REAL TIME DAM STABILITY FORECASTING

Ton PETERS [1], Frans VAN DEN BERG [1], Ahmed ELKADI [1]

ABSTRACT

In cooperation with the Karnataka Water Resources Department (KaWRD) a pilot project, called DAMSAFE, is currently being completed at the Bhadra dam and reservoir, located in Karnataka (India). In DAMSAFE an operational monitoring and forecasting system is implemented and the results are demonstrated to the dam operator. The overarching goal of the pilot project is to contribute to enhancing dam safety and water management in India. The innovative technologies that will be integrated in DAMSAFE are: PS-InSAR satellite measurements, in-situ measurements and the Delft-FEWS software platform. Delft-FEWS is used to integrate global weather forecasting and (measurement) data from different sources with automatic computations using different hydrology, hydraulic and geotechnical numerical models. The system supplies information on forecasting of inflow and water levels in the reservoir that can be used for Real Time Control (RTC) of reservoir operation. Based on water pressure measurements in the dam body and dam foundation the stability of the dam is calculated real time. In future, the forecasting of water reservoir levels allows for forecasting of dam stability. This information can be used to control flood risk and for emergency response actions.

Keywords: In-situ Measurements, Satellite Measurements, Dam Stability Forecasting,

INTRODUCTION

Demand for water is steadily increasing throughout the world and conflicting interests generate a complex and delicate field of work. Multi-purpose water reservoirs and dams play a major role for water supply, irrigation, hydropower and flood protection in India. The dams are aging, but are also facing different circumstances than when designed, often decades or more ago. This is due to changes in land use, socio-economic developments and climate change. In order to ensure long-term operation and safety of the dams, continuing investments have to be made in adaptation planning and actions including monitoring, maintenance, repair and retrofitting. The on-going Dam Rehabilitation and Improvement Project (DRIP) in India is one of the major endeavors targeting at improving the existing situation of the large dams in India (Pillai & Giraud, 2014).

In cooperation with the Karnataka Water Resources Department (KaWRD), a pilot project, called DAMSAFE, is currently being completed in which a number of innovative technologies on dam safety and water reservoir performance will be demonstrated on a site in this state by a consortium led by Deltares (https://www.deltares.nl/en/). The Central Water Commission (CWC) is involved in the project as a major stakeholder at national level. One of the project challenges will be to focus information from these technologies to the needs in the Indian dam safety and water management sector. That is why close interaction with the end-user KaWRD was established. (Peters & Giri, 2017).

[1] Deltares, Geo-Engineering Department, Delft, the Netherlands, https://www.deltares.nl/en/
E-mail: ton.peters@deltares.nl

The Deltares led DAMSAFE consortium further consists of the Dutch companies SkyGeo and Royal Eijkelkamp and the Spanish company iPresas. These companies provide high tech, specialist technologies on PS-InSAR satellite measurements, online monitoring systems and risk-informed dam safety assessment. The ambition of the consortium partners is to use this pilot project for building a long-term cooperation with end-users in this sector and to offer integral solutions. The role of Deltares as a research organization is to provide the needed integrating, enabling software technologies (Delft-FEWS, RTC-Tool, SOBEK and DAM).

BHADRA DAM-RESERVOIR SYSTEM

The pilot case of the DAMSAFE project is the Bhadra dam-reservoir system. Bhadra Dam is located across Bhadra River near Lakkavalli village, Tarikere Taluk, Chikkamagalore District of Karnataka State at an elevation of 601.00 m above Mean Sea Level (MSL). This is a multi-purpose dam, including irrigation, water supply and hydropower generation. (Peters et al., 2018)

Figure 1. Bhadra dam-reservoir system. Left: masonry dam (back). Right: saddle dam (front)

The dam was finished in 1962. It includes a main masonry dam and two saddle (earthen) dams. The main dam includes a spillway with four gates and has a total length of 76.8 m. The reservoir capacity is 2026 hm^3 (1 hm^3=1000000 m^3). The maximum height is 76.8 m for the masonry dam (main dam). The maximum height is 49.4 m for saddle dam 1 and 32.3 m for saddle dam 2. The base level is located at 583.39 m in the masonry dam (main dam), and at 612.95 m and 630.02 m for saddle dams 1 and 2, respectively. The maximum water level in normal operation is established at 657.76 m, being 657.15 m during the monsoon season. The spillway has a maximum discharge of 3012 m^3/s. The spillway crest level is located at elevation 650.60 m. The maximum spillway opening height is 7.16 m.

