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Long-term SHM system for a concrete gravity dam

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ABSTRACT: The present contribution deals with the concrete gravity dam at the Kurpsai Hydropower station in the Kyrgyz Republic situated in a seismic area. An international consortium is developing a new continuous structural health monitoring (SHM) system for the dam within the MI-DAM project, funded by the German Ministry of Education and Research (BMBF). The focus of this contribution lies on the application of various long-term deformation measurement techniques to assess the current state of the dam over the entire service life. It includes the GNSS (global navigation satellite system) sensors, the InSAR (Interferometric Synthetic Aperture Radar) measurements and the fiber-optical sensors. The measured deformations are used in the global 3D finite element model of the dam and surrounding hillsides to predict stresses under environment influences like temperature and soil settlements. The finite element model is validated by use of the dynamic and static measurements. The developed SHM system is installed in May of 2018. Some typical results and challenges will be presented and discussed during the conference.

1 INTRODUCTION

The authors represent a cooperative project MI-DAM "Multi-parameter monitoring and risk assessment of hydro-electric dams in the Kyrgyz Republic" financed by the German Federal Ministry of Education and Research. The project is carried out by a consortium of 4 German partners: the GFZ - German Research Center for Geosciences, Potsdam, the Technische Universität Berlin - TUB, the Alberding GmbH, Wildau and the Airbus Defence and Space GmbH, Potsdam. Local partners in Kyrgyzstan are the Central Asian Institute for Applied Geosciences (CAIAG) and the state corporation "Electrical Stations" operating all power stations in the country. The MI-DAM project is focused among others on modern measurement and assessment techniques for structural health monitoring of concrete dams and its comparison to the traditional ones.

MI-DAM aims at developing, installing and testing a robust, cost-effective and flexible monitoring system for the Kurpsai Hydropower Station (HPS) in Kyrgyzstan including a multi-parameter risk assessment due to earthquakes and landslides. The Kurpsai HPS (Figure 1) is situated on the Naryn River about 40 km downstream from the city Karakol and about 400 km to the South-West from the capital of the country Bishkek. The Kurpsai HPS was built in 1981 and designed for electric power of 800 MW. Due to its location in a seismic area, the Kurpsai HPS is subjected to multiple earthquake shocks a year and is continuously monitored by the local operators by traditional methods since its construction in 1981. The Kurpsai dam with the total length of 350 m, height of 114 m and the thickness from 15 to 80 m consists of several monolithic interlocked concrete blocks constructed with expansion slits in between to allow temperature deformations.

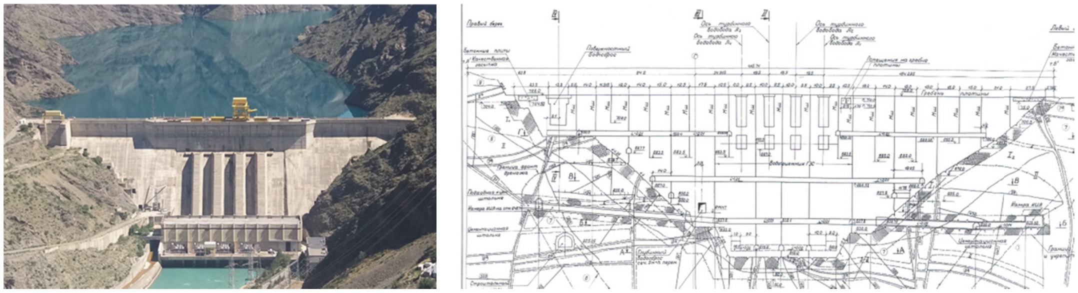


Figure 1. Kurpsai hydropower station and the drawing of the concrete gravity dam (vertical longitudinal section)

2 STRUCTURAL HEALTH MONITORING

Since its construction in 1981, the dam is being continuously monitored by traditional mechanical methods. The main one is to measure the amount of water seeping through the slits between the monolithic concrete blocks. In addition, each joint opening between the concrete blocks is monitored by measuring the distance change between the pins on the both sides of each joint (Fig. 2,a) or by optical measurements of the relative displacement of the wire between two overlapping tubes fixed in the dam body in different levels (Fig 2,b). Finally, the geodetical measurement (several times a year) of the deviation of special piles on a baseline along the dam (Fig. 2,c) gives the information on the displacements of each concrete block separately.

