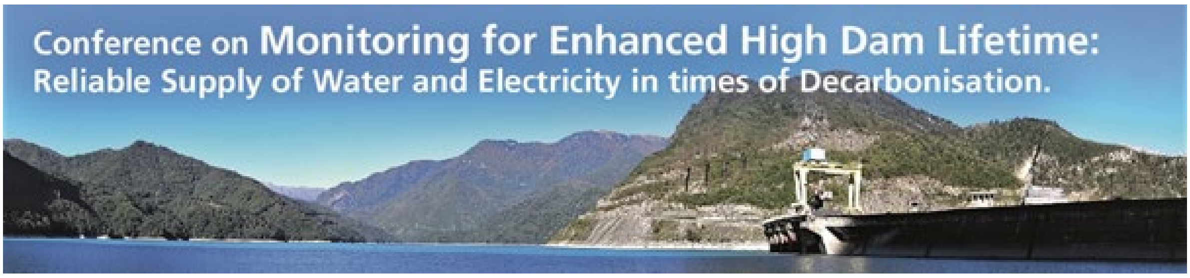


September 15, 2022, 9:00 a.m. to 4:00 p.m.

Ivane Javakhishvili Tbilisi State University

1 Ilia Chavchavadze Avenue, Second floor, Lobby of the assembly hall

This is the second conference on “**Monitoring for High Dam Lifetime: Reliable Supply of Water and Electricity in times of Decarbonization**”. The importance of water reservoirs increases due to the demand for a successful energy transition and climate change challenges, such as heavy precipitation and flooding on one and long droughts on the other hand.

The DAMAST project (2019-2022) aimed to make contributions to their long-term safe and efficient operation. The objective was to develop, install and test monitoring systems transferrable to other dams. The project used innovative methods for the collection and analysis of relevant data. DAMAST was dedicated to the long-term efficiency of reservoir operation and to avoid the construction of replacement storage capacity.

The succeeding project DAMAST -Transfer (2022-2024) aims on sharing the knowledge gained within DAMAST to help the freshwater management and to supply the public with clean, reliable and affordable power. This project is the first step towards a Scientific Centre of Competence in the Caucasus. Such a centre would be ideal to combine the goals of climate change and energy security.

Sustainable use of water reservoirs for irrigation and hydropower requires more recognition and a long-term strategy. Significant improvements in the performance and significant improvement in environmental protection can be gained by a holistic approach, from monitoring to adaptive reservoir management. These improvements will also meet expectations of society and authorities.

Goal of the Conference

The morning sessions of the conference will highlight the major results of the DAMAST project and the achievements which we have reached so far during the co-operation between Georgian scientists from TSU and GTU and German Scientists from EIFER, Piewak & Partner and KIT in co-operation with the Engurhesi Ltd. We will demonstrate the monitoring systems and the results of the first ca. 2 years of measurements in presentations on seismicity, geomechanics, regional and dam deformation studies as well as brand-new findings on internal sediment motion within the Jvari reservoir.

In the breaks there is the chance to visit the posters of our young and highly motivated PhD students.

The first part of the afternoon is dedicated as kick-off to the new DAMAST-Transfer project. Here we will indicate the potential of further investigations and training which is planned to be the first step towards a scientific centre with the focus on efficient and safe operation of high dams for hydropower, water supply and irrigation purposes.

Time	**Topic**
9:00 a.m.	Welcome KIT Welcome Notes Georgian Ministries, German Embassy, BMBF Delegation, TSU
Session I:	**DAMAST – Main Results**
9:25 a.m.	Seismicity Nino Tsereteli, Andreas Rietbrock, Michael Frietsch....
9:50 a.m.	Stress Investigations around Enguri High Dam: Field Observations and Numerical Modelling Thomas Niederhuber, Birgit Müller, Thomas Röckel, George Melikadze, Marian Kalabegishvili, Tamaz Chelidze
10:15 a.m.	Coffee/Tea Break
10:45 a.m.	Local and Regional Geodetic Monitoring Using Radar Interferometric Imaging and GNSS Matthieu Rebmeister, Jakob Weisgerber, David Svanadze, Hansjörg Kutterer, Malte Westerhaus, Andreas Schenk, Stefan Hinz
11:10 a.m.	Sedimentation and Morphodynamics Andreas Kron, Stephan Hilgert, Klajdi Sotiri
11:35 a.m.	Transfer: From DAMAST Project to further Research and Development on Dams and Seismicity Frank Schilling, Birgit Müller
Session II: 12:00 – 1:00 p.m.	Poster Session with Finger Food and Beverages

Session III:	**DAAD-SDG and DAMAST-Transfer**
1:00 p.m.	Student Training Activities in DAAD-SDG Andreas Schenk, Nino Tsereteli
1:15 p.m.	**DAMAST-Transfer Activities towards a local Scientific Centre on High Dams**
1:15 p.m.	Geomechanics - Monitoring Potential at Georgian High Dams Thomas Niederhuber, Birgit Müller, Thomas Röckel, George Melikadze, Marian Kalabegishvili, Tamaz Chelidze
1:30 p.m.	Towards Hazard analysis and Risk Mitigation: Early Warning and Measures Sadeeb Simon Ottenburger
1:45 p.m.	Geology: First Results of July Field Trip and Foreseen Activities Dennis Quandt, Onise Enukidze
2:00 p.m.	Sedimentation and Morphodynamics: Expert Training & Field measurements Andreas Kron, Stephan Hilgert, Klajdi Sotiri
2:15 p.m.	Using Modern Sensor Technology for Dam Monitoring Roman Zorn
2:30 p.m.	Regional and Local Deformation: Network Expansion & Expert Training Hansjörg Kutterer, Malte Westerhaus, Andreas Schenk, David Svanadze, Jakob Weisgerber, Matthieu Rebmeister
2:45 p.m.	Seismicity: First July Field Activities and Future Works Nino Tsereteli, Michael Frietsch, Andreas Rietbrock
3:00 p.m.	Discussion and Concluding Remarks
3:30 p.m.	Coffee/Tea Break, End of the Conference
4:00 p.m.	Internal Discussion Forum between Representatives of the Georgian Ministry of Economy and Sustainable Development, Ministry of Education and Research, the Delegation of the BMBF and leading Scientists of DAMAST-Transfer
7:00 p.m.	Dinner

Abstracts: Morning Session: DAMAST – Main Results

Current seismicity around Enguri dam reservoir

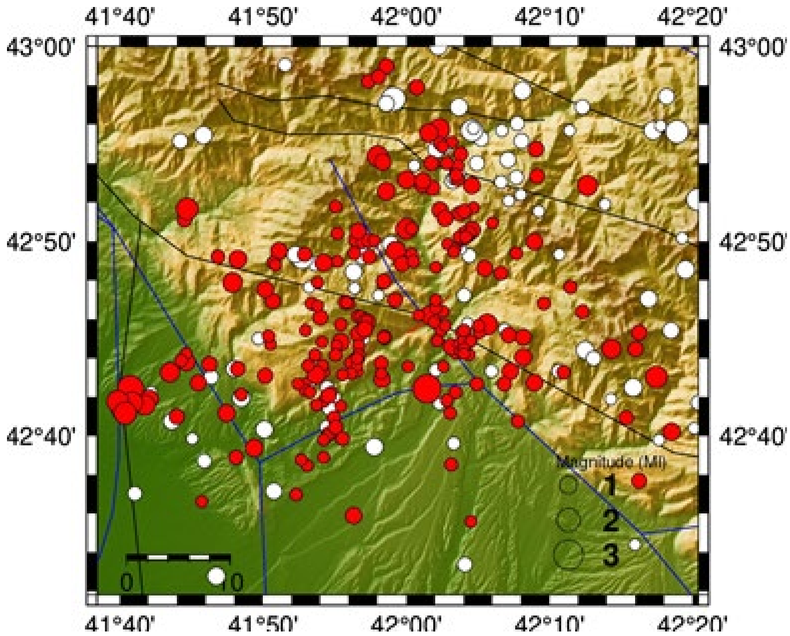
Nasim Karamzadeh, Nino Tsereteli, Emmanuel Gaucher, Nazi Tughushi, Tamar Shubladze, Michael Frietsch, Felix Bögelspacher, Andreas Rietbrock

In the framework of DAMAST (Dams and Seismicity) we deployed a dense high fidelity seismological real time network consisting of eight seismic broadband stations close to the dam structure. Particularly, high sensitivity detection capabilities is reached around Ingirishi fault segments. The network regional extent is completed with five surface stations in Nenskra region. We investigate the current state of seismicity at Enguri high dam area and Nenskra region in detail to study the possible relationship between the filling level of the reservoirs and seismicity. To lower the detection threshold by reducing the ambient background noise we installed four seismic stations in boreholes. From these KIT1 with a depth of ca. 250m is the deepest seismological station in Georgia. The remaining borehole stations are installed in 17-19 m depths. All stations are equipped with broadband sensor, Nanometrics Trillium compact posthole 20 s or MBB-2, Kinemetrics, while one offline short period sensor is installed in hydroelectric power plant building in Abkhazian territory, to increase the location accuracy of events occurring close to the Gali reservoir.

By analysing the data recorded until the early July 2022, more than 450 local events are detected, of which the location of 320 events fits into our area of interest. Ongoing seismicity monitoring of the area shows some local sources of seismicity, however identification of active faults branches, geometry and slip mechanism and the response of seismicity to the dam reservoir water level change are subject of our ongoing study. According to the current seismicity map, Ingirishi fault, which was one of the monitoring targets in this study is active and generates microseismicity. In addition, two distinct seismic swarms and several time-spatial clusters are observed in the area. The faults passing the dam, are active and generate earthquakes with magnitude above 1.5 Ml at close distances to the dam. While the estimated magnitude of most of events is below 1 Ml, two cases of magnitude above Ml 2 are also observed. The majority of events occurred in shallow depth of about 4 km.

Beside the real time monitoring of the seismicity around the dam, we updated the old analog data using up-to-date location methods to have a better image of seismicity about, during and shortly after dam installation. Comparing the old and recent seismicity of the region, location of active sources are consistent.

The local network is still in operation and the data processing is ongoing to provide resources to study possible correlation of seismicity and dam reservoir water level change. However, for an in depth study a longer time period of well located seismicity is needed to observe several cycles of dam water level change.

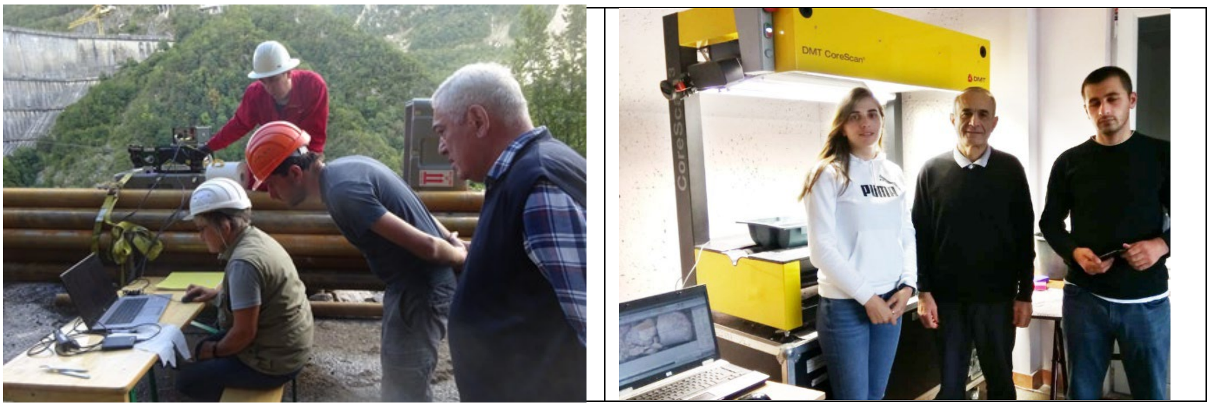


Seismicity map obtained using the local seismic network currently operating at Enguri site. White circles represent the events that are poorly located (error greater than 5 km in at least one of hypocentral parameters). Scattered seismicity as well as clusters close to the fault lines are observed. The size of the circles are scaled base on events magnitude.

