Structural health monitoring of the Kurpsai dam in the Kyrgyz Republic

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ABSTRACT: Plans to construct hydroelectric dams in the Kyrgyz Republic and the need to assess the state of existing structures, especially with respect to earthquakes and landslides, requires structural health monitoring (SHM) systems that provide rapid and relevant information to the operators of such structures, and to decision makers in the event of emergencies. The BMBF-funded project MI-DAM (Multi-parameter monitoring and risk assessment of hydro-electric dams in the Kyrgyz Republic) aims to develop, install and test a robust, cost-effective and flexible system for the Kurpsai hydropower station in western Kyrgyzstan. One aspect will involve the short-term monitoring of the dam's structural response to earthquake shocks and extreme operational regimes. The dam is currently being monitored by means of multi-parameter sensors placed at characteristic points on the structure and its surroundings. This allows critical monitored parameters (and, correspondingly, the fragility curves) to be directly integrated into on-site calculations for more responsive decision-making.

1 INTRODUCTION

The Kyrgyz Republic is a mountainous, land-locked nation in Central Asia with a high level of seismic activity, the ongoing response of the collision between the Eurasian and Indian continents (e.g., Thompson et al., 2002; Ischuk et al., 2017). For example, over the last 140 years, the region has been affected by a number of events with magnitudes greater than Mw (moment magnitude) 7, such as the 1887 Verniy (Mw = 7.2), 1889 Chilik (Mw = 8.3), and 1911 Kemin (Mw = 7.7) events, while more recently there has been the 1946 Chatkal (Mw = 7.5) and 1992 Suusamyr (Mw = 7.2) events (Kalmetieva et al., 2009, Figure 1).

With such a level of seismicity, it is therefore critical that major infrastructure such as dams are not only built to the required standards that accommodate the associated ground motion, but also are continuously monitored to ensure their ongoing structural integrity. It is with this in mind that the BMBF (German Federal Ministry of Education and Research) is supporting the MI-DAM (Multi-parameter monitoring and risk assessment of hydro-electric dams in the Kyrgyz Republic) project. The aim of MI-DAM is to develop, install and test a robust, cost-effective and flexible structural health monitoring (SHM) system for the Kurpsai hydropower station located on the Naryn River in western Kyrgyzstan (Figure 2).

The concept of SHM for the MI-DAM project distinguishes between two time scales: the long-term monitoring of static deformations over days, months and years, and the short-term monitoring of the structural response to earthquake-induced ground motion, changes in weather conditions, and extreme operational regimes. The long-term monitoring includes a combination of measurements of absolute static displacements made by GNSS (Global Navigation Satellite System) receivers and by fiber-optic strain sensors on an hourly basis, as well as long-term deformations measured by Interferometric Synthetic Aperture Radar (InSAR) on a 11-day basis. The latter are also employed for assessing the potential of landslides in the surrounding area. The short-term monitoring of changes in the dam and the surrounding hillside, which will be the focus of this contribution, is done by means of multi-parameter sensors placed at selected characteristic points on the structure and its surroundings. These sensors are meant to make in-situ measurements of the dam's response to seismic loading, which will allow not only their dynamic behavior to be determined, but also to provide a means of calibrating numerical models of the structure, another important aspect of the MI-DAM project (e.g., Koufoundi et al., 2018a). A critical point is that a fully decentralized approach will be followed, whereby the critical parameters for monitoring (and, correspondingly, estimating and updating the structure's fragility curves) are directly employed by the sensors in order to undertake on-site calculations. This will allow for a degree of decision-making at the structure itself without the necessity of involving a remote center.

The following section provides some information about the Kurpsai Dam itself. This will be followed by a brief discussion about the sensors that are currently installed on the dam and its surroundings. A summary of the current seismicity will be presented, and then an outline of the expected actions that will be undertaken. As of the time of writing, no significant seismic events have occurred in this area since the installation of the sensors. However, as will be described, efforts will be made to assess how the dam's structural behavior will vary under differing conditions not necessarily related to seismic loading.