a) b) c)

Figure 2. Monitoring the dam by mechanical measurements of pin displacements at joint (a), optical measurements of wire displacement between two overlapping tubes (b) and geodetical measurements of block movements aside from the baseline (c)

The concept of SHM on the Kurpsai dam within the MI-DAM project distinguishes two time scales: the long-term monitoring of static deformations over hours, days, months and years and the short-term monitoring of structural response to earthquake shocks and extreme operational conditions. This contribution is focused on the long-term, static deformation measurements. The short-term measurements of the dynamic response are carried out by the geophones provided by the GFZ. The corresponding geophysical and dynamic analysis will be reported in the accompanying contribution by Pilz et.al. (2019).

The long-term monitoring includes a promising combination of three various techniques. First, the absolute static displacements of the concrete blocks will be measured by special GNSS sensors placed on each block on the dam crest. The spatial resolution of static measurements (one value per day) shall be of the order of a few millimeters. Second, the opening of the slits between concrete blocks will be measured within the dam body by the fiber optical strain sensors. They are robust, insensitive to water and chemical conditions and exhibit no value drift even over the long time periods, see Peters & Inaudi (2014). Third, the dam deformation will be measured by means of the Interferometric Synthetic Aperture Radar (InSAR) technique that is a powerful satellite-based technique to measure deformation of the objects on the earth surface. The static resolution of displacements lies within a few millimeters. The last technique will be reported during the conference within the accompanying contribution by Lang et al. (2019). The whole SHM system has been installed on site in May 2018.

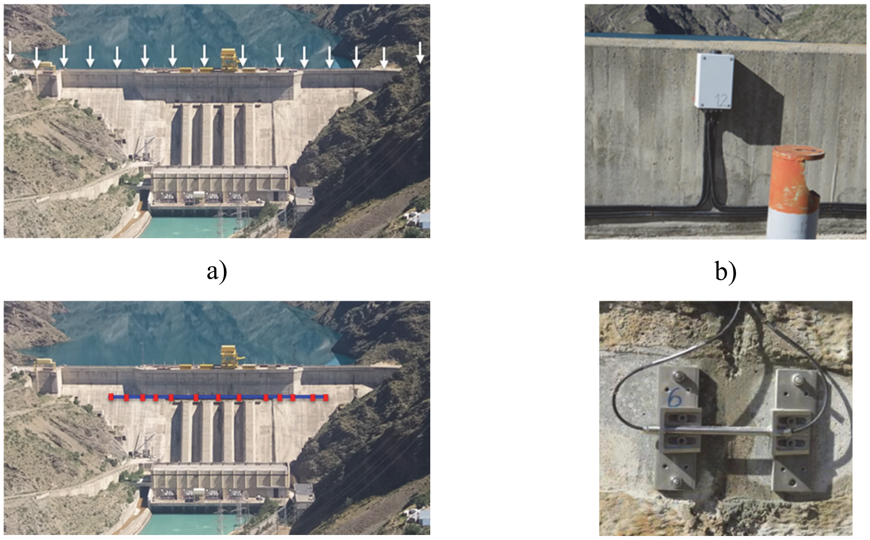

a) b)
c) d)

Figure 3. Positions (a) and side view (b) of the GNSS sensors; positions (c) and the side view (d) of the fiber optical strain sensors installed on the Kurpsai dam

The GNSS sensors are provided by the Alberding GmbH. They use the so-called GNSS of the differential type, i.e. they use a fix point to be determined by the GPS (global positioning system) signals quite accurately after a certain time. The displacements of each sensor will be then calculated with respect to that fix point. Such a technique allows for a significantly higher accuracy in the range of a few millimeters. Two sideways sensors in Fig. 3,a are installed on the hillside and considered as fixed regarding the dam sensors. Unfortunately, these two sensors are partly hidden by the hills from the satellite signals and, thus, almost useless for the measurement system. This challenge has been solved by the Alberding GmbH by using each of the sensors as a conditionally fix point and a sensor simultaneously. Special statistical processing techniques provided displacement accuracy within the subcentimeter range. The GNSS sensors were installed directly in the vicinity of the reference piles (Fig. 3,b) for the traditional geodetical measurements in order to compare the typical measurement data with the new one of the present project.