Geomechanics – Monitoring Potential at Georgian High Dams

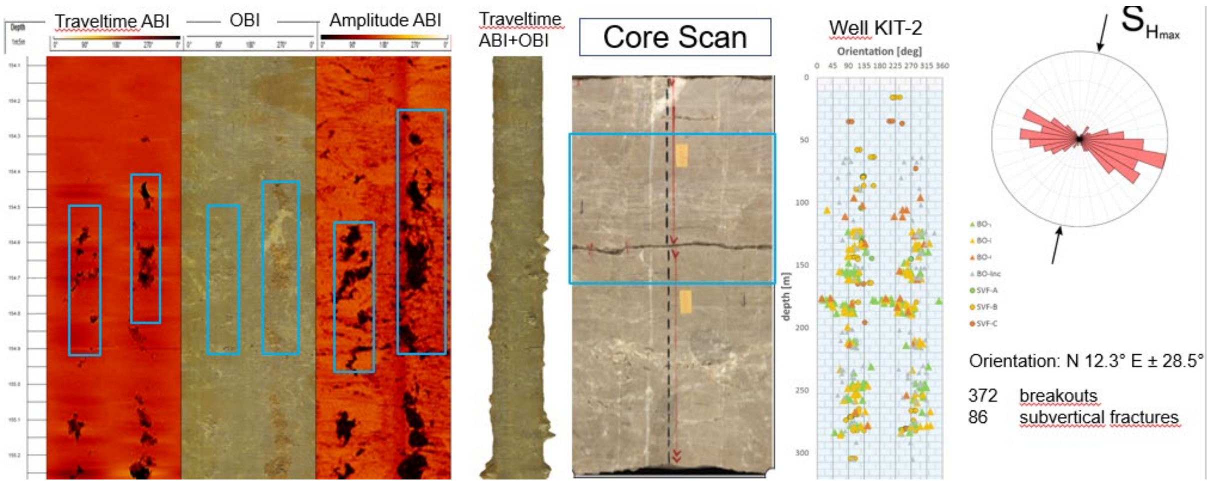
Birgit Müller, Thomas Röckel, Thomas Niederhuber, Frank Schilling (KIT), George Melikadze (TSU), Marian Kalabegishvili (GTU)

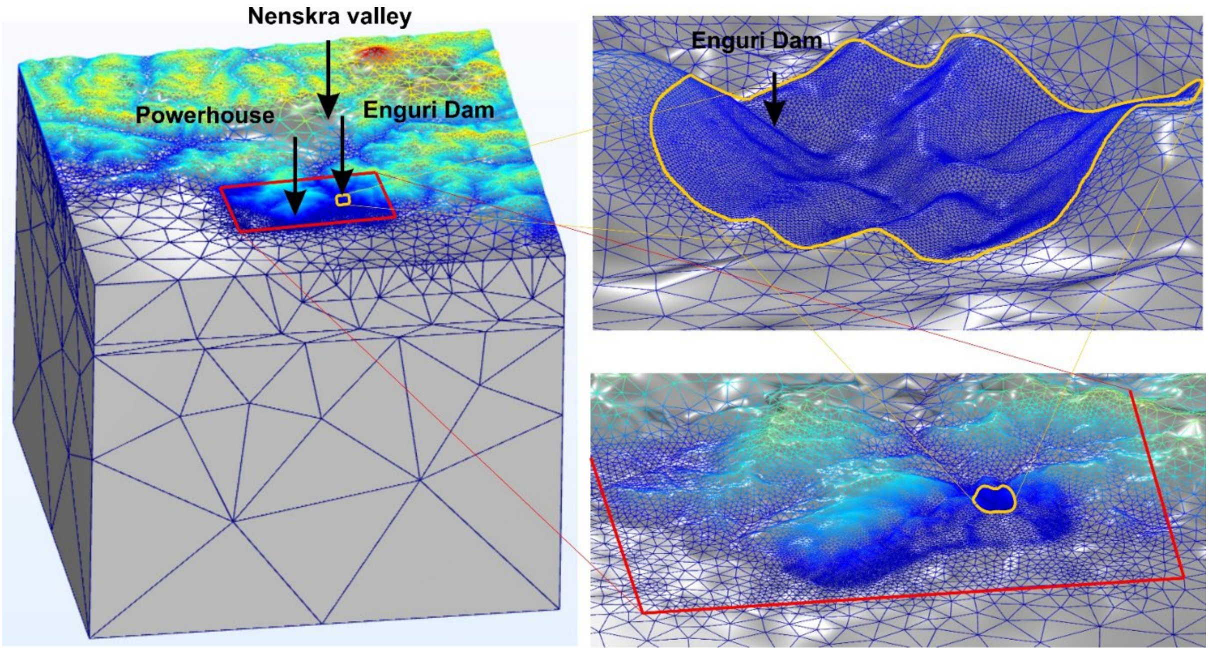
To reach our goal of understanding the state of stress at the fault systems around Enguri dam, drilling and logging and numerical modelling has been performed. In this framework we could provide also feedback to the companies providing the software, in order to improve the systems.



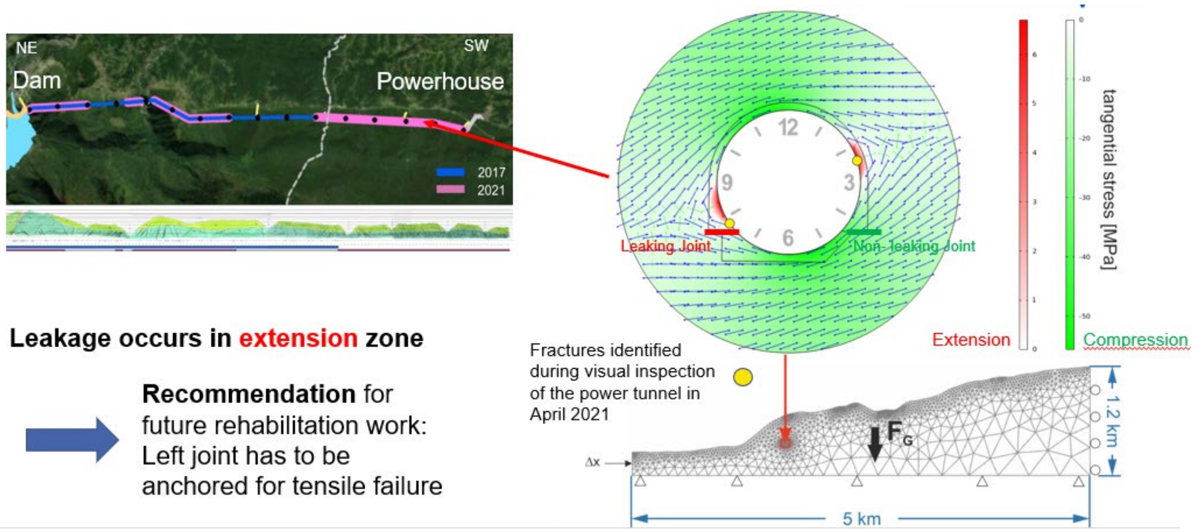
Left: Logging of Borehole KIT-1 with acoustic borehole televiewer (ABI). Right: Colleagues of GTU have been trained in scanning drillcores.

More than 1000 m of drillcores have been analysed so far. This was done with classical geological analysis in combination with scans of the Modern logging tools can provide optical and analytical images from the borehole walls along the depth. We compared these data with the analysed drill cores and high-resolution scans of drill cores. With this approach we could orient the drill cores and obtain detailed information on the stress orientation, which is an important information for future engineering activities at the flanks of Enguri dam. Additional information on stress magnitudes was obtained from minifrac measurements in some of the wells. This information is used (in combination with geodetic and seismological observations) to understand the processes of induced seismicity at high dams – not only in Georgia.





High resolution numerical modelling highlights the importance of topographical influence for the stresses around Enguri Dam. The stress field in the Enguri Valley is highly variable which has to be considered in the engineering also of other infrastructures such as power tunnels and rehabilitation works to stabilize foundations. The modelled stress field has been confirmed by the stress data from the field observations. This is important if it is used for engineering applications. We applied it to explain the asymmetrical leakage of construction joints in the power tunnel that links the Jvari Reservoir and Enguri Dam with the Powerhouse.



Local and regional geodetic monitoring using radar interferometric imaging and GNSS

Matthieu Rebmeister, Jakob Weisgerber, David Svanadze, Hansjörg Kutterer, Malte Westerhaus, Stefan Hinz, Andreas Schenk

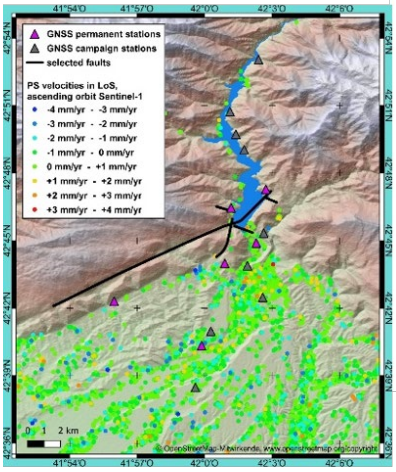
As part of the DAMAST project, geodetic infrastructure was established in the vicinity of the Enguri dam and the reservoir. It consists of a satellite-based component with a potential to observe regional tectonic and morphologic deformation, and a ground-based component with high temporal and spatial resolution in order to precisely monitor deformations of the dam and it's abutments. Fusion of the applied techniques is supposed to resolve 3D displacement vectors of the dam in response to different load sources.

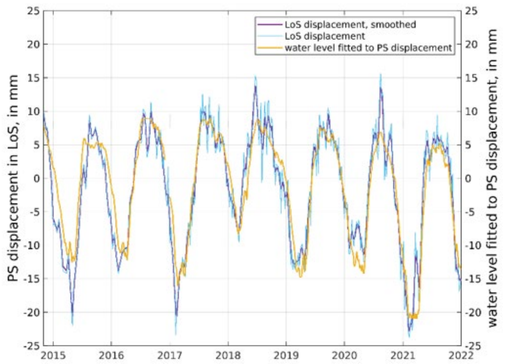
Deformation monitoring with space-borne geodetic observations

The aim of the spaceborne techniques is to record regional deformation. This generally includes ground movements in the regional strain field, specifically potential shortening tendencies due to convergent motions of the Arabian and Eurasian plates, as well as movements along the local Ingirishi fault and landslides. The system includes a high-resolution component dedicated to measure the response of the dam to the seasonal water level variations from space and to serve as a link to the ground-based observations. In order to fulfill the aims, satellite-based measurement techniques, namely GNSS (Global Navigation Satellite Systems) and SAR interferometry (Synthetic Aperture Radar interferometry) with different wave lengths is used.

