Structural health monitoring of a buttress dam using digital image correlation

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ABSTRACT: In order to improve the knowledge of the real behaviour of existing structures, structural health monitoring (SHM) is usually carried out. Initial calculations of a buttress dam located in Norway has been carried out to evaluate dam safety against the design loads. From this analysis, it was concluded that most of the pillars do not satisfy the required sliding safety factor. Despite of this, the dams shows very few signs of damage or damage development. Because of this it was believed that by installing appropriate sensors at critical locations on the dam structure the more informed decisions on future management of the dam could be made, based on the long-term measurements. This paper describes the use of Digital Image Correlation (DIC) technique for displacement monitoring and cracking assessment of a concrete pillar. The SHM monitoring system deployed proved its capability to provide remotely near-real time measurements of displacement, and crack progression. It was shown that the displacements are clearly influenced by the seasonal water level and temperature variations. Despite its extended use in laboratory environment, the current project highlighted the high potential of the DIC method which can readily be deployed for extended use in outdoor environments.

RÉSUMÉ : Afin de mieux connaître le comportement réel des structures existantes, une surveillance de l'état de la santé des structures est généralement effectuée. Les premiers calculs d'un barrage en contrefort situé en Norvège ont été effectués pour évaluer la sécurité du barrage par rapport aux charges nominales. Cette analyse a permis de conclure que la plupart des piliers ne satisfont pas au facteur de sécurité requis par glissement. Malgré cela, les barrages ne montrent que très peu de dommages ou d'évolution de dégâts. À cause de cela, on pensait qu'en installant des capteurs appropriés aux endroits critiques de la structure du barrage, il serait possible de prendre des décisions plus éclairées sur la gestion future du barrage, sur la base des mesures à long terme. Ce document décrit l'utilisation de la technique de corrélation d'image numérique (DIC) pour la surveillance du déplacement et l'évaluation de la fissuration d'un pilier en béton. Le système de surveillance SHM déployé a prouvé sa capacité à fournir des mesures de déplacement et de progression de fissure en temps quasi réel. Il a été démontré que les déplacements sont clairement influencés par les variations saisonnières du niveau de l'eau et de la température. Malgré son utilisation prolongée en laboratoire, le projet en cours a mis en évidence le potentiel élevé de la méthode DIC, qui peut facilement être utilisée pour une utilisation étendue dans des environnements extérieurs.

1 INTRODUCTION

In practice, the assessment of existing structures is usually based on standardized, yet simplified, procedures to evaluate the load-carrying capacity. In many cases, the result of such analytical approaches are imprecise and often too conservative (Cladera et al. 2016, Lantsoght et al. 2016). One way to improve the reliability of the assessment is to use advanced calculation methods [e.g. nonlinear finite-element analyses (NLFEA)]. Thus, a realistic estimation of the existing capacity can be obtained utilizing “surplus” capacities (de Boer 2015). However, such methods requires that input data is known with a high level of confidence, and demonstrated through experimental evidence. Such experimental evidence may refer to either laboratory testing of small-scale dam specimens or through structural health monitoring.

Structural health monitoring is the process of determining and tracking the structural integrity and evaluating the nature of a damage (Chang et al. 2003). The damage can be detected by observing a set of certain features such as structural vibration and static deformation. These are affected by changing environmental conditions, loading conditions, etc. (Lew and Loh 2014).

The focus in this paper is to explore the use of sensor technology for long-term monitoring in order to improve the knowledge of the real behavior of existing dams. A good candidate for demonstration of the monitoring program was the Kalhovd Dam. An initial investigation was carried out in accordance to NVE guidelines (NVE 2005). The sliding and overturning stability was verified against the loads from HRV+Ice. From this analysis, it was concluded that most of the pillars do not satisfy the required sliding safety factor (S=1.4). Despite of this, the dams showed very few signs of damage or damage development. Thus, it was believed that by installing appropriate sensors at critical locations on the dam structure the more informed decisions on future management of the dam could be made, based on the long-term measurements and behavior.