ONLINE MONITORING SYSTEM

A system, available online, has been implemented for monitoring of the water reservoir, main dam and saddle dams. The online monitoring system consists of two components:

- High frequency in-situ measurements providing data on water reservoir and dams at a number of specific locations.
- Low frequency satellite based measurements providing data on dam deformation at a wide range of locations on the dams.

The data of the online monitoring system is stored and presented in the Delft-FEWS software platform. The measurement data in combination with weather forecasting and numerical calculations is used to provide information on current and expected behavior of the dam-reservoir system. This is further explained in in the next sections.

In-situ measurement system

The focus of the in-situ measurement system is on weather, water flow, water levels and dam behavior. Therefore, the system includes:

- weather stations in the catchment area to measure rainfall, temperature, wind and sun radiation,
- devices for measuring surface water levels at the dam and at the rivers flowing into the reservoir, (pore) water pressures in the dam body and in the dam foundation, and
- outflow of water from the dam drainage systems.

Figure 2. Measurement station at the river inlet into the Bhadra reservoir

The measurement stations were installed by Royal Eijkelkamp with local assistance from the district in which the Bhadra dam and reservoir are located. Figure 2 shows an installed measurement station at the river inlet into the reservoir to determine the water inflow from the main river. It is equipped with a battery and solar panel for energy supply and a wireless connection for data transmission.

The acquired data in combination with other historical data from the pilot dam are the input for the numerical computations of dam stability. The measurements are fully automated and available real-time on a secured internet platform, which is accessible worldwide for stakeholders and project partners. Monitoring activities will also include a dashboard within the Bhadra dam control room to present the results to the dam operator and maintenance staff.

Satellite based measurement system

Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) is a radar technique used to generate maps of surface deformation, using differences in the phase of the waves returning to the satellite, as shown in Figure 3. The technique can potentially measure millimeter-precision changes in deformation over spans of days to years.

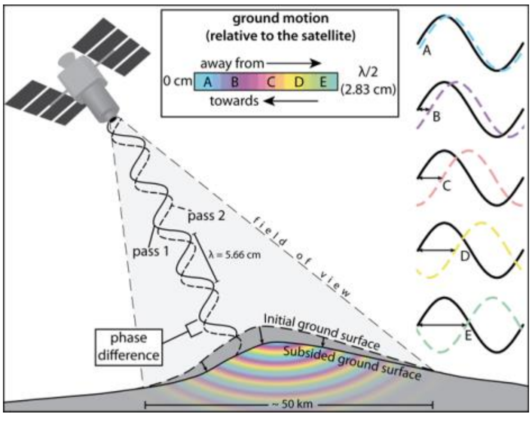


Figure 3. PS-InSAR Sattelite measurements

In general, there are two methods of applying PS-InSAR; using artificial reflection points and using natural reflection points. The method of natural reflection points has many advantages such as no access needed to the site, but it requires specialized data-processing (by partner SkyGeo) in order to optimize the measurements in terms of signal-to-noise ratio and allocation of the persistent scatterers.

The main limitation of the technology (McCormack et al. 2011) lies in the fact that not always sufficient energy is reflected back from the surface to the radar. This depends on the properties, direction and inclination of the reflecting surface.

An important advantage of the technology is that satellite images are 30x50 km or larger, meaning that, if sufficient reflectors are available, the whole dam can be monitored from the same source data. This includes many dam infrastructure assets (e.g. reservoir slopes, pumping stations, structural elements, supporting constructions, etc.), which cannot be achieved cost-effectively otherwise. The monitoring of dam deformation can be used to detect anomalies in dam behavior, of which the cause can subsequently be studied. New information can be added from future satellite images at a weekly, bi-weekly or monthly basis, depending on cost and availability of data.