The fiber optical sensors (Fig. 3,d) are provided by the Hottinger Baldwin Messtechnik GmbH (HBM). The strain measurement resolution is equal to μ (10^{-6}), although the real accuracy of strain measurements is of the magnitude 10μ. 10 sensors were installed in the left and the right part of the dam inside the dam body and 3 sensors in the middle part on the outer surface of the dam (Fig. 3,c). Besides, 3 temperature sensors were installed inside and outside of the dam in order to provide the temperature compensation of the strain measurements.

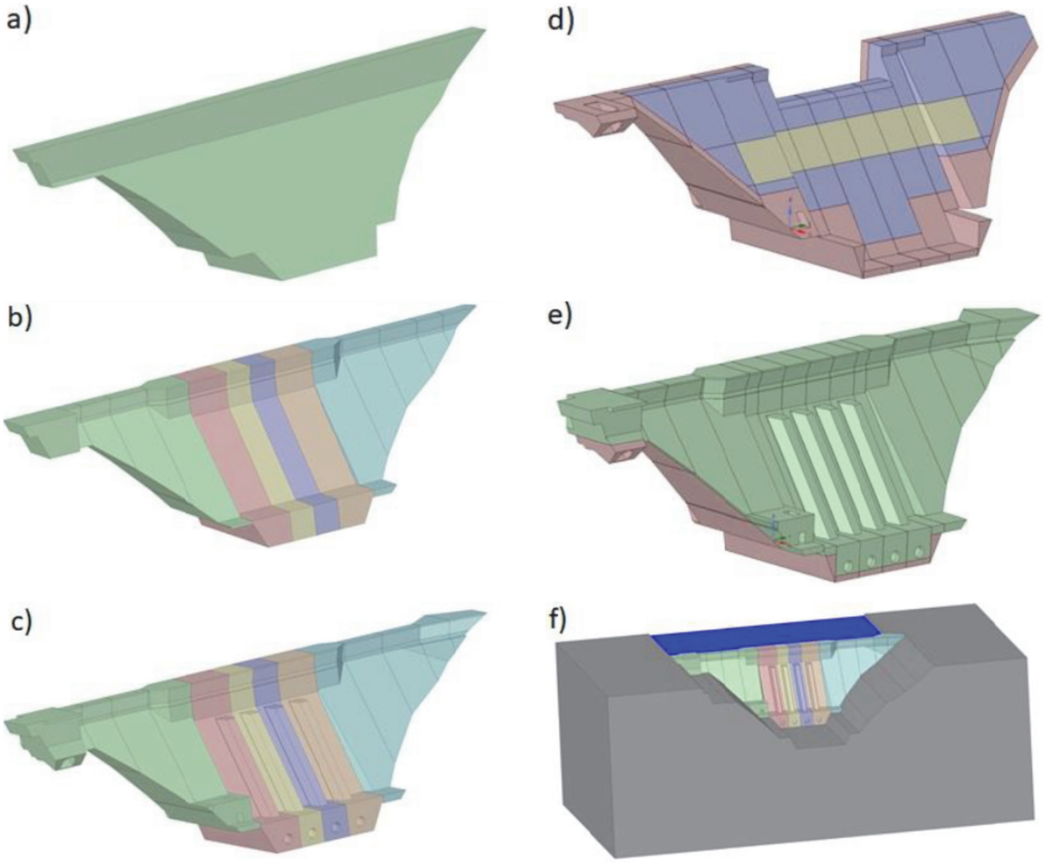


Figure 4. Various finite element models of the Kurpsai dam; (a) simple geometry model with homogeneous concrete; (b) geometry model of medium complexity with tension joints between concrete blocks; (c) geometry model of highest complexity; (d) model with concrete areas of different strength; (e) the model of highest geometrical complexity and realistic concrete properties; (f) dam model with adjacent areas of soil and water for fluid-soil-structure interactions

3 FINITE ELEMENT MODEL

The static deformations measurements alone cannot provide the full information on the state of the structure. Therefore, the full-scale finite element model of the dam including surrounding hillsides has been developed to get the measurement data as an input and to provide the state prediction. At that, each measured deformation state can be proved for plausibility by means of the FE model and a few alternative measurement techniques.