Six GNSS stations were set up in the study area on pillars with deep foundations, which provide permanent measurements. Furthermore, nine measuring points were marked, which are occupied by repeated GNSS campaign measurements. GNSS measurements provide three-dimensional movements of the stations.

For the radar interferometric evaluations, imagery from the Sentinel-1 satellites, as well as the TerraSAR-X and Alos-2 satellite is used. The satellites measure at different wavelengths, which opens up the possibility of comprehensive deformation analysis. With the processing approach of Persistent Scatterer Radar Interferometry (PS-InSAR), several 10.000s of measurement points establish in the entire study area. In total, six corner reflectors are installed in the field, which act as a stable reference for the radar measurements. Results of the interferometric radar processing are one-dimensional displacements between ground point and satellite.





Left: geodetic infrastructure in the Enguri valley and its foreland. Right: comparison of point displacements, observed by the SAR-satellite Sentinel 1, and water level.

The evaluation of GNSS data recorded during the project period shows low to moderate measurement noise, depending on the site conditions. The detection threshold of the network for a single observation is in the low cm range for vertical and few millimeters range for horizontal displacements. Long-term trends in the GNSS time series are not significant, indicating the stability of the foundations. Stations close to the reservoir reveal seasonal displacements of a few mm in the horizontal and few cm in the vertical, which correlate with the water level in the reservoir. The directions of movement do not conflict with a simple water load model. We conclude that the regional tectonic displacement rates are low, and that long-term observation is necessary to resolve tectonic shortening or fault-related movements. The fully operable station network will be handed over to the Georgian partners during the DAMAST Transfer project.

The PS analysis of the radar data results in a high density of measurement point (PS-points) in built-up areas. By adjusting the evaluation procedure accordingly, a number of measuring points establish on the dam wall and on the shoreline of the reservoir. For high-quality PS-points, displacements of a few millimeters are resolved. Correlations between the water level and displacement time series are seen for measuring points that meet the quality criteria for a reliable evaluation while being located on the dam wall or on the shoreline. Displacements of up to three centimeters are observed at the dam.

Imaging of structural deformation with ground-based interferometric SAR (GBSAR)

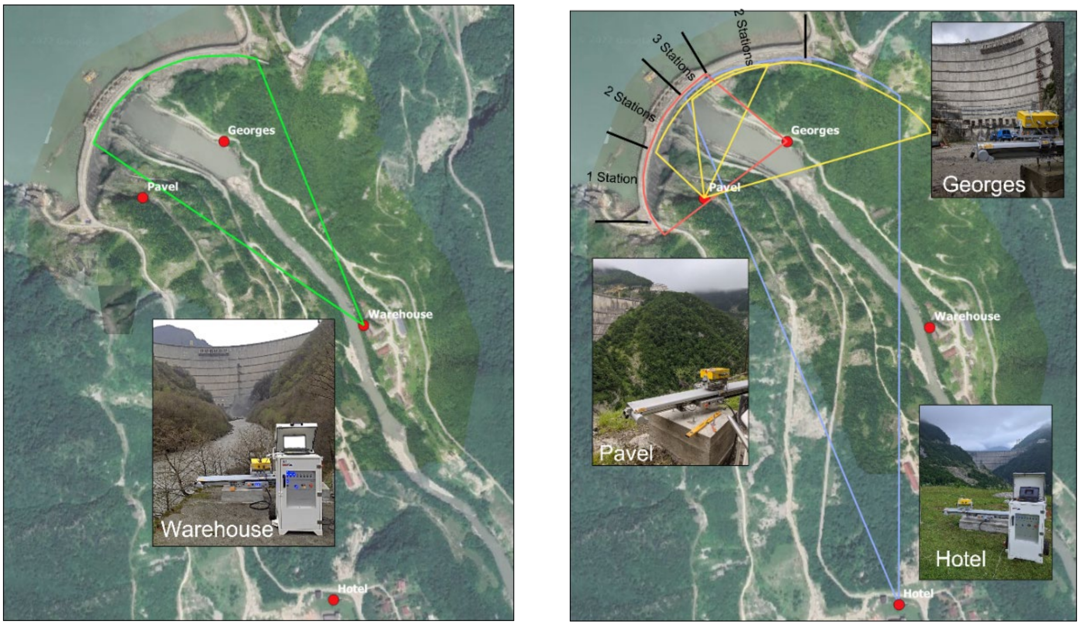
The local component of the combined geodetic and remote sensing monitoring network aims at imaging the displacement of the Enguri dam which is mainly caused by the changing water table in the reservoir but also by changing wind loads and thermal dilatation of the dam. It is important to study and understand the dynamic response of the dam to such expected regular stresses in order to be able to clearly differentiate such deformation from other sources like change in tectonic stresses or thrust bearings. Therefore, geodetic imaging with ground-based SAR (GBSAR) also includes the immediate vicinity of the dam in order to study deformation transfer.

In this project a ground-based Ku-band GBSAR measuring system is employed as the central element of local structural monitoring. GBSAR is comparable to satellite-based SAR interferometry in terms of the measurement concept. Based on interferometric analysis, the movement of the dam can be mapped. However, compared to satellite-based SAR interferometry, the spatial and temporal resolution of GBSAR is much higher. Unlike space-borne SAR, the ground based sensor is more sensitive towards horizontal displacement because of its more or less horizontal imaging geometry. Therefore, both systems in combination provide an optimal geodetic measurement setup.

The GBSAR is used in two measurement programs to regularly monitor both the dam structure and its connection to the mountains and the slopes along the reservoir:

- Campaign measurements are carried out from three observation positions twice a year.
- The rest of the time, the GBSAR is installed at a central observation point and used as a permanent measuring device for dam monitoring. The high-resolution GBSAR data is evaluated using an adapted PSI methodology, taking into account metadata such as temperature and water level.

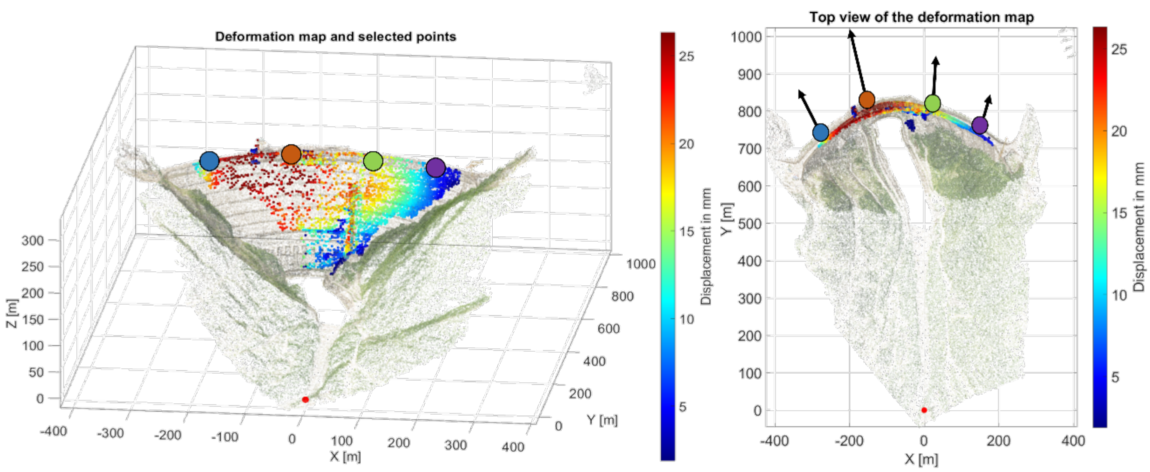
Special Ku-band corner reflectors are installed at 9 observation points on the dam. They serve both as a local link for repeated campaign measurements and for integration into the geodetic datum provided by the GNSS survey.



GBSAR installation concept at Enguri dam - Left: Longterm station – Right: Campaign stations

The GBSAR provides a complete observation of the dam every 2 minutes, allowing continuous and automatic monitoring of the dam. The processing of GB-SAR data requires many different algorithms and steps. Therefore, a complete software was developed to process and evaluate the data. Averaging of nighttime observations is a practical solution for a processing of GBSAR data to minimize the atmospheric signal i.e. an apparent displacement of the observed points caused by variation of the atmospheric conditions.

These results shows a very high correlation between the water level and the displacement. The maximum displacement for points at the dam is 35 mm for a total water level change of 60 m. If the water level decreases rapidly, the pressure at the dam will decrease and the dam will move in upstream direction away from the GBSAR. When the water level is fairly constant in the successive time period, the points at the dam then show a small movement in the opposite direction. This phenomenon may be explained with creep.



Results for the period from 06/10/2021 to 06/04/2022 from the Warehouse standpoint.

The campaign measurements enable a monitoring only a few times a year, but from different observation points. They also deliver a deformation map of the whole observed part of the dam, meaning several thousands of observed points under a different line of wight and thus enable to observe the full 3D displacement vector at parts of the dam. Processing of these data is a much more laborious task, but first results of present campaigns show good agreement with the magnitude of the displacement from observed from the long-term monitoring station.

Fusion of methods

The combination of the applied methods with respect to the 3D deformation field is a main focus of the scientific part of the DAMAST transfer project. A prerequisite is to solve challenges with phase unwrapping and georeferencing along the 270 m high, vertically and horizontally arched wall. Adapted algorithms are currently finalized.

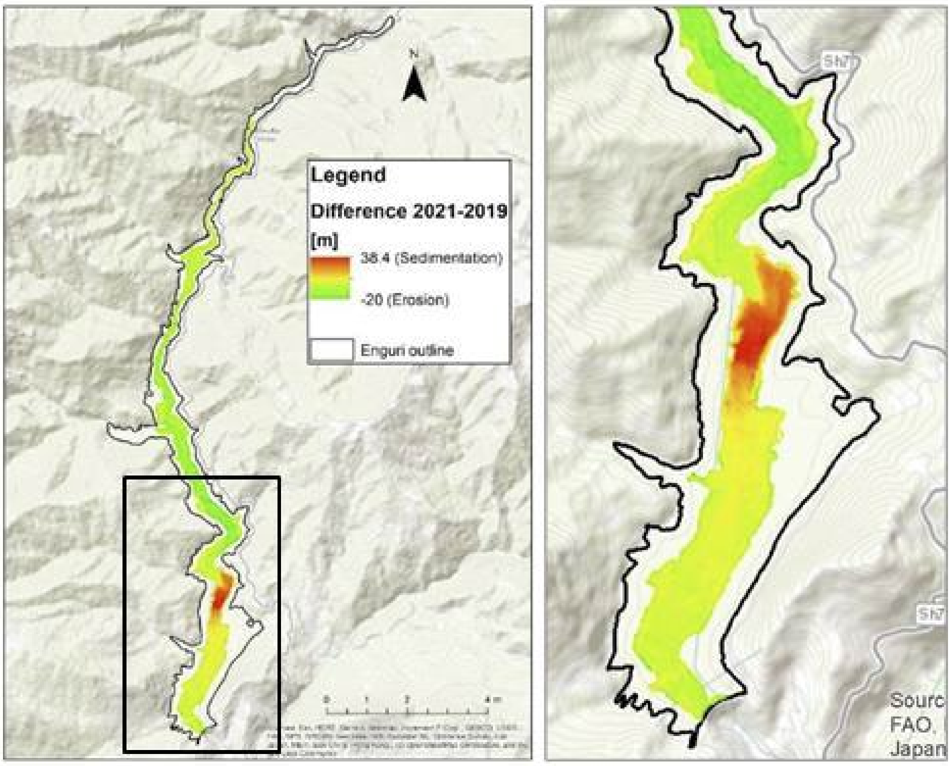
Sedimentation and Morphodynamics

Andreas Kron, Stephan Hilgert, Klajdi Sotiri

Bathymetric Survey

In order to record the change in reservoir volume and thus the rate of siltation, the lake was surveyed over its entire area in October 2019 and October 2021. The recorded acoustic data were corrected using vertical sound velocity measurements to obtain accurate results even in areas of great water depth. Water level fluctuations were documented over the measurement periods and used to correct the depth measurements. Once the outer "survey outline" was defined, various filters could be applied to the bathymetric dataset. Approximately 14,000,000 individual survey points were defined as the final point cloud for the 2019 survey and approximately 20,000,000 for the 2021 survey. Depth grids with a resolution of 1x1m were generated for both surveys. From this, 3D models were created, which were used to derive the level-volume curve and interpret the morphology. Volumes could be assigned to the varying water levels, which already allows to calculate the variations of the surcharge.