2 FIELD DEPLOYMENT: THE KALHOVD DAM

The scope of the work was to perform long-term (>1 year) monitoring of the response of a pillar to understand if the degradation process is continuous. The work comprise:

- A desk study to identify the optimal pillar to be instrumented
- Installation of six LVDTs to monitor displacements
- Installation of a digital image correlation (DIC) system for crack progression monitoring
- Installation of two thermocouples to monitor inside/outside temperature

The monitoring is carried out on the Kalhovd Dam, Norway. The 386-m-long flat slab dam was built during the period 1940-1948 and consists of 66 pillars with the height between 1.5 and 10 m. The interax distance between the pillars is about 5 m. A general view of Kalhovd Dam is shown in Figure 1.

Figure 1. Aerial view of Kalhovd Dam.

Prior to the field trip, a desk study was conducted in order to identify the most suitable pillar to be instrumented. The following conditions had to be fulfilled:

- The sliding safety factor has to be lower than 1.4 according to the initial calculations
- Cracks around the interface must be present for demonstration of optical methods (DIC system)
- A clear contact of the rock-concrete interface should be available
- A dry medium would be preferable to avoid any environmental damages to the monitoring equipment.

The selection was based on field inspection notes, freehand sketches and photographs available from a preliminary visit. The following pillars were selected as good candidates: Pillar #33, Pillar #49, Pillar #44, Pillar #59 and Pillar #63. The final pillar to be instrumented had to be decided on site depending on the topography of the rock. This condition was important as one of the objectives was monitoring using a tailor-made DIC system. This meant that conditions of the test site had to be favorable for positioning the camera in a stable location. In addition, it should be possible to capture an existing crack. Pillar #49 fulfilled all abovementioned conditions, and therefore was selected to be instrumented. A schematic view of the instrumented pillar is shown in Figure 2.

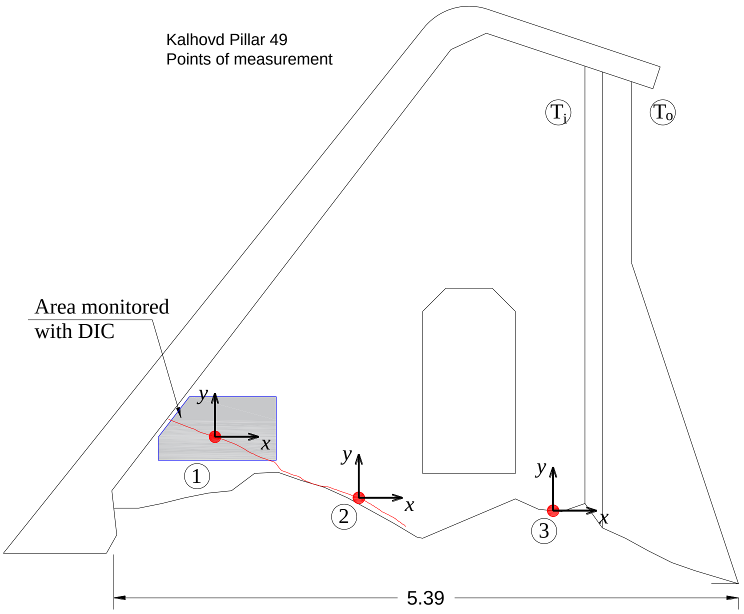


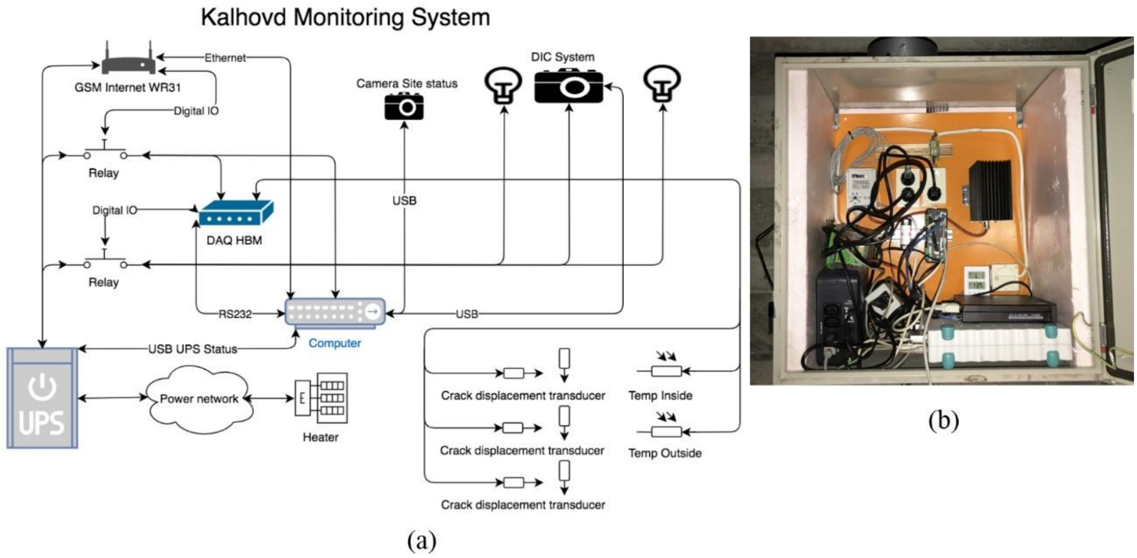
Figure 2. Monitoring plan of pillar #49 from Kalhovd Dam.