As can be seen form Fig. 1, the Kurpsai dam is a quite complex 3D structure with a large amount of specific geometrical, physical and constructional details. In view of its dimensions, the finite element model can be quite complex as well. The actual challenge is to find a proper compromise between complexity of the model and efficiency and accuracy of the predictions. In spite of voluminous design information on the dam and construction site, there are still many uncertainties with respect to material properties, constructional details, state and pre-damage of the dam. Accordingly, the computer model can be of different order of detailing, which depends on the aims of analysis and predictions.

Fig. 4 shows various finite element models of the dam including or excluding the variation of the geometry and concrete properties, boundary conditions, joints, surrounding hillsides and water. The model was developed within the ANSYS software which is capable to model not only the structure itself but also the soil and the water volume in the neighborhood of the dam.

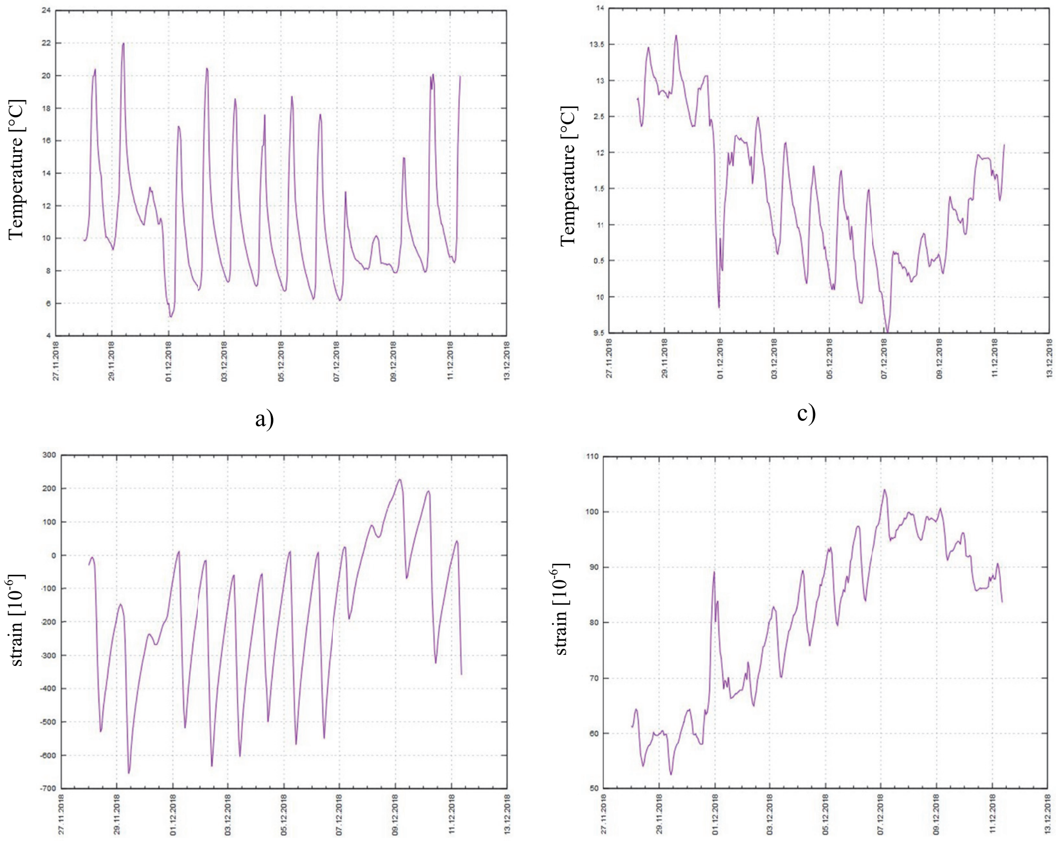
The FE model was validated by the data of the operational modal analysis obtained on site. For this purpose, 9 geophones have been placed on the crest of the dam during the instrumentation campaign in May 2018. The ambient vibration measurements were then used to determine the natural frequencies and vibration modes of the dam, which were directly compared to the calculated ones by use of the models from Fig. 4. The corresponding details are given in Tab. 1. Details of this comparison and some conclusions on a suitable detailing level will be discussed during the conference.