The two depth grids were superimposed, and the difference calculated. The areas with erosion or deposition could be determined. In addition, the precise measurements allow the determination of the change in sediment volumes.



Seismic Survey – Sediment Volume and Stratigraphy

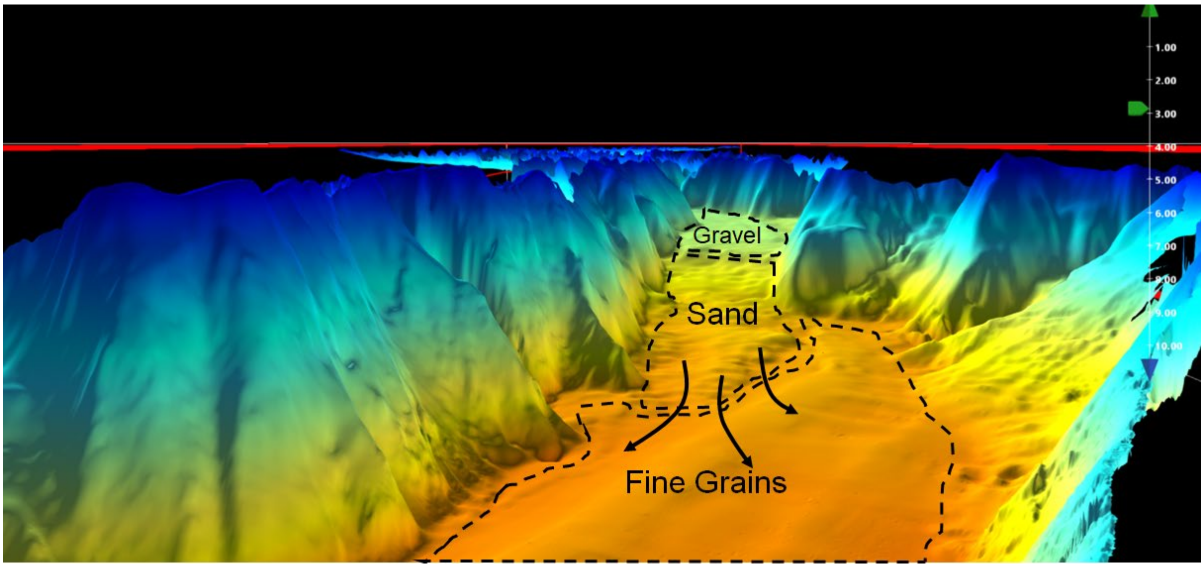
With the aim to investigate the sediment stratification and the sediment thickness in the Jvari reservoir, two measurement campaigns were carried out. In parallel to the bathymetric survey with the multibeam echo sounder, seismic measurements were made with two different sub-bottom profilers. For the investigation of sediment layering and sediment thickness, a survey was made using a sub-bottom profiler (SES 2000 compact). The survey was repeated with a stronger SES 100 medium. The increased strength of the SES 100 aimed to better explore the stratification in the sediment front.

From the data, it appears that the sediment front is of great safety interest. In addition to the progressive movement of the front, the structure or stability also seems to be of importance for dam safety. The front had an elevation difference of about 45m from crest to bottom in 2019. This makes the front potentially steep enough to start moving during an earthquake. In 2021, the front still exhibited a steep flank, although it was about 5m lower than in 2019, remaining still a potential safety hazard. In the same time the sediment front moved ca. 800 m towards the dam.

The sedimentation rate of the Jvari reservoir has been calculated and is 0.52%/year. This corresponds to an accumulated sediment volume of about 220 million m³ and about 420 million tons. Due to the shift of the sediment front towards the dam, the results underline the urgent need for action in the planning and improvement of measures such as sediment flushing.

From the area which forms the dam root during low water, coarse grains separate from fine grains. There is a strong gradient in grain size distribution along the "sediment front" about 4 km upstream of the dam. Here, gravelly sediments transition to sandy and then to fine, silty sediments.

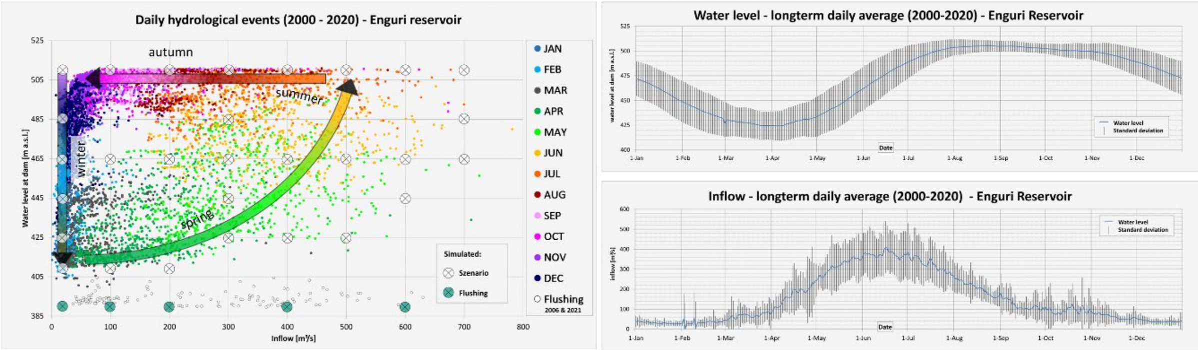
During the investigation of the sediment front, the penetration with the SES 100 medium was only slightly improved. From this, the composition of the upper layer on the front can be deduced. It is a compact gravel-sand mixture several meters thick. From the resurvey in 2021, an additional important aspect can be deduced. The sediment front, with its primarily coarse constituents, is pushing over the previously deposited fines. From a reservoir management perspective, this is an important fact. When the soft and fine sediments are covered by sand and gravel, it becomes particularly difficult to remove them from the lake by measures such as "flushing". There is no economic-technical solution for such a sediment condition.



Data evaluation and derivation of scenarios

Based on the data of the HPP Enguri, the boundary conditions relevant for the numerical modeling (inflow, water level, water withdrawal etc.) has been derived. Water losses due to seepage and overflow as well as event-specific discharge via the spillway were taken from the provided data of Engurhesi Ltd.

From the period 01.01.2000 to 16.02.2020 daily data for a total of approx. 7,000 individual events has been taken for evaluation. These were classified according to discharge and water level and finally bundled into 29 representative events for hydraulic simulation.



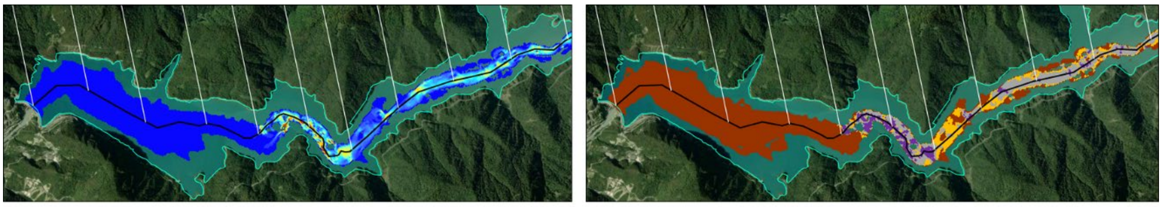
Model setup

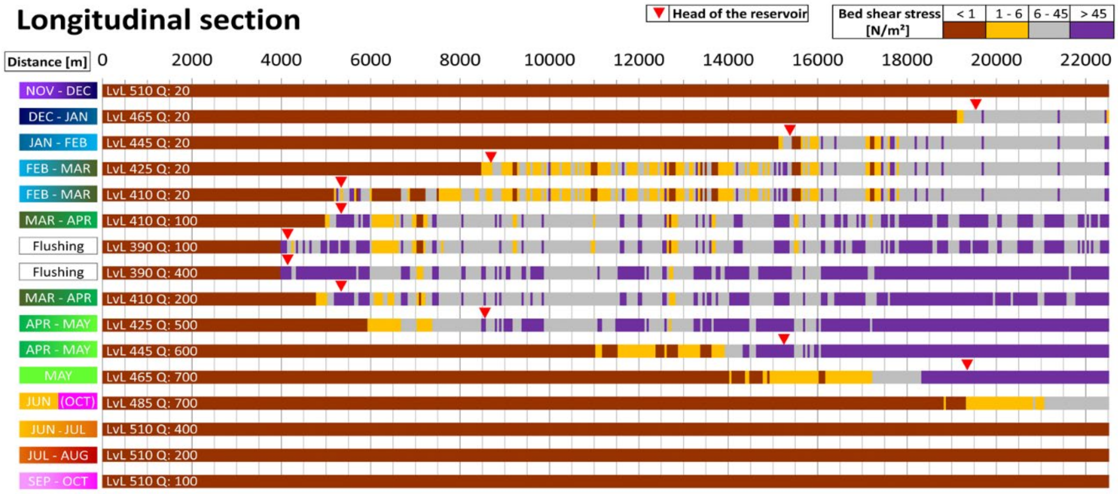
For the hydrodynamic-numerical simulation the software Delft-3D (deltares) was used. The final model consists of 241.040 cells with a size of 16.7x16.7 m each. the total length covers an area up to approx. 22,5 km upstream of the dam. The model is vertically discretized into five layers with a 20%-sigma model, which adapts the cell height to the water depth. Discharge is used as the upper and the water level as the lower boundary condition.

The head of the reservoir is mainly dependent on the water level at the dam and only to a lesser extent on the discharge rate. The seasonal dynamic of water level is crucial for the sediment transport.