Delft-FEWS FORECASTING

Delft-FEWS is a software platform developed by Deltares that is used to integrate **data** from different sources and to perform computations automatically using different numerical **models**, e.g. SOBEK

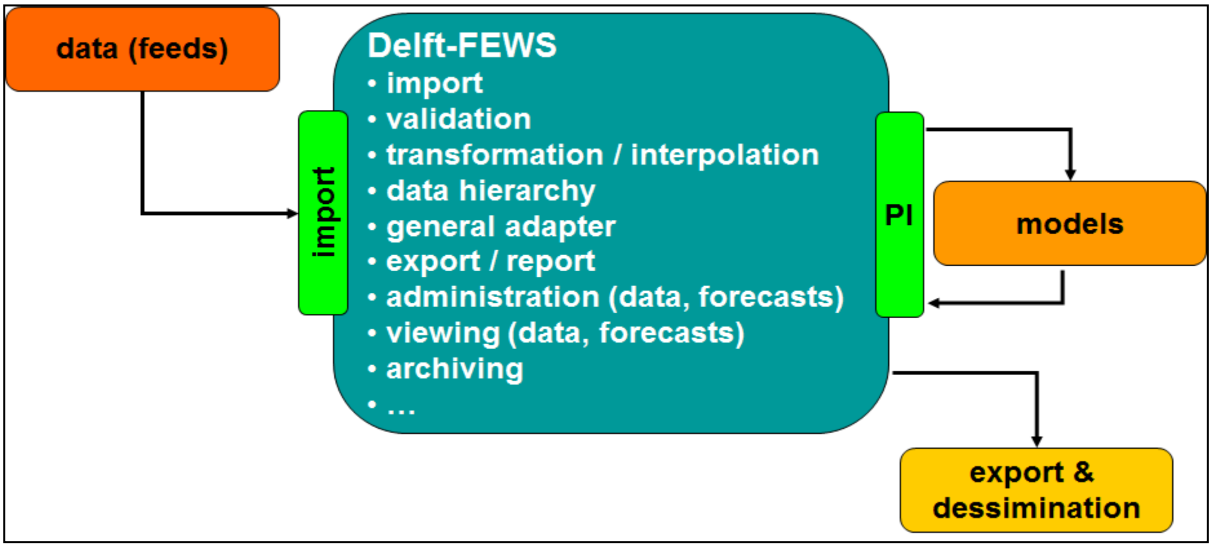


Figure 4. Overview Delft-FEWS software platform.

and DAM. SOBEK is a powerful modelling suite for hydraulic and morphological simulations including inundation, dam-break, dam/weir operation integrated with a Real-Time-Control (RTC) tool. DAM is software that assesses the strength of a dam or dike based on certain failure mechanisms (Peters and Van den Berg 2016). The DAM software is designed to routinely integrate data from different sources in a GIS environment, to perform automated, high density calculations of dam safety and to present the results in Delft-FEWS and in a GIS environment.

DISCUSSION OF RESULTS

In this section, the results are discussed of the measurements and the integration of measurements with numerical geotechnical modelling. The focus in this paper is on the aspect of dam safety, however the system also provides forecasting of inflow of water into the reservoir and expected water levels.

Dam deformation measurements

After processing of the PS-InSAR measurement data, the reflecting locations are presented on a map. Figure 5 shows the main (masonry dam), in which each dot represents a reflector on the surface. The colors indicate deformation in mm/year: downwards (yellow-orange-red) or upwards (blue). In green the deformation is small (only a few mm/year).