3 INSTRUMENTATION

3.1 *Hardware and system architecture*

The overall architecture for the SHM system is shown in Figure 3. In Figure 3, the connection of different sensors employed to gather the data (traditional LVDTs, DIC, thermocouples) with the data acquisition system can be seen. The data acquisition system collects and stores the data from sensors and monitoring instruments on a central computer from which the data can be wirelessly accessed. The wireless communication is cellular based (data provider: Telia). The wireless communication was used not only to access the data, but also to connect remotely to the data logger and control measurement intervals or restart the unit in case of a power failure.

The system is housed in a ventilated and heated enclosure, which was wall mounted on pillar #49. Within the enclosure various supporting electronics exists (Figure 3b), including an uninterruptible power supply (UPS) and remote power regulators to provide control of power and reboot functions, and to mitigate the need for on-site interventions in the event of a system failure.



(a) (b)

Figure 3. The overall hardware and system architecture: (a) design scheme of the SHM program and (b) wall mounted enclosure with the monitoring unit

3.2 *Displacement monitoring*

The displacement was monitored along an existing crack at three discrete points numbered 1-3 in Figure 2. At each measurement point both vertical and horizontal displacements are monitored. The displacement is measured relative to the fixed part, i.e. the rock (point 2 and 3 in Figure 2) or the concrete block below the main crack (point 1 in Figure 2). In total, six displacement sensors were installed. A general view of the LVDTs installed on all three locations is shown in Figure 4.

(a) (b) (c)

Figure 4. Installation of LVDTs: (a) LVDT #1 (horizontal and vertical displacements); (b) LVDT #2 (horizontal and vertical displacements); (c) LVDT # 3 (horizontal and vertical displacements). #1, #2 and #3 refer to displacement sensors at indicated positions (Figure x for details)

3.3 *Crack monitoring*

Crack monitoring involved the use of an optical method, i.e. digital image correlation (DIC), see Figure 5.

The DIC technique is a contactless optical method able to track pixel movements between images recorded. The DIC is an optical non-destructive measurement technique used to acquire information on the state of the structure without interrupting its normal service. This information relates to geometry, displacement and deformation data using three main components: an image acquisition tool (digital camera), image processing tools and enablers (lightning, robots, etc.). A series of images are recorded using digital cameras, and coordinates of points (targets), patterns and features in the images are subsequently identified using image processing techniques.

