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Application of the dynamic data analysis in the real time monitoring of high dam body behaviour

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Abstract: Large engineering constructions such as dams, bridges, high towers etc. are complex structures which are characterized by nonlinear dynamic behavior. The safety of these constructions depending on the extent of their stability which in its turn, is function of loading. At present it becomes clear that the State of the art using of the modern nonlinear data analysis methods is essential to understand features of the time behavior of such constructions and decrease possible risks. In present research we continue investigation of dynamical characteristics of the body of high Enguri dam. This 271m high arch dam was built in west Georgia in seismically active region 30 years ago. The high seismic and geodynamical activities together with a high population density of the adjoining region has made the Enguri dam a potential source of a major threat. Together with the other measures aimed at evaluation of dam stability, in the last years by M. Nodia Institute of Geophysics was developed cost effective telemetric monitoring system for dam tilts. Long and high quality data sets collected by this telemetric monitoring system are carefully analyzed by modern data analysis tools including methods of nonlinear time series analysis. In present report we present results of dynamical analysis of Enguri dam body behavior. These preliminary results show interesting long-term and short-term patterns of tilts of the dam foundation and body under influence of water level variation in reservoir.

1. Introduction

Dams are man-made barriers, constructed on terrain in order to control or store large amount of water in artificial reservoirs. They are highly important edifices for the generation of electricity, flood protection, irrigation, providing drinking water resources, etc. At the same time, dams are regarded as the source of high potential environmental hazard; enormous water masses behind a large dam, potentially contain threat to the human lives, economy, infrastructure, ecology, etc. of adjoining regions downstream the barrage. Thus safety control of dams is highly important practical problem.

Usually, the safety level of a dam is established at the design stage and is depending on the extent of their stability. In its turn, the mechanical stability of

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construction depends on many factors (e.g. aging, quality of materials, exploitation regime, etc.) but mainly it is function of loading [1]. Thus, the essence of mentioned dam-related threat is the risk of the loss of their stability under influence of many load factors and caused by them possible failure or damage [1, 2]. As a rule, in the case of dam there are main pre-defined operational load factors for which it has been designed. It is primarily the horizontal force field caused by the stored water masses; the second main category is the load of geophysical environmental processes such as tectonically induced loading, pore pressure variations or fracture processes [1, 9]. Other categories could be abnormal water influx, flood waves generated by landslides or meteorological causes, thermo-elastic effect caused by air temperature variation, mutual co-influence of the foundation and the dam, the transfer of stresses between the various zones of the dam, etc. [1, 3].

At certain loading conditions, visco-elastic dam structure as a whole or its separate elements may react to it through the time-dependent inelastic deformations. There always are safe deformation limits of dam structure allowed for mentioned above predefined operational loadings. At larger loading values, extensive, beyond limit, deformations may occur which may cause a loss of dam stability and as a result its damage and failure. In this research we focus on the technical hazards connected with the state of the dam and its components. Because of all above said it is clear that behavior of dams is complex. Indeed, the majority of environmental processes presently are recognized as high-dimensional (unpredictable from the linear point of view) [4, 5, 8]. Application of modern methods of nonlinear dynamical pattern recognition and forecast methods, created for analysis of high-dimensional complex dynamics, may help to improve the situation and provide correct evaluation of dam future behavior. Unfortunately, full scale monitoring, especially in the case of relatively old dams (like built 30 years ago Enguri dam), is rarely achievable. So we should derive characteristics of the whole unknown dynamics using few or even one carefully selected and correctly measured (with the frequency desired) continuous data sets [6, 7]. Indeed, having such continuously recorded high quality sets of a few (or even one) dam geotechnical characteristics (scalar data), modern methods of time series nonlinear analysis provide tools to accomplish valuable reconstruction of the main dynamical features of the entire unknown complex vector process (here - dam deformation) [6, 7, 8, 9, 10].

In this report we present preliminary results which demonstrate reliability and importance of using modern data analysis methods for qualitative and quantitative evaluation of dynamics of high dam behavior.

2. Used Data and Methods of Analysis

Used data have been recorded at the Enguri International Test Area (EDITA), which was established by Council of Europe in 1996. More than 30 year ago, in the 1970s, the 271 m high Enguri arch dam, the highest (in its class) dam in the world, was built in the canyon of Enguri river in West Georgia. The dam is located in a zone of high seismicity what makes as a potential source of a major technological catastrophe in Georgia, dam is located close to the Ingirishi active fault system. From the very beginning in EDITA the unique geotechnical, geodynamical and geophysical monitoring has been carried out [9]. So it is possible to analyse dynamics of local Earth crust, dam foundation and dam body behavior at different stages such as dam construction, reservoir filling and its operation. The database of observations (tilts, strains, etc.) contains information accumulated during more than 30 years of observation.