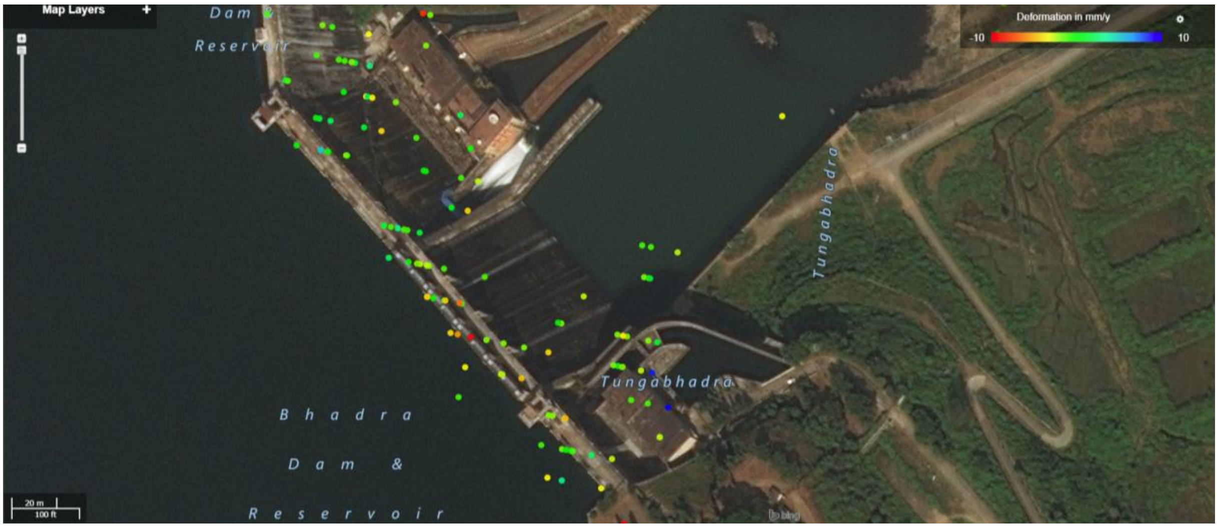


Figure 5. Main dam deformation (period 29 September 2016 to 11 March 2018)

During interpretation of the results it has to be noted that the direction of deformation is not necessarily exactly vertical but is depending on the position of the satellite compared to the reflecting surface. The results also have to be evaluated using information from the ground that can be supplied by the dam owner. The main conclusion from Figure 5 is that, though there a few reflectors showing some deformation, the overall situation of the masonry dam is stable.

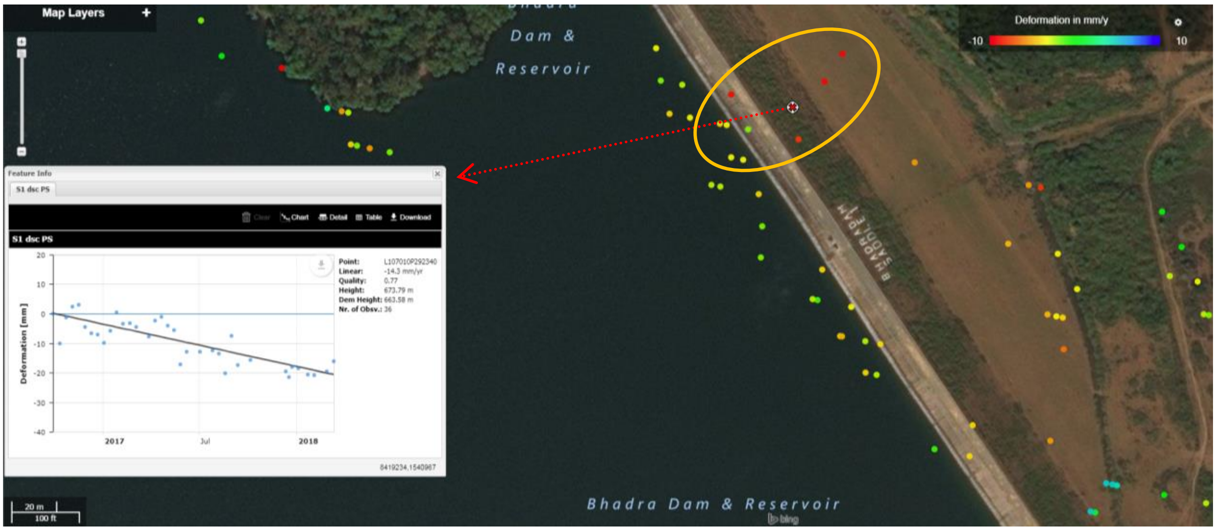


Figure 6. Saddle dam 1 deformation (period 29 September 2016 to 11 March 2018)