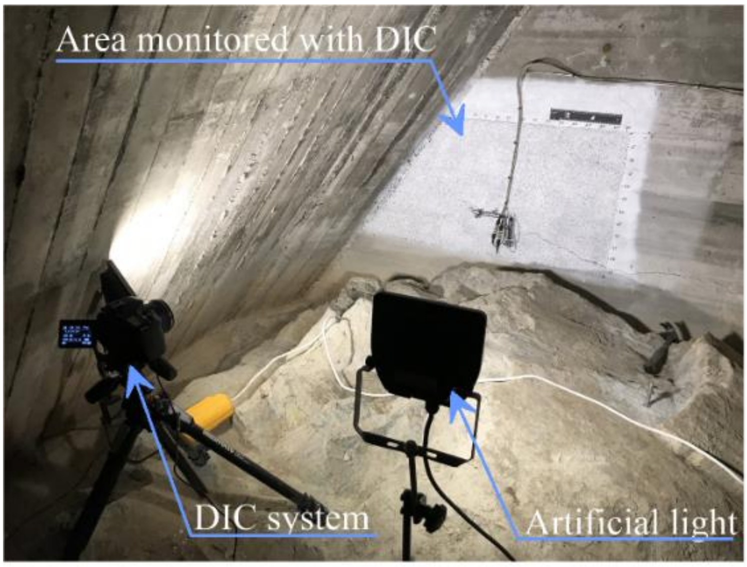


Figure 5. Digital image correlation setup

To enable DIC measurements, the monitored surface needs to be prepared beforehand. The preparations require a high contrast stochastic speckle pattern, on the monitored area. This was achieved by first cleaning the surface from any debris, then applying a white base layer. After the paint has dried a random black-dot pattern was manually created. The size of the dots as well as the distance between them must be correlated with the distance to the camera as this will influence the readings quality. In order to be able to analyze displacements, a ruler was added within the scene (see Figure 5).

Only 2D measurements were acquired in the pillar's strong-axis plane. The area monitored (700 × 550 mm) was chosen near the pillar's toe to be able to capture the crack starting from the plate and developing downwards along the interface. The equipment consisted of a digital single-lens reflex camera (DSLR), a Canon 80D. This is equipped with an APS-C (22.3 × 14.9 mm) complementary metal–oxide–semiconductor (CMOS) optical sensor giving 24 megapixels (6000 × 4000 pixels) resolution. The camera was equipped with a Canon EF 35mm wide-angle prime (fixed zoom) lens. The camera was set to ISO 100 exposure with an f/2.8 aperture and a shutter speed of 1/30 sec. Two led lamps were used to create adequate artificial light. To avoid interference with the lightning, the illumination system of the dam was disconnected in the bay where the measurements are taken. The camera was fixed 1.65 m away from the pillar using a Manfrotto carbon-fiber tripod. The camera was accessed through the computer using the Canon's remote app. The photos were taken one every 90 minutes. However, only one photo/day was used in the post-processing. The computation was done in GOM Correlate software (GOM).

3.4 *Temperature monitoring*

Two thermocouples were installed on the dam near the pillar #49. One of them measures the outside temperature and the other the inside temperature. The thermocouples were connected to a signal conditioner located inside the housing box.

4 DAM RESPONSE

In the following, the sensor measurements are shown. The results should be read together with the real loading acting on the dam as given by water level and ice loading computed from temperature variation.

4.1 *Load monitoring*

4.1.1 *Water level*

The water level fluctuated between 1080.06 and 1086.27 (the HRV level is 1086.61). The crest of Kalhovd dam is situated at level 1087.9 m above sea level and pillar 49 is roughly 6 m tall from the crest to the upstream foundation. This means that for a water level of about 1081.9 m and lower there would be no hydrostatic pressure acting on pillar 49. The historical measurements of the water level is shown in Figure 6.

4.1.2 *Temperature* variations *and predicted ice loads*

Figure 7 shows the daily temperature variation together with the ice load acting on the dam. The ice load was computed based on air temperature from *senorge.no* assuming absence of snow (Petrich et al. (2015)). A sudden change in air temperature would give a rapid transition from compressed ice (positive values in Figure 7) to ice fracture (negative values in Figure 7).

