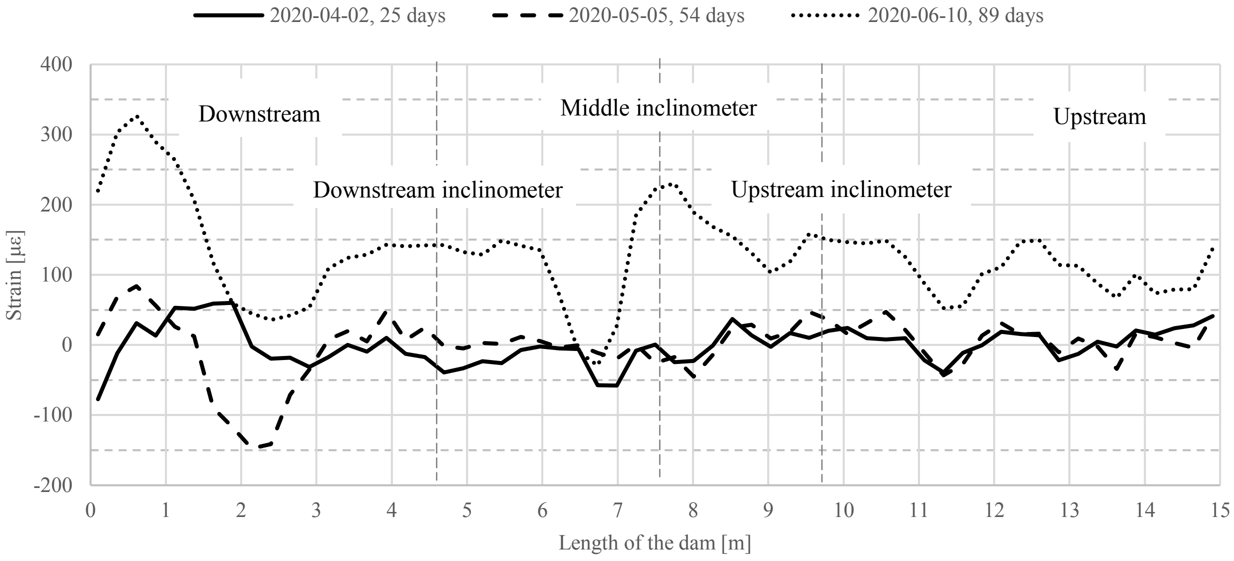

Figure 10. Strain measurements in one section of the dam

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