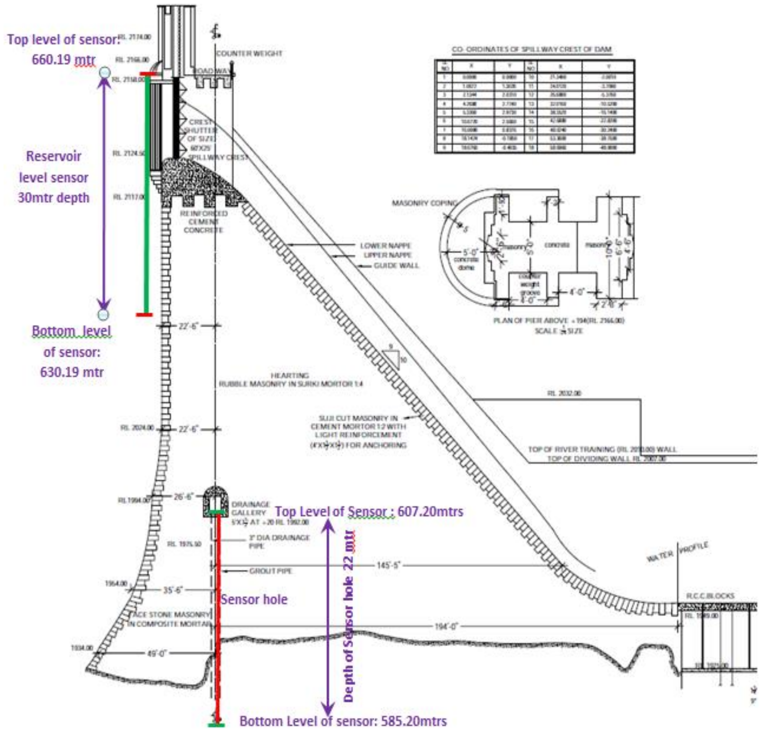
In Figure 6 the deformation of one of the embankment dams, including the deformation graph of a selected reflector, is presented. In the orange marked section of the dam there are locations on the crest of the dam, slope and hinterland that show deformation up to 14 mm/year. This is an indication of possible instability that needs further inspection to verify the observation and, if necessary, investigate the root cause and implement actions to prevent possible damage. These two examples show the added value of the used approach for verifying dam stability and to focus addition inspection to areas that show anomalies.

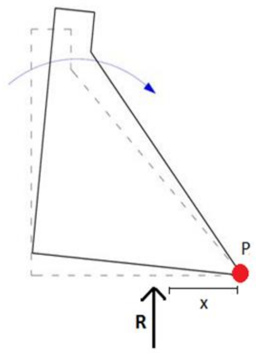
Integration of in-situ measurements with numerical calculations

Main dam

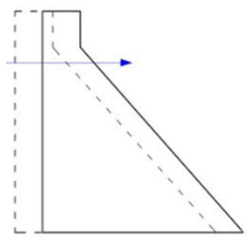
In Figure 7, the cross section of the spillway of the main dam is depicted including the installed monitoring instrumentation. The aim of the instrumentation is to feed the two stability models in real time. So the stability of the main dam is continuously known in detail. These two models are:

- Overturning of the main dam
- Horizontal sliding of the main dam





Overturning failure mechanism



Sliding failure mechanism

Figure 7. Instrumentation of the main dam with a water level sensor and a pore-water pressure sensor in the dam foundation, including considered dam failure mechanisms

Figure 8 shows the real-time stability of the main dam as a graph in the operational Delft-FEWS system. The stability calculation is based on the measurements of the pore-water pressures sensors, which are installed under the gallery of the main dam, and the reservoir water level. The measurements of the pore-water pressures and the reservoir level are presented in this graph in meters to Reference Level (m RL) for the period from 17 March 2018 till 27 April 2018. Next to that the safety factor for real time dam stability for the overturning and sliding mechanisms are presented in this graph.

During the depicted time period, the Bhadra dam reservoir level was decreasing from 645.71 [m RL] till 638.74 [m RL], that is a diminution of approximately 7 m. This diminution is the result of the water use for irrigation and drinking water and because of evaporation.