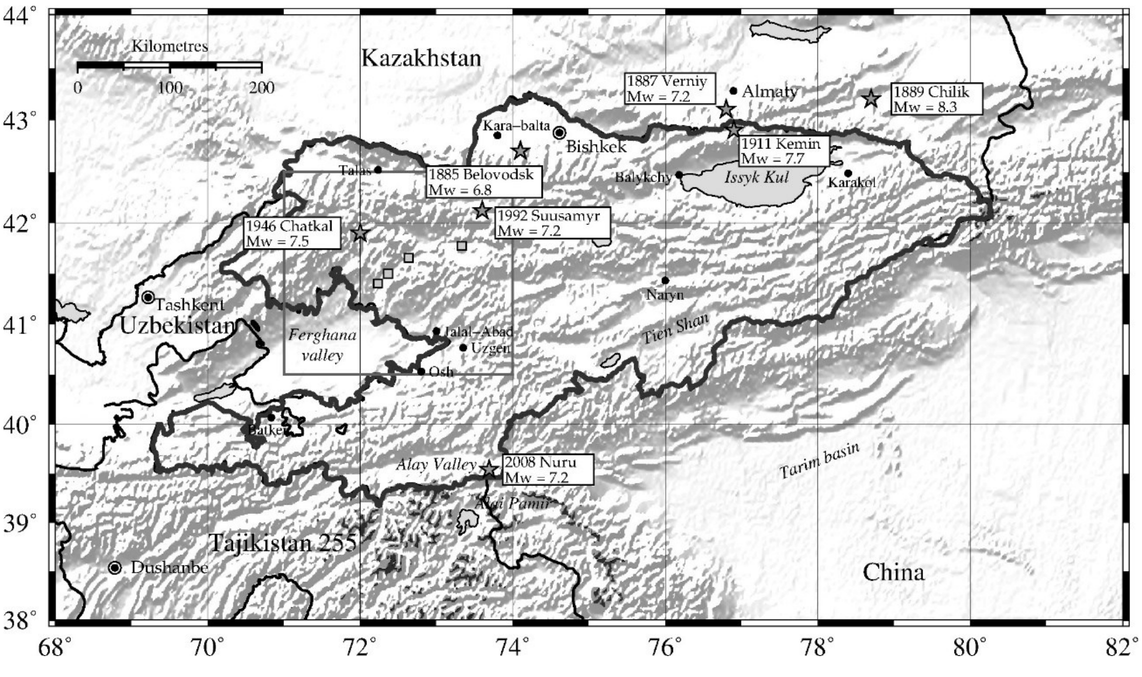

Figure 1. The Kyrgyz Republic with examples of larger seismic events that have occurred over the past 140 years (stars). The grey bounded area marks the region considered for seismic activity with respect to the Kurpsai Dam (grey squares indicate the dams located on the Naryn River in the vicinity of the study area).

2 THE KURPSAI DAM

Given its mountainous terrain, Kyrgyzstan makes extensive use of hydroelectric power for both domestic use and export. The Kurpsai Dam (Figure 2), completed in 1981, is a gravity dam located on the Naryn River in western Kyrgyzstan and is one of a sequence of hydro-electric power plants along this river. It is 113 m high with a crest length of 364 m. The dam is sectionalized by contraction joints into 13 segments. It creates a reservoir of 370 million m^3 volume, of which 35 million m^3 is available for power generation, with the level of the reservoir regulated by the upstream Toktogul dam. The Kurpsai Dam has a power generation capacity of 800 Mw, resulting in an average annual production of 2630 million kWh (Kornev, 1981).

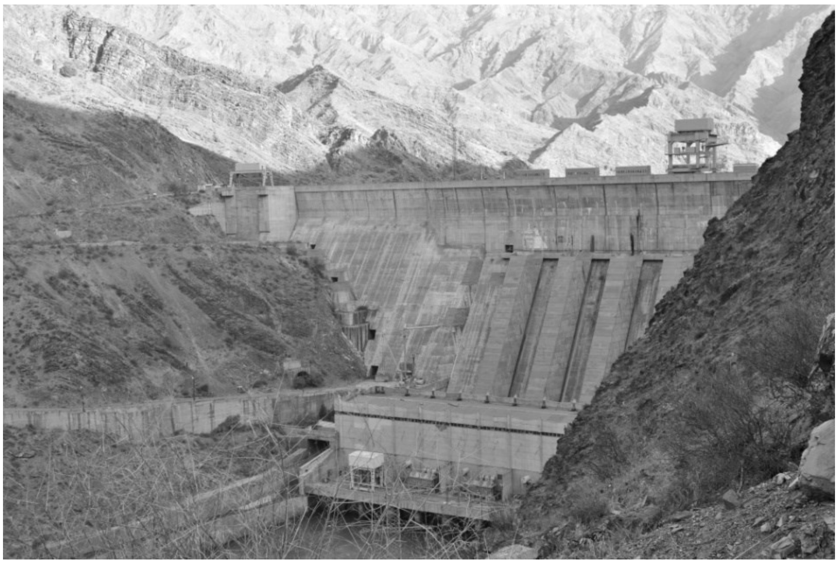

Figure 2. The Kupsai Dam, as seen from the south (the reservoir is located to the north).