Table 1. Natural frequencies of the dam

	Mode No.				
Frequencies	1 [Hz]	2 [Hz]	3 [Hz]	4 [Hz]	5 [Hz]
Measurement	3.30	4.41	5.82	7.56	8.63
Model 1	3.32	4.45	5.64	6.97	8.42
Model 1	3.10	4.58	6.11	7.50	8.69
Model 3	3.13	4.70	6.32	7.81	9.02
Model 4	2.99	4.43	5.81	7.13	8.43
Model 5	3.30	4.53	6.15	8.00	9.05

4 STATIC DEFORMATIONS OF JOINTS

The main influences on the dam structure are either of static or dynamic origin. The static ones mainly originate from the temperature fluctuations, landslides and water pressure. The temperature variation is a source of primary interest, since thermal deformations of individual concrete blocks can open the joints to the water flow and become instable in critical conditions. Therefore, expansion joints are thoroughly monitored since the early construction of the dam. The main joints inside and outside of the dam body are continuously monitored since May 2018 by use of the fiber optical sensors provided by HBM. Fig. 5,a shows the temperature deviation on the sun side outside the dam during the time period between November 28 and December 13, 2018. The corresponding strain data on the same joint position outside the dam is shown in Fig. 5,b. Obviously, an inverse proportionality between the day-night deviations of the temperature and strain at the joint can be observed. The inverse relationship can be explained by the fact that contraction of the concrete block due to the temperature decrease causes the joint opening, i.e. positive strain, and vice versa. The same relationship can be observed also for the temperature variation inside the dam in Fig. 5,c and the strain change at the same position shown in Fig. 5,d. Evidently, the temperature influence is dominant in the static dam deformations during the year.



a)

c)

b)

d)

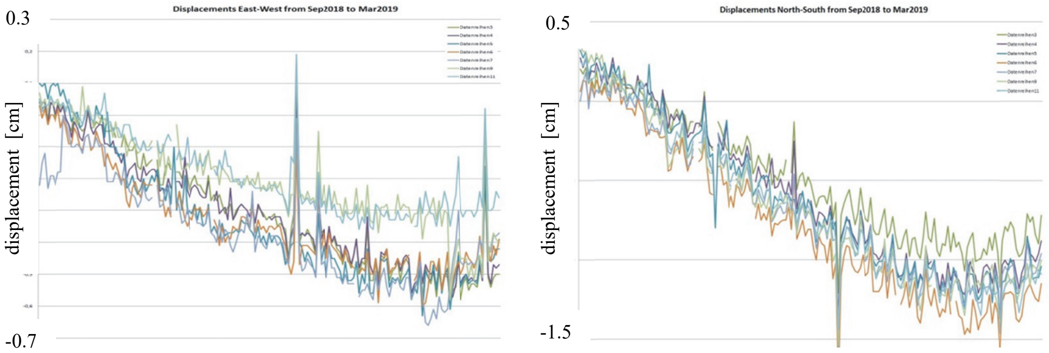
Figure 5. Temperature measurements in °C outside (a) and inside (c) the dam and corresponding strain measurements in μ (10^{-6}) outside (b) and inside (d) the dam, respectively, over the time period between Nov. 28 and Dec. 13, 2018.

5 STATIC DISPLACEMENTS OF THE DAM CREST

Absolute static displacements of the dam crest with respect to the reference state were measured by the GNSS sensors provided by Alberding GmbH. The reference time and state have been set in September 2018. According to the GPS technology, the positioning signals are recalculated afterwards into the global East-West, North-South and vertical directions. Fig. 6 exemplarily shows the static deformations of the dam in the East-West (E-W) and North-South (N-S) directions in the time period between September 2018 and March 2019.

Without going into details, it can be observed that N-S displacements are generally larger than the E-W displacements. This is due to the fact that the dam longitudinal axis is slightly sloped with respect to the E-W direction. It means that the N-S displacements are mainly lateral to the dam, and the E-W displacements are mainly longitudinal.

The second observation over the winter time is that the displacements of the crest reach the order of magnitude of 10-15 mm, although measurement values themselves are not always stable.



a)

b)

Figure 6. Static displacements at various positions on the dam crest in the East-West direction (a) and North-South direction (b) for the time between Sept. 2018 and Mar. 2019

6 ACKNOWLEDGEMENT

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