The piezo-metric head sensors WA1 and WA2 showed in that period also a decrease of the piezo-metric head values as a result of the lowering of the Bhadra dam reservoir level. Probably due to grouting activities, as part of the rehabilitation program, some of the sensors show fluctuating pressures. This is shown as some irregular activities in the graph line of the sensors. However, the trend lines for the sensors are showing a decrease.

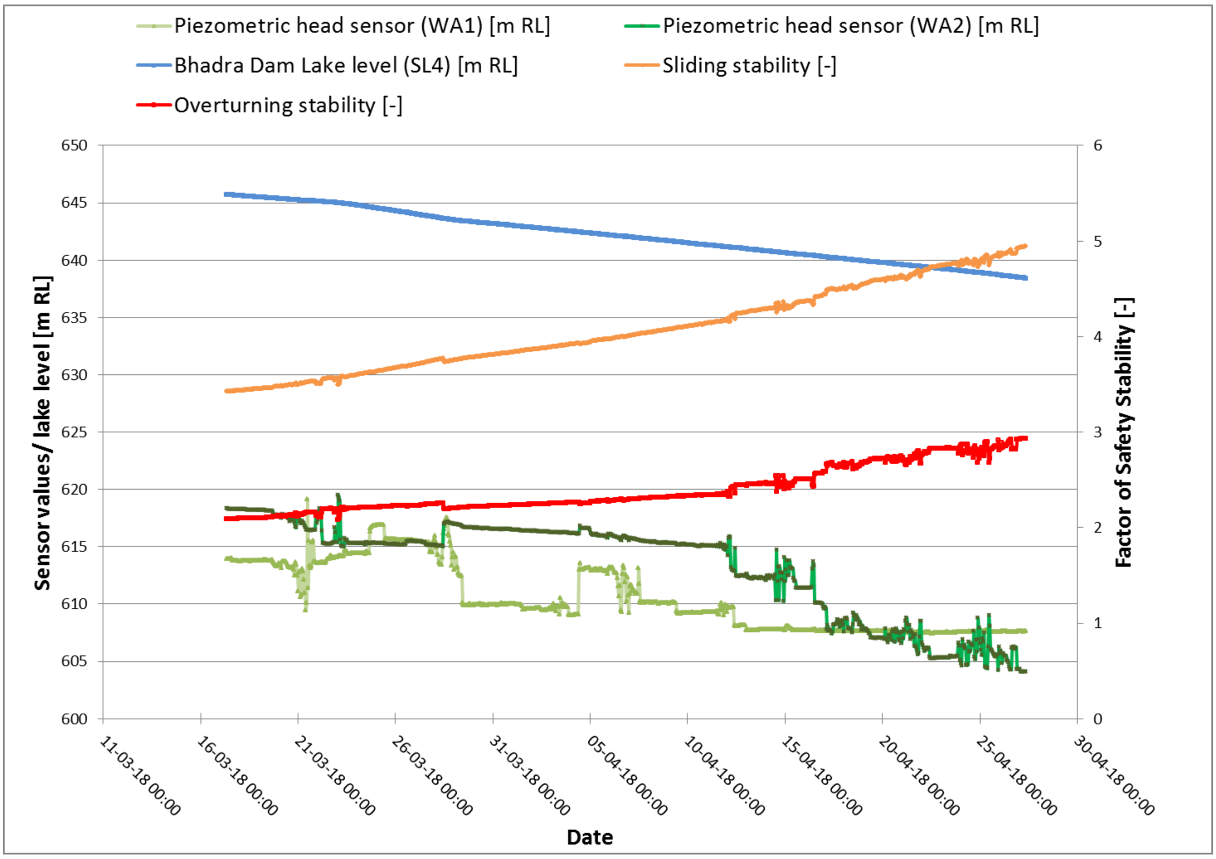


Figure 8. Stability Spillway (sliding and overturning)

Immediately after collecting the data from the sensors the system calculates the real time stability for overturning and horizontal sliding. As a result of the lowering of the reservoir level the stability for overturning and horizontal sliding will increase, this is as expected. The factor of safety for the overturning stability has increased from 2.09 to 2.93 in this period and for the horizontal stability there is an increase from 3.42 to 4.94. Based upon these result it can be concluded that lowering the reservoir level will result in an increase of stability of the main dam.