3 INSTALLED SENSORS

For the short-term monitoring of the dam, eight sensing units have been installed on or beside the dam, with another installed in the control room of the complex (a separate building). These units, referred to as MPwise (Multi-Parameter wireless sensing system, Boxberger et al., 2017) are connected to velocimeters and have been set up to transmit their data to the Central Asian Institute for Applied Geoscience (CAIAG) in Bishkek, Kyrgyzstan, and the GeoForschungsZentrum (GFZ) in Potsdam, Germany, in real time, with a daily transfer to the Technical University – Berlin from GFZ.

The MPwise units (a descendant of a system referred to as the SOSEWIN – Self-Organizing Seismic Early Warning Information Network, Fleming et al., 2009) are designed to be robust, flexible, easy-to-install units that may be connected to a variety of sensors. These units make use, as far as a possible, of off-the-shelf components to provide a relatively low-cost system. Although these units were originally designed for earthquake early warning, they have also found use in structural monitoring (i.e., for general structural assessment, as well as for monitoring a structure before and after an event, including during aftershocks, e.g., Picozzi et al., 2011), and site assessment. With regards to their intended early warning role, by making use of WLAN communication schemes that are incorporated into the sensors, a cluster of sensors would allow an adaptive network to form that can take into consideration changes in circumstances (e.g., a unit ceases operation) to ensure the optimal data transmission capacity. Their principle value is the ease by which they can be installed. For example, for building monitoring, tens of minutes are all that is required to ensure a unit is installed, provided naturally that an adequate power supply and view to GNSS satellites is available.

Figure 3 shows the location of the installed MPwise sensors on the dam (red boxes) as well as the GNSS receivers (smaller white boxes). The GNSS receivers are each located on one of the segments (13) that make up the dam, as well as on either side of the dam on the surrounding bedrock. The available MPwise sensors are installed close to some of the receivers, including two sensors, denoted as 33 and 34, located off to the side of the main structure. The specific sites of the receivers and sensors are simply a matter of being in convenient locations. Note that the reservoir is to the north of the dam. In general, the sensors have been continuously recording and transmitting their data, although there are intermittent periods when the sensors are not operating properly, for example, during excessively cold periods.

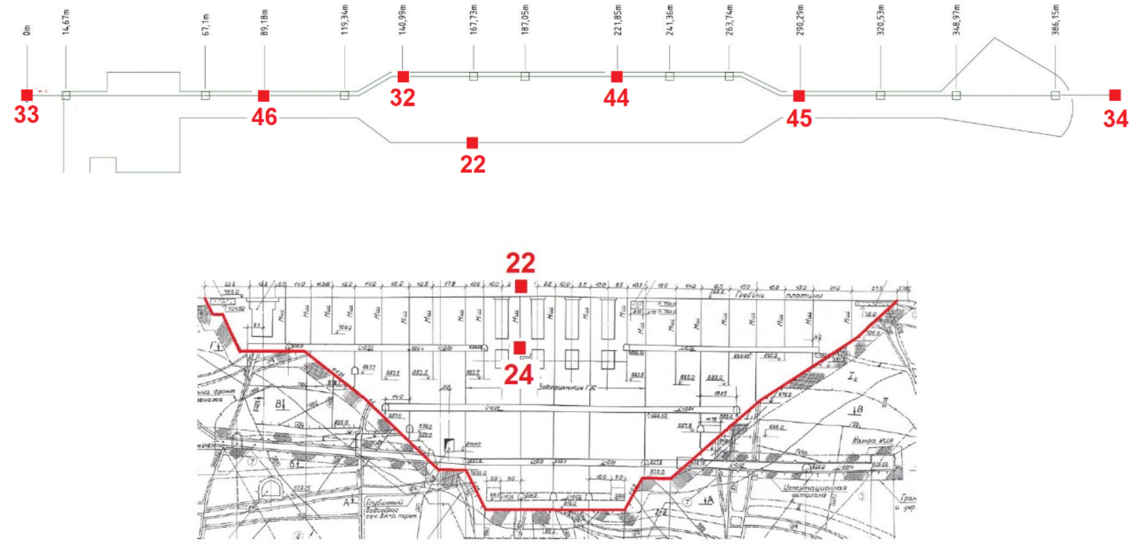

Figure 3. The location of the eight MPwise sensors (red boxes) installed on the dam, as seen from (top) a bird's-eye perspective and (bottom) the south. Note two sensors, 33 and 34, are located just off to the side of the main dam structure. The smaller boxes correspond to the GNSS receivers installed on each of the dam’s segments (with the distance from the far left or west noted), and at each side of the dam.