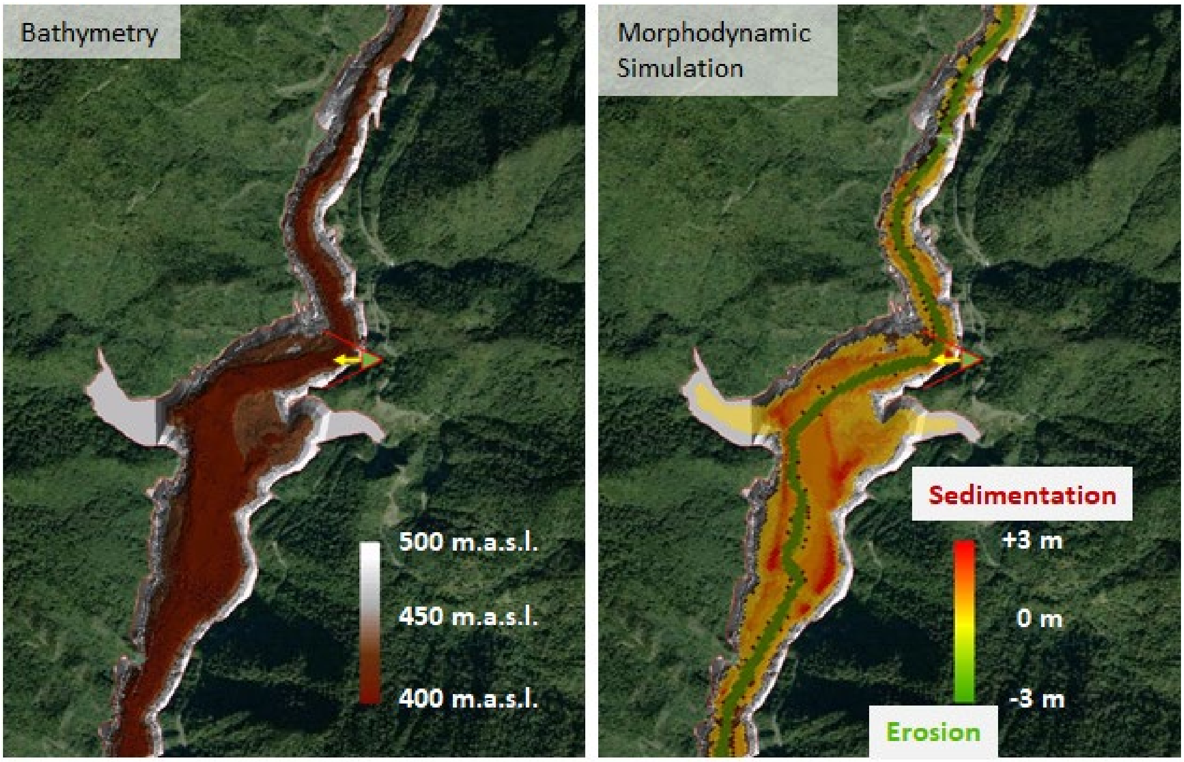
During summer, autumn and winter months an input of only fine material (brown) takes place, in the spring months transport of gravel (grey) and sand (yellow) is possible up to a distance of approx. 4 – 5 km to the dam. As a result, an alluvial cone has formed at this point, which could be verified in the measurements.

Likewise, reservoir flushing measures in the vicinity of the dam wall show movements of only very fine material.





The period of water level drop (October 2019 - March 2020) was simulated based on the recorded bathymetry and assuming sediment parameters to analyze the sedimentation and erosion processes in the reservoir. Results show that even complex areas of the impoundment as well as the observed erosion processes can be reproduced by the model. A further improvement of the morphodynamic model results will be achieved with additionally determined sediment parameters and the iterative adjustment of the model in the next project phase.



Abstracts Afternoon Session: DAMAST-Transfer Activities towards a local Scientific Centre on High Dams

Geomechanics – Monitoring Potential at Georgian High Dams

Thomas Niederhuber, Birgit Müller, Thomas Röckel, George Melikadze, Marian Kalabegishvili, Tamaz Chelidze

Within DAMAST Transfer in cooperation with the DAAD SDG Caucasus, we intend to set up a monitoring well at the Enguri Dam, where researchers, technicians and students can be trained with modern logging equipment. Currently the drilling works are ongoing (202 m of 300 m have been drilled).

With drilling we get many drill cores, e.g. for KIT-2 we had 307 m of core data. These data will be analyzed for stress induced features such as petal & centerline fractures as well as natural fractures. In addition, the drillcores of the boreholes Nenskra and Spartak will be scanned with a special high resolution core scanner. The data gained from the drillcores will be compared to data gained from borehole logging.

From September 19 to September 23 students of GTU and TSU will be trained to perform drill core analysis, core scans, borehole logging and to finally do the interpretation of the data with modern software tools in order to derive tectonic stress and to address wellbore stability. Furthermore, as the next steps include a workshop on data infrastructure, the geomechanics team will contribute with expertise on archiving of drill cores and logging data.

Towards Hazard Analysis and Risk Mitigation: Early Warning and Measures

S.S. Ottenburger (KIT)

A sustainable energy system can only function in the long term if it has characteristics that help it to cope effectively with future risks and uncertainties. Central to this is the ability to provide early warning and, coupled with this, the ability to initiate effective countermeasures in a timely manner in order to minimize the effects of hazards and risks. In this context, the following questions have been investigated in DAMAST:

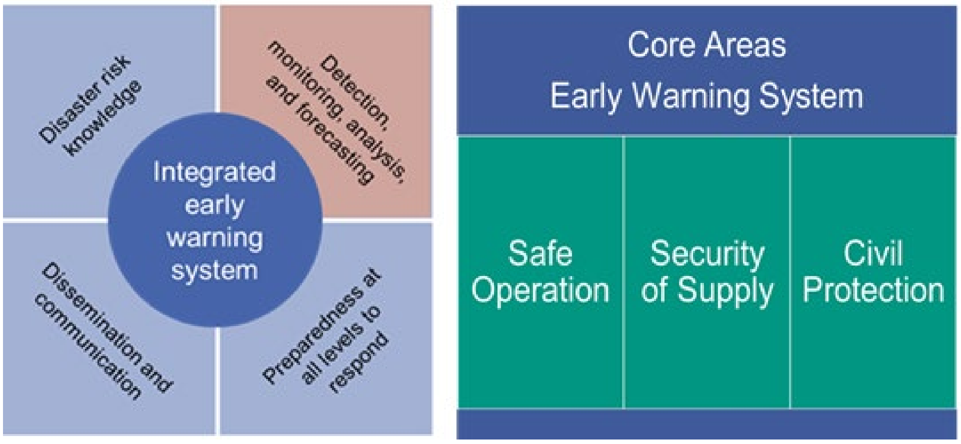
1. What are the objectives of an early warning system in the context of a dam and hydropower plant of the size and relevance of the one operated by Engurhesi, what are the risks in focus, and how does this affect the modularity of an early warning system?
2. What are the challenges in short- and medium-term data-based predictions of stress distribution on the dam e.g. in the context of (predicted) extreme precipitation events, which become more likely with climate change? Key aspects here: (i) Understanding nonlinear relationships and dynamics between measured quantities and stress distribution on the dam through data-driven methods and (ii) Dealing with rare events and extrapolation of unlearned extreme events – important for robustness and reliability of prediction.

A guiding principle of the work in DAMAST was: Safe operation of a dam in the face of extreme events can in many cases only be guaranteed if the operators have sufficient time, based on an appropriate forecast, to initiate countermeasures in advance. In this context, crucial and necessary criteria for a high-quality early warning system are the following: Ability to reliably and robustly predict critical situations with sufficient lead time until their possible occurrence, with timing as well as information on the possible impact of anticipated events being key variables here. These criteria are universal and must be understood and taken into account comprehensively in the core areas of ‚safe operation‘ (dam and power plant operators), ‚security of supply and energy system‘ (power plant and grid operators) and ‚civil protection‘ (authorities and emergency response organizations) when developing an integrated early warning concept.

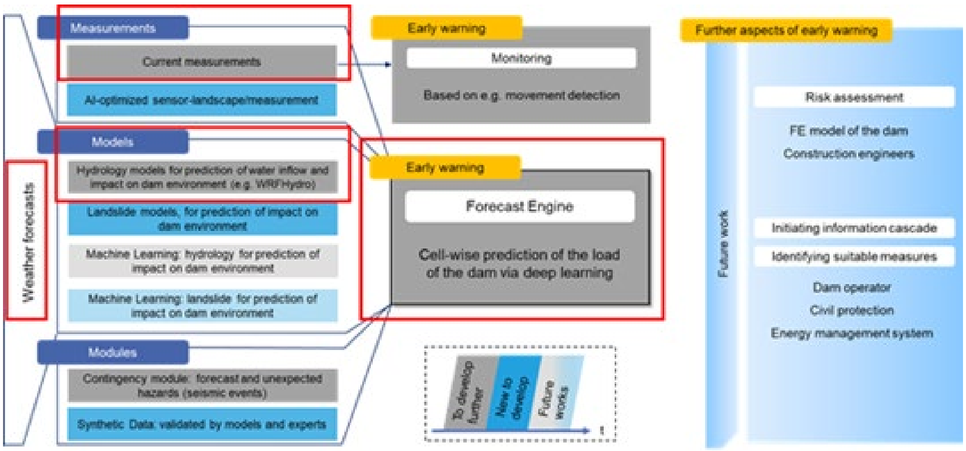
Even though in principle all core areas were considered in the overall concept, the focus in DAMAST was on the core area ‚Safe Operation‘ and a ‚Risk Prediction Module‘, which is ultimately fundamental for all core areas of an integrated early warning system, as this triggers all further activities, measures, etc. from the other core areas. In addition, this focus was primarily aimed at generating added value from the measurement data obtained in DAMAST for the prediction of induced hazards and risks, e.g. in the context of stress distribution on the dam or seismicity in the ambient environment. The scenario chosen in DAMAST was the stress distribution on the dam in the context of extreme precipitation, where the stress on the dam is influenced by level changes, pore pressures and (induced) seismicity, among other factors.

An essential knowledge base for the development of an early warning system, e.g. as an integral part of a geo-research center, has been developed in DAMAST. In addition to topics on the content scope of an integrated early warning system (prediction, core areas, communication interfaces, measures, etc.), questions on the scientific level, in the context of data science and risk prediction coupled with building parameters, as well as in the area of cyber security still need to be clarified for a technical implementation. Here, in DAMAST-Transfer, there is the possibility and necessity of a structured exchange with all relevant stakeholders from the core areas, a close cooperation on the scientific level, especially in the intersection of Data Science, Computer Science, Engineering and Geoscience.

DAMAST-Transfer creates further essential foundations and preconditions for enabling long-term safe operation of dams and a resilient and sustainable hydropower-based energy system. Due to new approaches and relevant issues, e.g. in the context of data-driven forecasting methodologies, new impulses for research are also generated, which sustainably enriches science in Georgia on different levels. Based on the approaches developed here, Caucasian countries and especially Georgia can take a leading role in the field of innovative early warning systems (e.g. data-based risk prediction) in the context of hydropower-based energy systems in the long term.



Modular concept for an integrated early warning system with the core areas (right).