Saddle dam

In order to calculate the macro stability of the saddle dam, pore-water pressure sensors have been installed in the downstream slope, see Figure 9. The macro stability will be calculated in real time with the input of the installed pore-water pressure sensors and the reservoir level. In Figure 10, the results of the calculations for the period from March 17 till April 27, 2018 are shown.

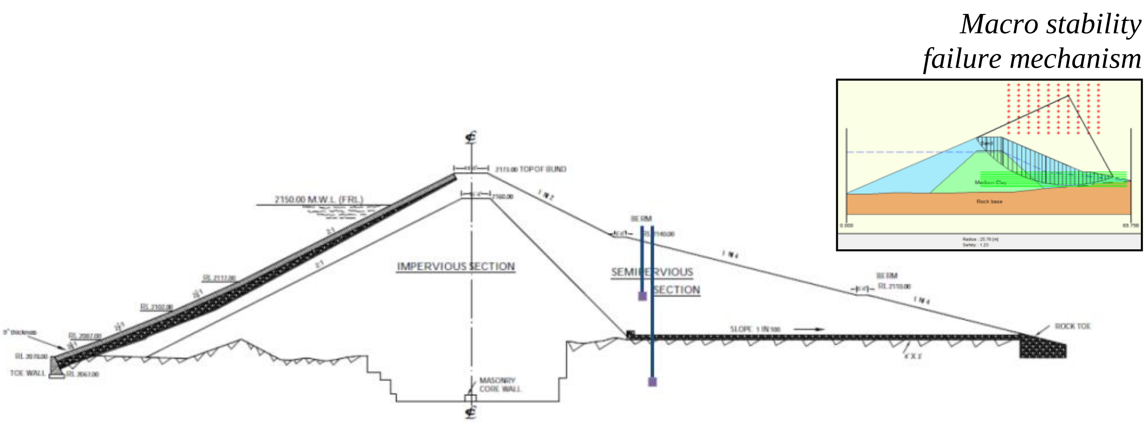


Figure 9. Instrumentation of Saddle dam 1 with a pore-water pressure sensor in the dam body and in the dam foundation, including considered failure mechanism

During the period from March 17 till April 27, 2018 the Bhadra dam reservoir level was decreasing from 645.71 [m RL] till 638.74 [m RL], that is a diminution of approximately 7 m. This diminution is result of the water use for irrigation and drinking water and because of evaporation.