4 RECENT SEISMICITY

Figure 4 presents the most recent seismic activity in the vicinity of the dam. This catalogue covers the period from 01.08.2018 to 27.03.2019, and has been obtained from the International Seismological Centre[1]. The area selected was a radius of 150 km centered about the Kurpsai Dam. The largest event recorded during this period was mb (body wave magnitude) 4.5, located to the northwest of the dams on the Talas-Ferghana Fault (the main fault running from the northwest to the south east), while the vast majority of events are between mb 3 and 4, with mb 3 being the

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[1] http://www.isc.ac.uk/iscbulletin/search/catalogue/

lowest magnitude being considered. In fact, the Talas-Ferghana fault is the largest strike-slip fault in Central Asia, with recurrence rates of *ca.* 300 years expected for events of magnitudes greater than 7 based on paleoseismic studies (Korzehnkov et al., 2014), although other studies suggest that it may inactive or locked (Feld et al., 2019).

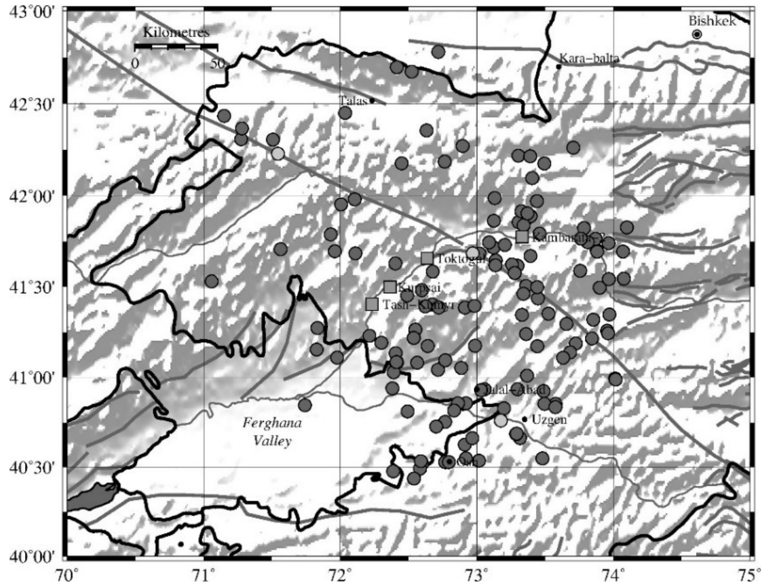

Figure 4. The recent seismicity in the vicinity of the Kurpsai Dam. The dark grey circles represent events from mb 3 to 4, while light grey circles are those greater than mb 4. The grey squares indicate the locations of the dams in this area, located on the Naryn River. The grey liniments represent the known faults, in particular the Talas-Ferghana fault running from the northwest to the southeast.

5 ANALYSIS OF RECORDED SIGNALS

Besides seismic events, the continuous recording of seismic noise, i.e., the persistent vibration of the ground due to a multitude of natural and anthropogenic causes, will allow for the continuous assessment of the mechanical characteristics of a dam (and hence, fragility curves) and any changes therein. After a careful data processing, in a first step, we apply a statistical approach based on power spectral density functions (PSDs) to evaluate the range of seismic noise. The PSD is a more fundamental description of the frequency content of ground motion. Here, for each time window of one hour, we removed the mean and applied a digital filter with a passband of 0.5 to 25 Hz for each short-period sensor. Each time series is divided into 150 segments, overlapping by 75%, to reduce the variance in the PSD calculation, while applying a 10% cosine taper to reduce spectral leakage. The spectrum of each segment is then computed via the FFTW (Fast Fourier Transform, Brigham 2002) algorithm. The PSD is thus a representation of the distribution of power over the frequencies that make up the recorded ground motion.

Figure 5 presents the PSD measured from seismic noise for the second term of 2018 for the central station on the dam's crest. The colours represent the variations of the normalized daily average of PSD. The maximum values (indicated by reddish colours) correspond to the resonance frequencies of the dam along the direction roughly perpendicular to the dam-water interface. There is some variability in the resonance frequency, ranging between 3 and 5 Hz. During the first three months of the sensors' deployment, this is relatively stable, being generally around 3.5 Hz, corresponding to the period when the water levels in the dam's reservoir were at their maximum and varied little. From November onward, there is a more rapid variation between 3.5 and 3.9 Hz, corresponding to the greater amount of variability in the water level resulting from the higher water usage for power generation during the winter months. The reasons for the variability for now are not clear, with possible causes being, for example, weather and changes in the dam's operations.