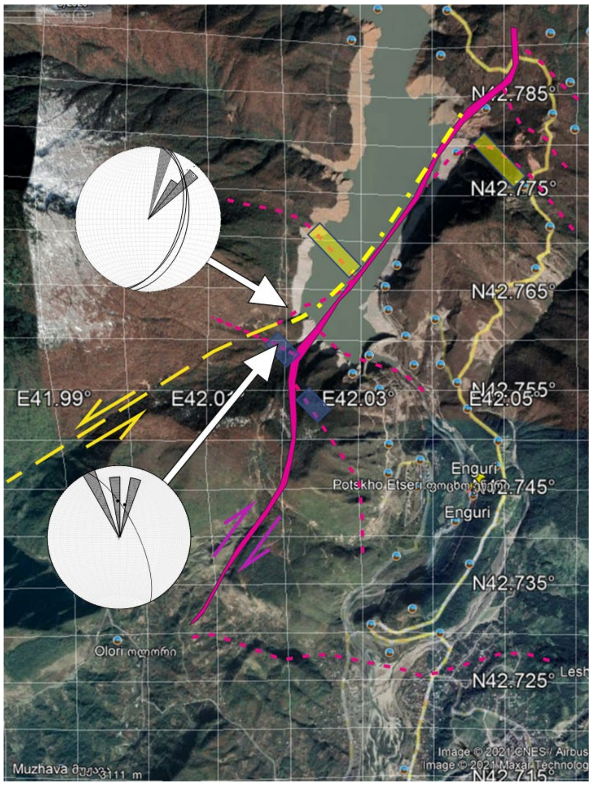


Left: Modular early warning concept (technical). The red boxes mark the focal points in DAMAST. Right: Topics addressed in DAMAST-Transfer which include information interfaces and countermeasures.

Geology: First Results of July Field Trip and Foreseen Activities

Dennis Quandt (KIT), Onise Enukidze (TSU), Jonas Greve (KIT)

In July 2022, a team of structural geologists from KIT and TSU together with students from TSU joined to investigate geological structures in the area of the Enguri Dam. Based on interpretations of old maps and surface morphological characteristics indicated by satellite data in the area of the Enguri Dam, a branching strike slip fault systems consisting of a sinistral and dextral branch was previously suggested by colleagues from the Institute of Technical Petrophysics at KIT.



Map of the Enguri Dam area showing the interpreted strike slip fault systems. The most promising study areas are located in the SW of the Enguri reservoir (white arrows) where rocks are exposed and approachable by boat.

View onto slickensides (see wet surfaces) measured in the SW of the Enguri reservoir. The slickensides indicate a sinistral shear direction on a NNE-SSW striking plane.

The goal of this field trip was to verify the previously interpreted strike slip fault system on-site using compass measurements and drone survey. For this purpose, suitable rock outcrops exposing faults were identified based on the study of satellite images. Promising study areas exposing rocks were approached by boat, drone and afoot. Fault plane orientations and shear directions of faults were determined using a geological compass. Out of five different study areas that were investigated in detail, two study areas in the SW of the Enguri reservoir proved to be of importance. Both were approached by boat. The structural data acquired at the northern of the two locations confirm the previous interpretation. There, slickensides indicate a sinistral shear direction on a plane striking NNE-SSW. The structural data acquired at the southern locations provided a NNW-SSE strike of a fault plane with dextral shear indicators contrasting the previous interpretation. However, dense vegetational cover and poor outcrop quality within a stream bed complicated the measurements.

In addition to the investigation of geological structures in the field, the Damast Transfer project also includes the establishment of a research center. Within this part of the project, the Institute of structural Geology at KIT-AGW contributes equipment and know-how to set up a thin section laboratory in Georgia. This equally involves technical equipment, accessories, and supplies as well as technical support via online and hands-on training. This in combination with the petrophysical properties will help to improve the understanding of the subsurface of the Enguri Dam area.

Sedimentation and Morphodynamics: Expert Training & Field measurements

Andreas Kron, Stephan Hilgert, Klajdi Sotiri

In the DAMAST project, extensive data were collected via the hydrographic-sedimentological explorations of the reservoir from the 2019 and 2021 measurement campaigns. From surveys from multibeam echo sounder, more than 15 million data points were collected, which were transferred into 2D maps and 3D models. From these data, information on sediment thickness and volume balancing can be obtained, which also provides information on the possible further development of sedimentation. In further measurement campaigns, which will be carried out together with Georgian colleagues, this data basis can be further improved and processed together. The aim is to teach the basics of hydrographic surveying with different echo sounders as well as of seismic exploration of the sediment layers. KIT will provide the equipment for the joint measurement campaigns. Afterwards, the workflow for data correction and the generation of 2D and 3D maps and grids will be developed. In the future, the Georgian partners should be able to process hydrographic and seismic data independently and to extract required information (e.g. reservoir volume) and to investigate it with respect to their questions. In perspective, the center should also be equipped to record the measurement campaigns with its own equipment.

The recording of sediment characteristics is an essential basis for the numerical simulation of the hydraulic-morphydynamic flow processes in the Enguri and the Jvari reservoir. A basic hydrodynamic-numerical 3D-model from the previous project is to be further elaborated together with colleagues from Georgia in order to develop a forecasting tool for estimating the annual sedimentation and relocation processes in the reservoir. With this tool, the effects of targeted reservoir flushing at different times and with different intensities can be estimated in order to develop an optimized sediment management. In the previous project, two discharge gauges were set up at Enguri and Nenskra, which are permanent measuring stations that measure water levels and flow velocities several times a day and use them to calculate discharge. These data will be made permanently available to the center for processing. In addition, measuring systems for mobile discharge measurement are to be purchased and used in joint measuring campaigns.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Using Modern Sensor Technology for Dam Monitoring

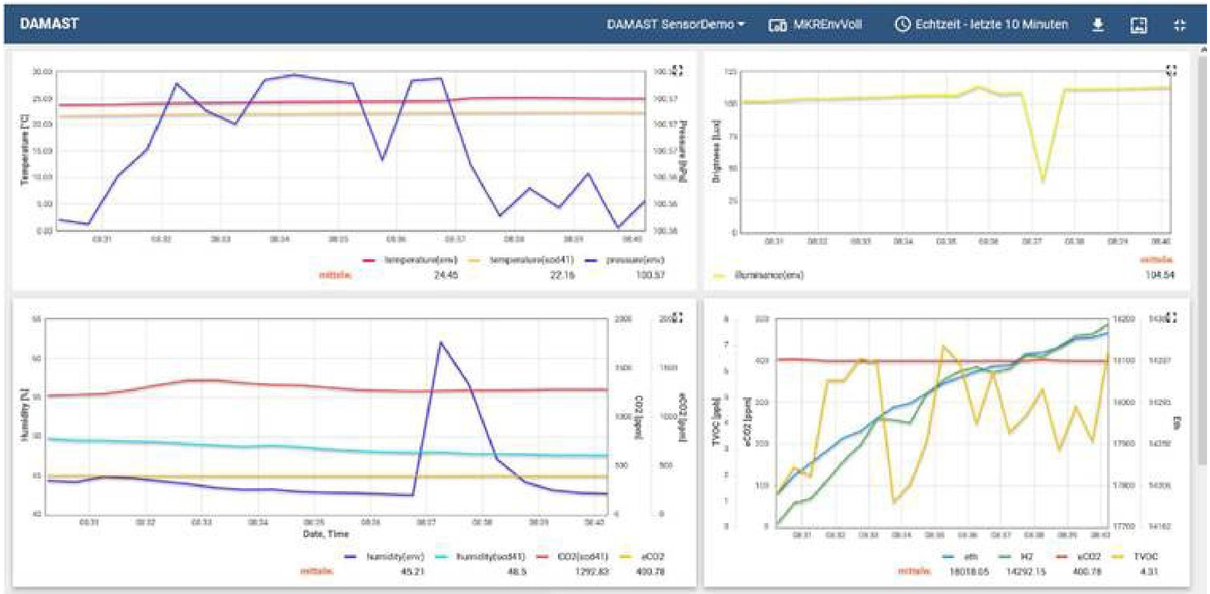
Roman Zorn

With prototypes developed and tested in advance, work continued in several steps in 2021 on mobile measuring systems suitable for the field. There are now >40 "larger" self-sufficient Raspberry-based systems available.

These sensor boxes can be used as simple movement, spatial position, and climate stations.

They are expandable, so that even more complex measurements can be made. The following additional sensors are already used with individual sensor modules:

- GNSS, GPS (5 measuring stations prepared, planned installation at the Enguri, for the geodetic measurements)
- Light sensors (3 measuring stations, for the evaluation of the radiation intensity on the dam surface)
- Gas sensors (x stations expandable, CO2, VOC, etc., to assess local climate conditions)
- High-resolution temperature sensors (PT1000, PT100, NTC, >3 probes can be used)



Regional and Local Deformation: network expansion & expert training

Hansjörg Kutterer, Malte Westerhaus, Andreas Schenk, David Svanadze, Jakob Weisgerber

The GNSS permanent station network established in the DAMAST project is to be expanded to provide connectivity to the Georgian reference station network. In its current state, the local network consists of two fully equipped reference stations and four auxiliary stations equipped with compact antennas and operating in single frequency mode. At the beginning of the transfer phase, these stations will be equipped with precise choke-ring antennas and the multi-frequency option. This will set the stage for possible integration of the stations into the Georgian network and will ensure ongoing technical support and long-term operation of the Enguri network. For the post-processing of the GNSS data using free software (e.g. RTKLIB), training courses for Georgian partners are organized.

In cooperation with the dam operator, it is planned to install four new GNSS stations with compact antennas on the Enguri dam crest. In addition, a new reference station will be installed on an existing pillar below the administration building to provide correction data for the auxiliary stations on the dam. The additional local network is used to analyze 3D-deformations of the dam structure and possible instabilities of the eastern abutment. It will deliver ground truth for the interferometric SAR methods. For monitoring purposes, it is proposed to use the software Leica GNSS Spider and to grant access project partners as well as the dam operator. Appropriate training is planned.