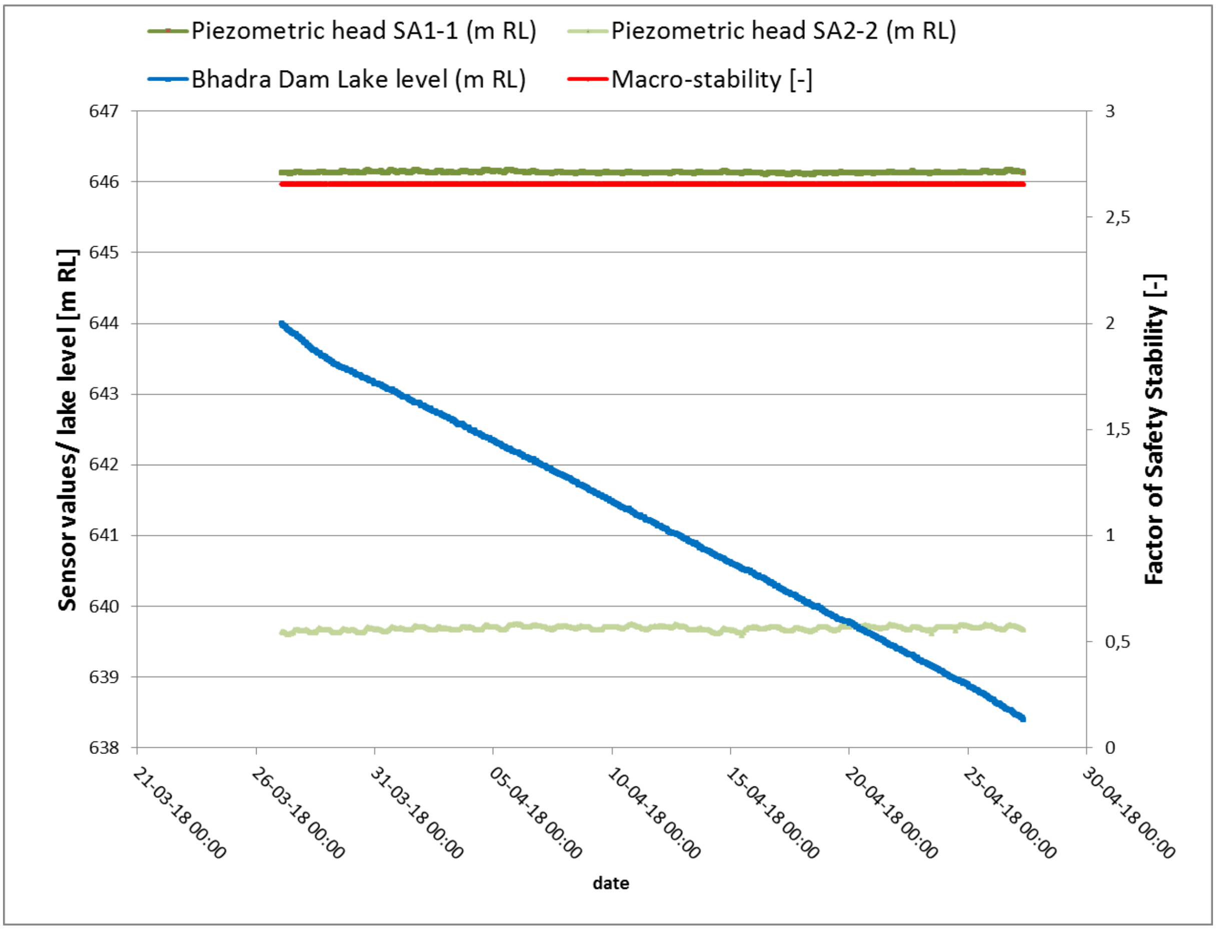


Figure 10. Macro stability down stream Sadde dam 1

The piezo-metric head of sensors SA1-1 and SA2-2 showed in that period no response to the decreasing of the Bhadra dam reservoir level. The sensors gave a relative flat line for that period. The reason for that is the impermeable core of the saddle dam. Because there is no direct response of the piezo-metric head to the lowering of the Bhadra dam reservoir (as shown in the graph of Figure 10), it can be concluded that on this location the dam core is functioning well. As a result also no change is observed in the safety factor of the real time calculated macro stability.

CONCLUSION

In this paper an innovative approach was presented on the monitoring of stability of dams. The use of PS-InSAR (radar) measurements from a satellite platform offers the possibility to detect anomalies in the dam deformation pattern indicating a possible deterioration process. Further inspection of detected anomalies is needed to verify the observation and, if necessary, investigate the root cause and implement actions to prevent possible damage. The systematic monitoring of dams with PS-InSAR will in the long-term contribute to optimization of Operation and Maintenance (O&M).

In the pilot of the Bhadra dam-reservoir system, the integration of in-situ measurements with numerical calculations is demonstrated using the Delft-FEWS software platform. Based on observed water levels in the reservoir and pore-water pressure measurements in the dam body and dam foundation, the stability of the dam for certain failure mechanism is calculated in real time. This information can be used by the dam owner to control flood risk.

Based on weather forecasting, the Delft-FEWS system also supplies information on forecasting of water inflow and expected water levels in the reservoir. In combination with Real Time Control (RTC) of reservoir operation, this information can be used to improve water management and that will increase performance of the reservoir.

A next step will be the correlation between observed water levels in the reservoir and the pore-water pressure measurements. This will be possible when sufficient data becomes available of the reservoir at low water level and maximum water level during the monsoon. The forecasting of inflow of water in the reservoir and expected water levels at the dam will then allow us to go beyond real time stability monitoring. This means that the safety factor of the dam for the considered failure mechanisms can be forecasted days ahead. In critical situations this information will be important for dam owners, first responders and responsible government agencies and allow for a timely deployment of emergency response actions (e.g. evacuation).

AKNOWLEGDEMENTS

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