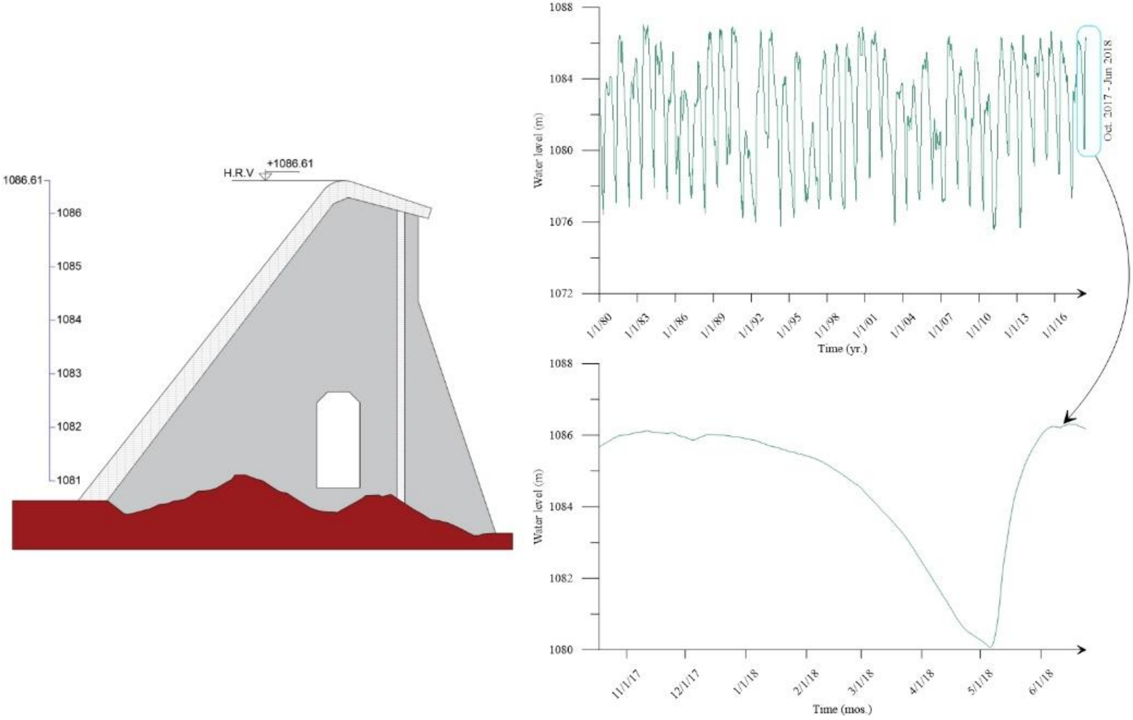


Figure 6. Water level on the Kalhovd Dam during the monitoring period

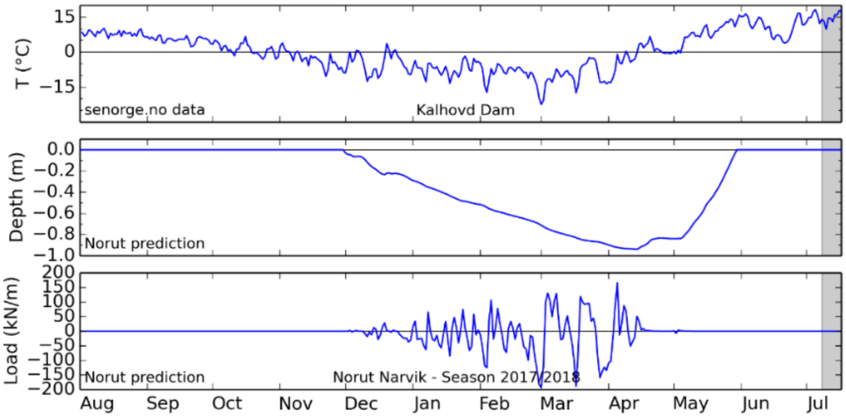


Figure 7. Ice loads predictions based on daily temperature variations (https://ndat.no/sd/) Calculations based on Petrich et al. (2015)

4.2 *Displacement profiles*

Figure 8 shows displacement time histories for the pillar #49 at the measurement points indicated in Figure 2. The displacement is divided into horizontal (H) and vertical (V) components. The negative values of the measurements corresponds to a lateral displacement from upstream to downstream for horizontal component, and an uplift of the pillar for the vertical component. Following the convention, one can identify two feasible "movement" mechanisms: (1) negative H + positive V = pillar sliding and (2) negative H + negative V = pillar rotation