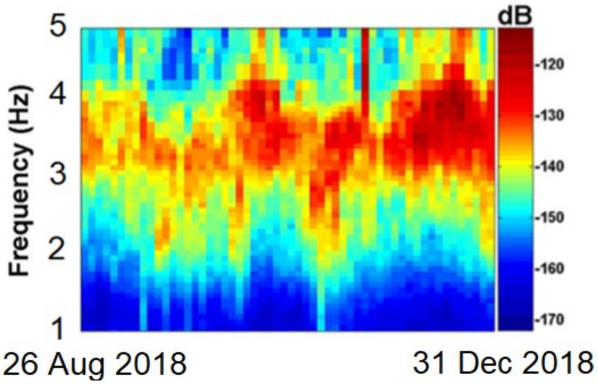

Figure 5. PSDs (power spectral density) in the frequency band 1 to 5 Hz for station 44 for the period between August and December 2018.

It is expected that the strong motion recordings will show that the dam exhibits a transient non-stationary behavior as its fundamental frequency changes in the event of strong motion induced by a sufficiently strong event, then returning to the starting value after each event. Figure 6 presents a time-frequency representation for the only event of moderate magnitude which has been recorded. It is possible to see a slight decrement of frequency during the strong motion phase, and the restoring of the initial frequency on earthquake coda. The similar but less significant behaviour was observed for the other sensors on the dam's crest while no changes have been observed for the stations off the side of the dam.

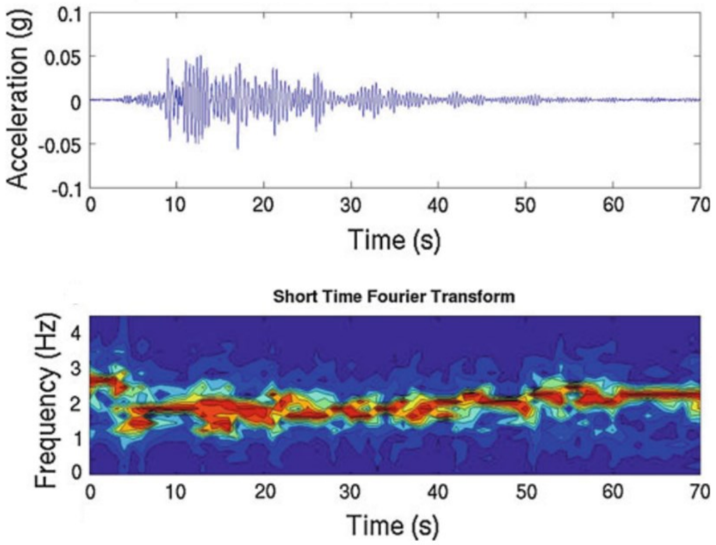

Figure 6. Top: Recording (north-south component) for station 44 during the 20 August 2018 (mb 4.5) event. Bottom: Time-frequency-plot.

Once a sufficient number of strong motion events has been recorded, lapse time coherency analysis will allow the monitoring of the spatial changes in the phase of ground motion (e.g., Koufoudi et al., 2018b), which may indicate the opening/closing at the joints, and allowing the identification of the lateral excitation of the dam's structure.

6 CLOSING STATEMENT

The use of an experimental set such as that presented in this work has the potential to provide a relatively simply and cost-effective means of monitoring the health of strategic structures such as dams. Although the analysis of the recordings is being carried out at centers removed from the dam site, it can be easily envisaged that such a system can be established to allow dam operators themselves to monitor the structural health of the dam, allowing immediate decisions as to the appropriate response in the event of a significant seismic event occurring.

Please note that during the periods when the site has been visited by the project team, no structural changes (e.g., changing or additional cracking) have been observed in the dam. However, as mentioned above, there have been no large seismic events since the start of the monitoring.

In the future, data from a nearby meteorological station will be employed to determine if dependency on any recorded parameters (wind, temperature) may be identified. Similarly, the response of the dam to changes in the outflow of water for power generation will also be examined. With regards to the monitoring, our plans involve continuing the current operations for the foreseeable future (at least until the end of the MI-DAM project, in December 2019). There are plans for additional sensors being installed in the surrounding area to assist with the landslide potential monitoring.

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