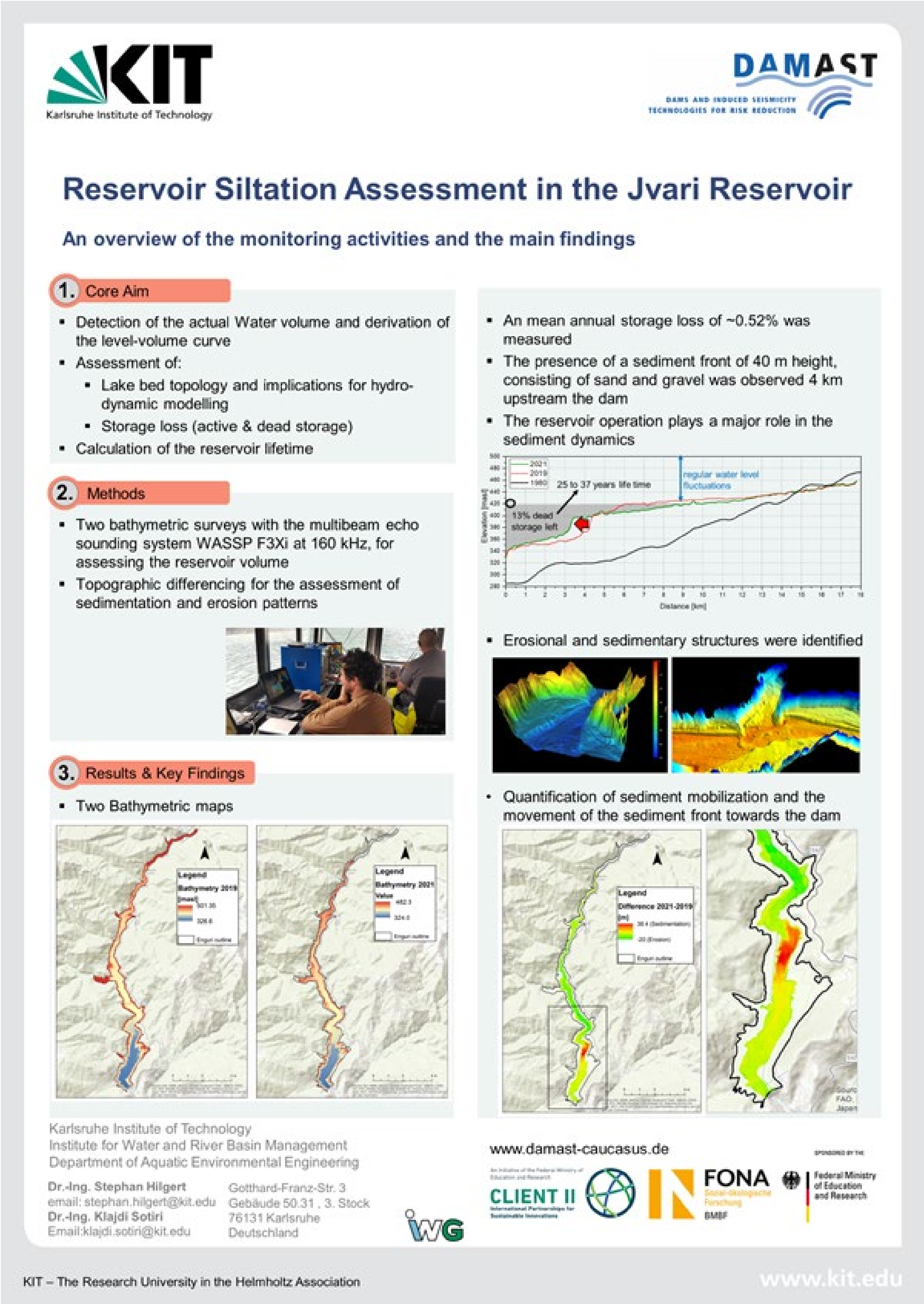
The acquisition of satellite-based SAR scenes in the C- and X-band as well as ground-based SAR (GBSAR) imaging is to be continued. A major focus is on the integration of the different SAR-interferometric data sources and other geodetic data (GNSS, repeated levelling) with the aim to map high-resolution 3D deformation of the dam. On-site training courses for GBSAR operation and station maintenance are part of the Transfer project as well as lab courses for interferometric SAR processing and interpretation in Tbilisi and Karlsruhe.

Seismicity: First July Field Activities and Future Works

Nino Tsereteli, Michael Frietsch, Andreas Rietbrock

In July 2022 the first geophysical student training in the framework of the SDG Caucasus projects took place. Lecturer Prof. Tsereteli went with students to the field took place. Students learned about the deployment of seismic stations, the typical installations to ensure the safety of the station as well as the data transfer. AT home they will be trained to analyse and interpret the data. This learning by doing course took mainly place in Nenskra valley. Felix Bögelspacher from KIT provided technical assistance and expertise from the KIT. The young generation of geophysicists enjoyed this field training.

Posters



Karlsruhe Institute of Technology
DAMAST
DAMS AND INDUCED SEISMICITY TECHNOLOGIES FOR RISK REDUCTION
Reservoir Siltation Assessment in the Jvari Reservoir
An overview of the monitoring activities and the main findings
1. Core Aim
▪ Detection of the actual Water volume and derivation of the level-volume curve
▪ Assessment of:
▪ Lake bed topology and implications for hydro-dynamic modelling
▪ Storage loss (active & dead storage)
▪ Calculation of the reservoir lifetime
2. Methods
▪ Two bathymetric surveys with the multibeam echo sounding system WASSP F3Xi at 160 kHz, for assessing the reservoir volume
▪ Topographic differencing for the assessment of sedimentation and erosion patterns
3. Results & Key Findings
▪ Two Bathymetric maps
▪ An mean annual storage loss of ~0.52% was measured
▪ The presence of a sediment front of 40 m height, consisting of sand and gravel was observed 4 km upstream the dam
▪ The reservoir operation plays a major role in the sediment dynamics
25 to 37 years life time
regular water level fluctuations
13% dead storage left
Distance [km]
▪ Erosional and sedimentary structures were identified
▪ Quantification of sediment mobilization and the movement of the sediment front towards the dam
Legend
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TECHNOLOGIES FOR RISK REDUCTION

Sedimentbudget of the Enguri Dam an its implications for the energy production

1. Core aim

- Completion of two detailed seismic surveys
- Investigation of rheological sediment parameters
- Definition of physical sediment properties
- Identification sediment layers
- Reconstruction of sediment remobilization in relation to reservoir operation
- Discussion of possible mitigation measures for extending the reservoir lifetime

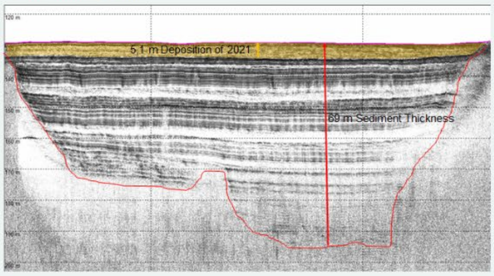
2. Methods

- Seismic survey of reservoir sub-bottom with two different parametric systems
- Use of a dynamic freefall penetrometer for assessment of sediment characteristics

3. Results & Key Findings

- Optimal sediment management strategy
- Ecological and structural downstream effects (river & coast)

- An mean annual storage loss of ~0.5% was measured
- The presence of a sediment front of 40 m height, consisting of sand and gravel was observed 4 km upstream the dam
- A sediment thickness of almost 70 m was observed near the dam



- The reservoir operation plays a major role in the sediment dynamics
- Around 4 million m^3 of sediment are missed in the Black Sea coast every year

4. Open Questions

- Optimal sediment management strategy
- Sediment threat
- Ecological and structural downstream effects (river & coast)

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Geomechanics: Results of Borehole Data Analysis

Thomas Niederhuber[1], Thomas Röckel[2], George Melikadze[3], Shota Gogichaishvili[3], Birgit Müller[1]

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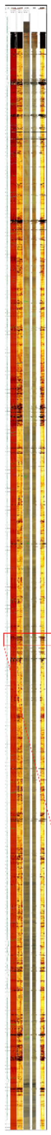

Location of Enguri Dam and Wells drilled within DAMAST project

Fig. 1: Location of KIT-1, KIT-2, KIT-3, KIT-4 and shtolna wells drilled as part of the project. The data of the two deep drill holes KIT-1 and KIT-2 were used for the evaluation because numerous stress indicators such as breakouts or drilling induced fractures could be observed in these wells. The well KIT-1 was drilled at the western slope of the Enguri valley and KIT-2 was drilled close to the valley bottom.

Tab. 1: Data Overview of the 5 Wells drilled within the project of DAMAST close to Enguri Dam. The NENSKRA borehole is located in the Nenskra valley. Wells KIT-1, KIT-2, KIT-4 and shotlna had been logged with acoustic televiewer and KIT-2 and KIT-4 wells also with optical televiewer. In KIT-4 the acoustic televiewer has been used before and after hydraulic testing.

Name	Depth [m MD]	Logging [m]
KIT-1	214	113 – 139 161 – 214
KIT-2	307	9 – 305
KIT-3	25	-
KIT-4	71	19 – 66
Shtolna	20	0 – 15

Example of a Breakout section from KIT-2 between 186.2 – 188.8 m MD (measured depth)

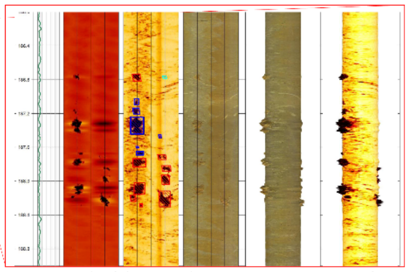

Fig. 2: Example of the section between 186.2 – 188.8 m MD from well KIT-2, where breakouts can be seen. Red boxes indicates Breakouts of a high quality developed on both sides of the borehole wall. Blue indicates still a high quality but only on one side of the wall. Cyan indicates a lower quality as the features are only hardly visible

Fig. 3: Example of a drillcore from the section of Fig. 2, where breakouts are developed. The breakout section corresponds to the bundle at locally formed horizontal fissures.

Results

The orientation of the maximum horizontal principal stress was determined using Mardia's circular statistics. The determined breakouts and drill induced fractures were weighted with their length and quality.

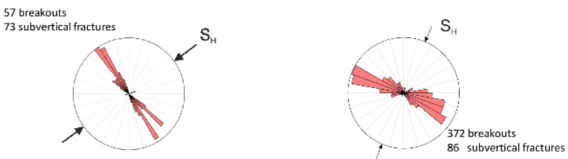

Fig. 3: Results of the Borehole Stress Analysis for the Wells KIT-1 and KIT-2. Good results were obtained for both holes with consistent breakout orientations. The results of borehole KIT-2 which is located in the bottom of Enguri Valley correspond to the overall tectonic stress orientation. KIT-1 stress orientation differs with a stress field rotated clockwise by about 30°.

Stress orientations from borehole data analysis show a N 15°E stress orientation for KIT-2 well and a N 45° E stress orientation for the KIT-1 well. The results for KIT-2 correspond to observations from Tibaldi et al. 2019, World Stress Map (http://www.world-stress-map.org/) and own compilations within the DAMAST project for the regional trend.

Interpretation (also based on numerical model (see talk Niederhuber):

- Stress orientations of both wells show a high influence of topographic stresses.
- Influence of topography is higher in KIT-1 which is drilled on the slope, while KIT-2 is drilled near the bottom of the valley

Geomechanics in Underground Technologies for Renewabel Energy supply: The example of Enguri power tunnel leakage

Thomas Niederhuber[1], Birgit Müller[1], Thomas Röckel[2], Mirian Kalabegishvili[3], Frank Schilling[1], Bernd Aberle[4]

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Location of Enguri Dam and power tunnel

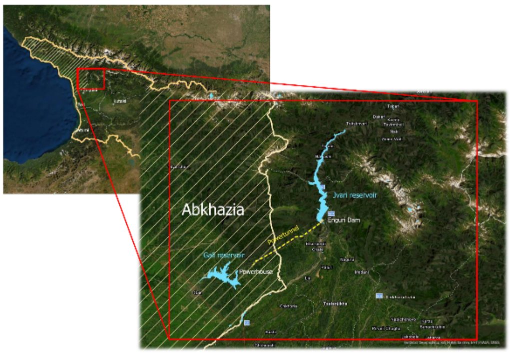


Fig. 1: Location of the Enguri dam, power tunnel and powerhouse as well as the two main reservoirs (Jvari and Gali) in the NW-part of Georgia. Hatched the region of Abkhazia.

The power tunnel connects the Jvari reservoir with the powerhouse (Fig. 1). Before rehabilitation works in 2021 a huge water loss was observed.