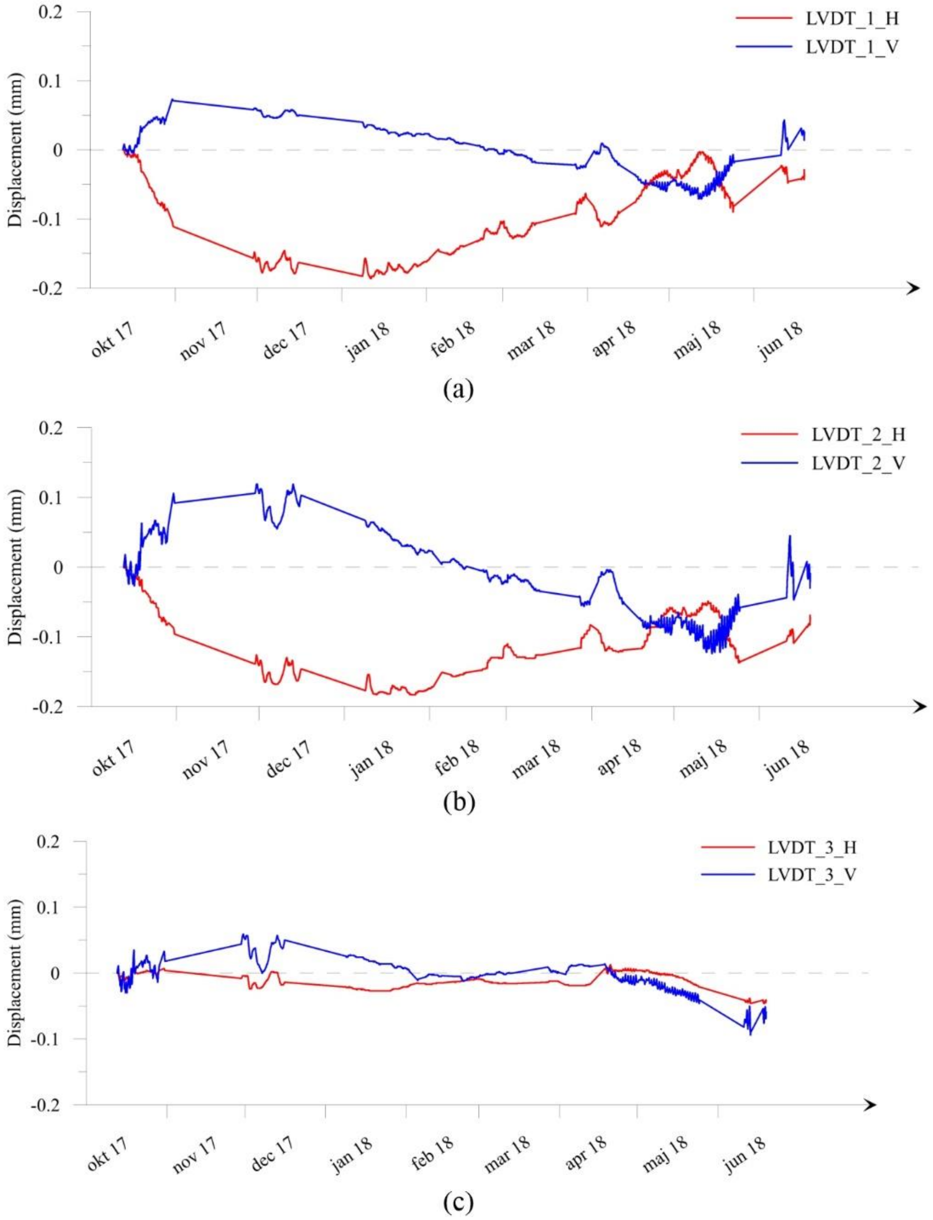
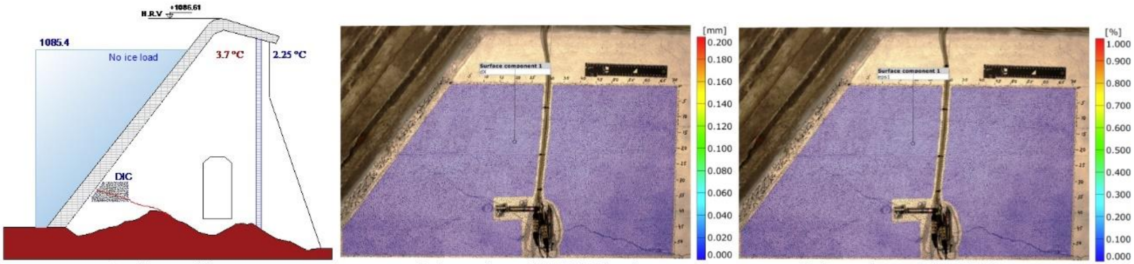


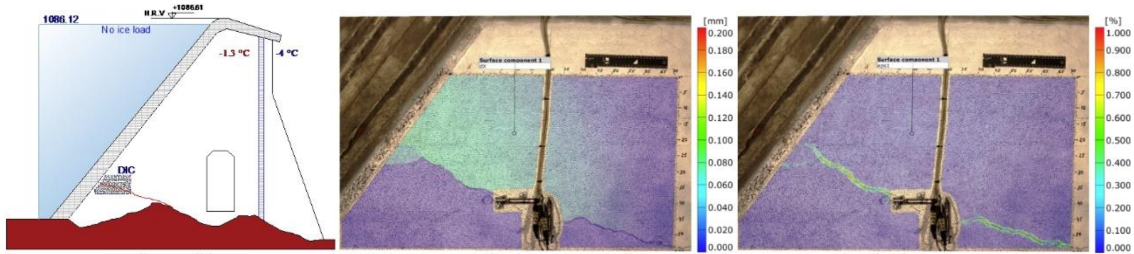
Figure 8. Displacement measurement for LVDT: (a) no. 1; (b) no. 2 and (c) no. 3

4.3 *Crack progression*

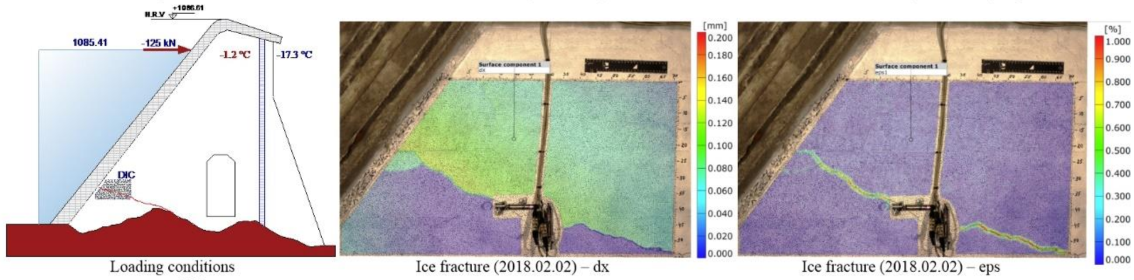
In addition to traditional sensors, a contactless technique, i.e. DIC, able to monitor cracks' progression was supplementing the monitoring plan. The method will show whether the monitored crack is active or not. Major strains and horizontal displacement around the main crack were extracted from the image analysis and plotted for selected dates in Figure 9. These dates are related to the maximum/minimum load conditions as follows: (1) min/max water level and (2) min/max ice load.



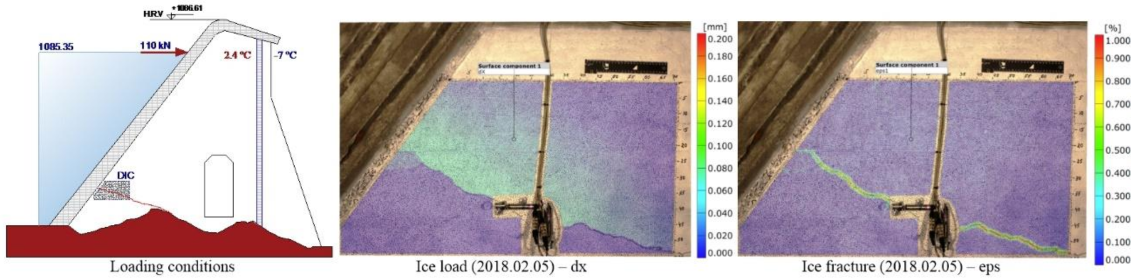
Loading conditions Reference image (2017.10.18) – dx Reference image (2017.10.18) – eps



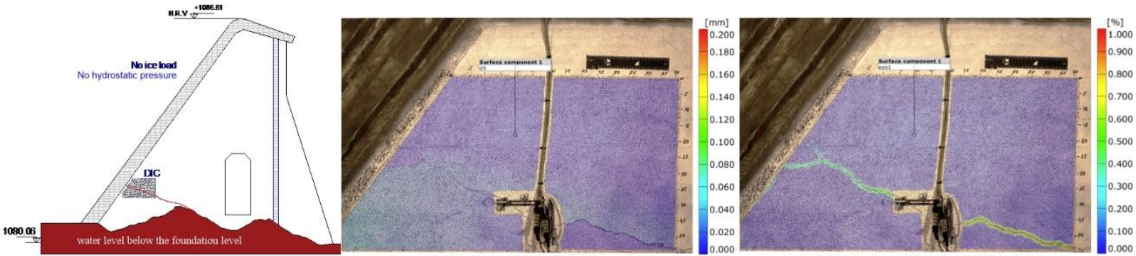
Loading conditions Max water level (2017.11.11) – dx Max water level (2017.11.11) – eps