- Length: ~ 15 km
- Diameter: 9.5 m
- Flow: ~ 450 m³/s

-> water loss of 10 m³/s (10000 l/s)

Detection of failure during Tunnel Surveys 2021

- Numerous tensile fractures and open joints on the power tunnel wall
- In the fish area (Fig. 2): opening of a joint over a length of 40 m with an aperture of 20 mm and a depth of 50 mm was observed

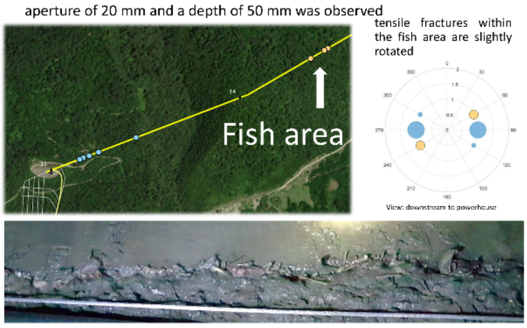


Fig. 2: Numerous tensile fractures were observed in the area between km 13.5 and 13.8 from the entrance of the power tunnel. The area around km 13.7 m is called fish area. Dots show the location where tensile fractures have been observed. In the fish area, these are shown as orange dots. On the right figure these fractures are projected on a 2D cross-section plot (down stream). The rotation by about 30 degree counterclockwise could be observed for the fractures in the fish area. These fractures indicate the orientation of the maximum principal stress. In the bottom, a picture shows a section of the construction joint facing downhill. Here pieces of wood, organic material, plastic and even fish were found. Photo by Aberle.

Acknowledgement
The DAMAST project is part of the "CLIENT II - International Partnership for Sustainable Innovations" funding programme of the Federal Ministry of Education and Research (BMBF) BMBF Project 03G0874 – DAMAST

Model

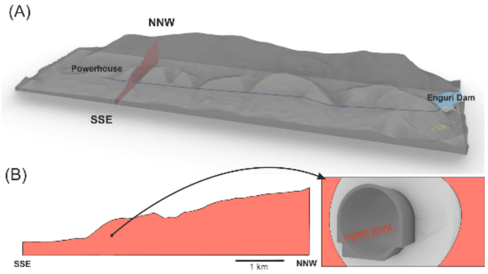


Fig. 3: (A) Location of the power tunnel (blue) in the mountain ridge as well as the position of the NNW-SSE profile (red). (B) A detailed view shows the position of the power tunnel with lining (dark gray) and grouting areas (light gray) on the cross-section.

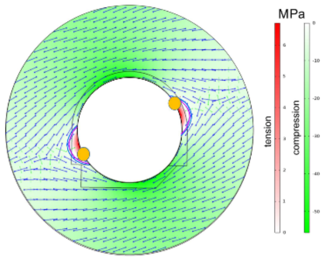
Model Parameter and Assumptions

Property	Variable	Value	unit
Young's modulus	E	45	GPa
Poisson's ratio	ν	0.25	1
Density	ρ	2600	kg/m³

- 2D is valid (insignificant of topographic changes along the tunnel)
- Linear elastic material
- S_{Hmax}/S_V ratio between 3 and 5

Results

Example for S_{Hmax}/S_V ratio of 3



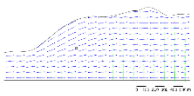


Fig. 4: Cross section through the mountain range with the power tunnel. The stresses (normalized principal stresses) are topographically influenced and inclined with respect to vertical in the area of the power tunnel.

Fig. 5: The figure (downstream) shows the stress distribution for S_{Hmax}/S_V ratio of 3 around the power tunnel and the location of identified fractures at the power tunnel wall. The stress orientations and magnitudes change around the tunnel. Red colors represent tension, green colors represent compression. Lines mark the isolines at which the tangential stress is zero for: no internal pressure (purple) and a maximum internal pressure of 1.6 MPa (blue). In the tunnel, the left-side construction joints are in zones of tensile stress, and the right-side construction joints are in zones of compressive stress.

Conclusion

- Zones around the tunnel where tensile stresses occur are rotated about 20 degrees counterclockwise with respect to the horizontal due to the influence of steep topography.
- The downslope construction joint is affected by the tensile stresses, which means that it can potentially be opened. This could explain the opening over a length of 40 m.
- A higher S_{Hmax}/S_V ratio and/or internal pressure increases the areas of tension, making an opening under operation more likely.

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TECHNOLOGIES FOR RISK REDUCTION

Observation of Dam Deformation with Ground-Based Interferometric Radar (GBSAR)

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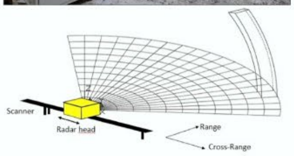
Measurement tool



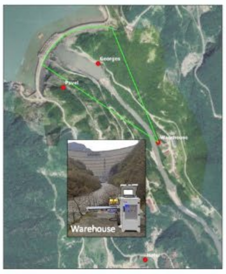
Synthetic Aperture Radar Interferometry (InSAR) uses the coherence of the transmitted Electromagnetic signal to determine displacement from the interferometric phase

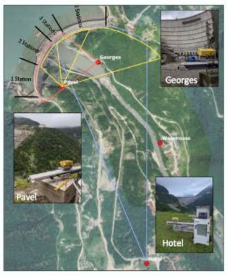
The Ground-Based installation enables to acquire an image from a scene. The particular geometry of the SAR system sums up all the elements in the same elevation.

Ground Based SAR Highlights:

- Completely autonomous measurements
- Acquisition every 2 minutes day and night
- Very high accuracy (0,5 mm)
- Very high spatial resolution (0.75m x 3m)

Measurement concept





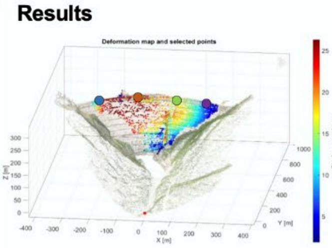
***Continuous station*:**

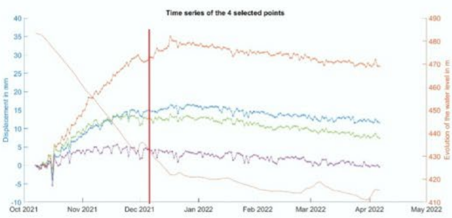
- Monitor the dam over one year to determine its behaviour
- Compare the GBSAR results with existing techniques to assess the feasibility of a Dam monitoring and early warning with this tool

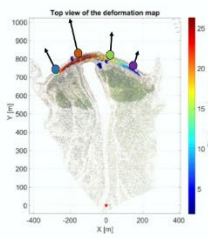
***Campaign station*:**

- Observe the dam from different points of view to determine the 3D displacement
- Combine the GBSAR results with the satellite SAR results

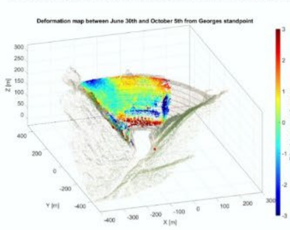
Results

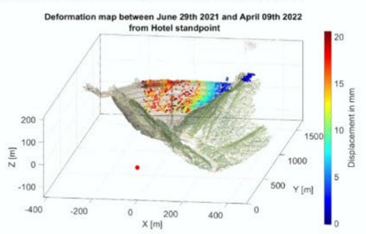


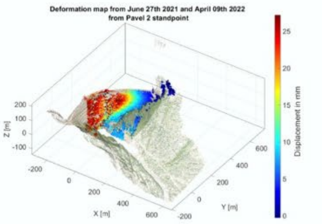




The results of the continuous monitoring show a strong correlation between the deformation on the dam and the water level in the reservoir. For a water level change of 70 meters, we can notice that the maximum observed displacement is in the centre of the dam and is about 3 centimetres.







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Structural Geology, petrophysics, and petrography of limestones from the Enguri Dam area and KIT-2 and KIT-4 drill cores

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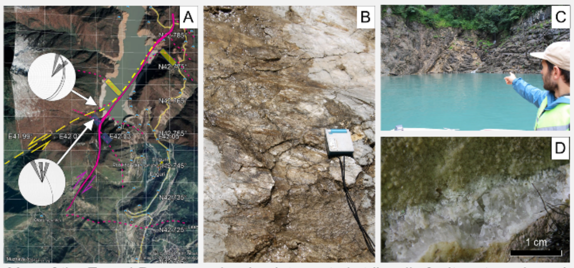
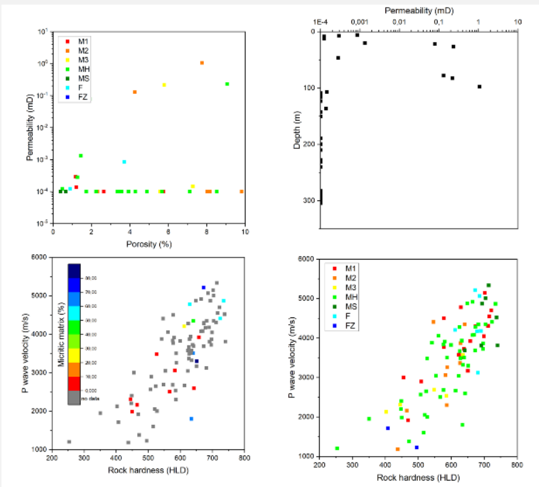
In this part of the project DAMAST, the subsurface of the area of the Enguri Dam was characterized on different spatial scales involving field work, core logging, thin section petrography, and petrophysical measurements. The data acquired here improve our understanding of the subsurface with regard to dam safety and may be further used for geomechanical model calculations.

Structural geology



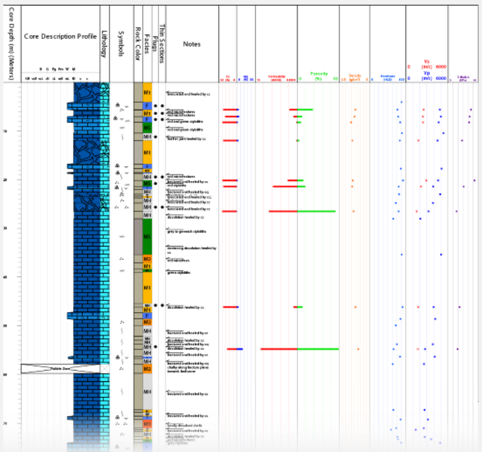
Map of the Enguri Dam area showing interpreted strike slip fault systems based on old maps and satellite images (A). The most promising study areas are located in the SW of the Enguri reservoir (white arrows). These areas were approached by boat and measurements were taken. Fault zones are primarily evident by slickensides (B) and secondarily by cataclastic rocks, deformed beds (C), and mineralized fault planes (D).

Petrophysics

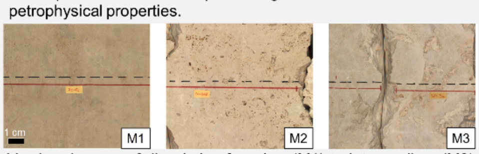


Petrophysical parameters plotted against each other with colour codes indicating lithological characteristics. These plots highlight the importance of the specific rock type on petrophysical properties.

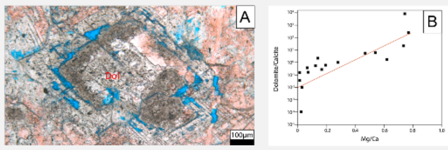
Core logging and petrography



Extract of the lithological column based on logging of drill core KIT-2 (372 m core material) including measured and calculated petrophysical properties.



Varying degress of dissolution from low (M1) to intermediate (M2) to high (M3) of limestones samples from drill core KIT-2.



Thin section (A) of a mudstone showing secondary porosity (blue colours) associated with dissolution of dolomite (Dol) that developed typical rhombic crystal habits with zoning patterns. Dolomite is the most common mineralogical phase (up to 98.0 % per sample) followed by micritic matrix (up to 81.3 %), and calcite (up to 78.7 %). Point counting analysis and handheld XRF geochemistry are in accordance (B, see positive correlation).