Loading conditions Ice fracture (2018.02.02) – dx Ice fracture (2018.02.02) – eps



Loading conditions Ice load (2018.02.05) – dx Ice fracture (2018.02.05) – eps



Loading conditions Min water level (2018.05.06) – dx Min water level (2018.05.06) – eps

Figure 9. Actual loading conditions and image analisys using digital image correlation at selected dates

5 ANALYSIS OF RESULTS

On all three locations where displacements are monitored, negative horizontal displacements are accompanied by positive vertical displacements. This corresponds approximately for the period October to mid-February. During this time the water level is at its maximum with the ice loads peaking at about 100 kN/m. Following the convention made (negative H + positive V = pillar sliding) we can assume a predominantly sliding movement of the pillar. The results are in line with those obtained from DIC (see Figure 9).

From mid-February onwards, the horizontal displacements remained negative on a descending trend towards zero displacement, while the vertical displacements dropped from positive to negative values. During this time, the water level dropped markedly (with a minimum in the beginning of May, i.e. 6 m drop) followed by a rapid increase to the same maximum level in just one month. From mid-February, the ice loads continued to increase up to a level of 160 kN/m in the beginning of April and decreased to zero shortly thereafter. Although there are still recorded negative horizontal displacement, the descending trend suggest the pillar is "sliding back" towards its original position.

The above two conditions are considered to be "extreme" in the sense that neither a pure sliding nor a pure rotation could happen in reality. For example, a pure sliding would mean that the level of displacement would be identical when comparing displacements recorded at the heel with those at the toe; this was not found to be true. Overall, the maximum displacement was about -0.2 mm and +0.12 mm for horizontal and vertical displacement, respectively. These measurements were recorded during November-January months, and decreasing thereafter in line with ice loads and water level intensity reduction. The response of the monitored pillar was analyzed for different load conditions in order to identify the effects of e.g. low water level-high ice loads.

The DIC system enabled us to investigate two main aspects: (1) evaluate the feasibility of using an optical method over a long-term period in outdoor environment and (2) whether the crack is active or not. Given the harsh environment, the system proved to be robust enough to provide the necessary data. The analysis of the images acquired proved that the method is well suited to follow the evolution of the crack throughout the whole monitoring period. Moreover, cracks that were not visible by naked eye could also be detected (see Figure 9 on the 2018.05.06). It appears that the crack monitored was active throughout the whole period, with its maximum width developed during November – January month, being in line with LVDTs measurements.

6 CONCLUSION AND FUTURE WORK

The SHM monitoring system deployed at Kalhovd Dam proved its capability to provide remotely near-real time measurements of displacement, temperature and crack progression. It was shown that the displacements are clearly influenced by the seasonal water level and temperature variations. Despite its extended use in laboratory environment, the current project highlighted the high potential of the DIC method which can readily be deployed in outdoor environments making the application on Kalhovd Dam – to the best knowledge of the authors – the first of its kind.

In a pragmatic way the data shows that no significant damages occurred with displacements returning almost to the initial starting values. Ideally, every change in displacement would be clearly correlated to the temperature/water fluctuations. Given the complexity of such structures this was not entirely possible, and therefore, future investigations are needed to better understand the real behavior of such structures. Besides further analyses, continuous monitoring is extremely important to gain robustness in the monitored data.

It is believed that once installed an SHM system would provide the opportunity of a historical record of the progress of deterioration. Together with the real loading conditions would enable the prediction of future trends in dam behavior. Based on the presented work on SHM of Kalhovd Dam it has become clear that a number of technical issues are worth further investigation.

- The response of the pillar indicated a strong dependence on seasonal temperature variations. Thus, a thermal analysis considering the ambient temperature might help in understanding its effects.
- The cumulative effect of different loads acting at the same time on the dam makes the interpretation of the measurements rather difficult. Performing stochastic FEM analyses might help to differentiate between each component's effect. This will also help establishing indicative criteria for the interpretation of the results (i.e. admissible displacements).

7 ACKNOLEDGEMENTS

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