In addition to this, two years ago the cost-effective real time geotechnical telemetric monitoring system of large dams (DAMWATCH) was developed. This low-cost early warning system consists of network of sensors (tiltmeters). The main purpose is the early detection of small incipient changes in order to recognize possible approaching of future critical deviations from the model-predicted dynamics of the behavior of the dam body under different natural and/or human impacts.

In this work we analysed time series of tilt measurements. Earth tilts hourly time series involved measurements before construction of dam, during construction and in the period of operation. Such high quality data sets enabled us to investigate behavior of dam foundation and dam body for different stages of construction and dam operation: 1) long before the reservoir fill, 2) immediately before and 3) just after starting the fill, 4) after the second, 5) third and 6) fourth stage of reservoir fill and 7) long after the completion of the reservoir fill. In addition to this data dam body tilt time series recorded for last two years also have been investigated.

We used different data analysis methods both linear and nonlinear. Namely, spectral and time frequency properties have been calculated, long-range properties of datasets have been tested using detrended fluctuation analysis (DFA). Also, recurrence quantitative analysis (RQA) and algorithmic (Lempel-Ziv) complexity measurement calculation of tilt data series has been performed.

3. Results and discussions

We started from the analysis of measurements data sets of displacement of sides of, mentioned above, Ingirishi fault.

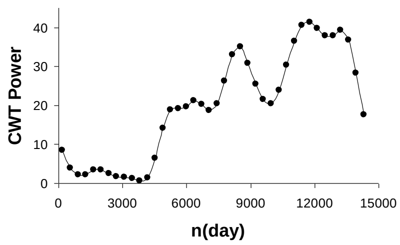

Fig.1. Variation of power of continuous wavelet transformation of daily displacement data sets from 1974 to 2013. Frequency band of close to one year periodicity cycles are considered.

Measurements have been carried out far before start of dam construction, so it was quite expectable, that periodic water level variation related with functioning of Enguri hydro power plant has influenced the displacement of fault sides. Indeed in Fig. 1, we see that power of cyclic components, close to one year periodicity, essentially increased when related with power plant operation variation of water level became periodic.

Besides of changes in the displacement of fault sides, interesting dynamical changes occurred in the variation of tilts of foundation of high dam.

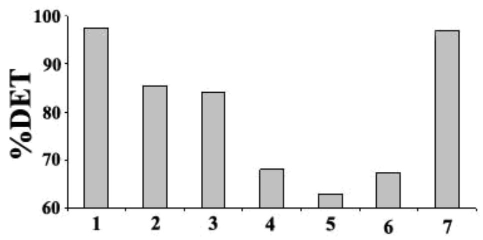

Fig. 2. RQA determinism measure calculated for Earth tilt data series for different stages of observation. Numbers in abscissa correspond to periods of observation (see the methods section).

We see in Fig. 2, that RQA which is recognized as a suitable tool for both qualitative and quantitative analysis of complex relatively short time series [10], indicates changes at above mentioned 7 stages of observations.

Next we used LZ algorithmic complexity measure to quantify changes in dynamics of earth tilts generation. Calculated values of LZ complexity for tilt time series, shown in Fig. 3, also indicate a non-random character of the tilt process ($LZ \neq 1$), which are characteristic for systems with close to a quasi periodic type of behavior [8, 10, 11].

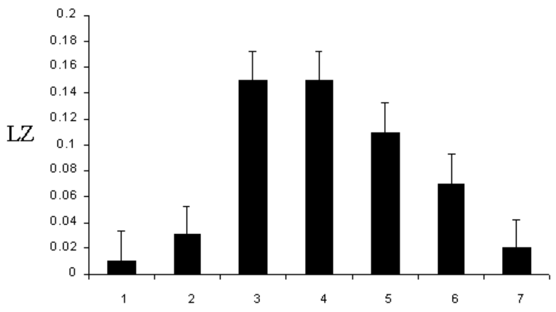

Fig. 3. Lempel Ziv copmplexity measure calculated for tilt dam foundation data series for different stages of observation.

Then in order to explore our data on the subject of long-range correlations, what is characteristic for dynamics with quantifiable value of determinism and also to avoid effects of non-stationarity in tilt time series, we performed DFA testing. As we can see in Fig.4, DFA results show that calculated scaling exponents of Earth tilt time series are mostly in the range of 1.2-1.4. Thus, the dynamics of Earth tilts indeed should be close to the non random Brownian like process [11]. At the same time, for the time frame of the reservoir filling, the DFA exponent decreases to persistent (close to 1/f type noise) values; revealing some effects of specific human influence on the scaling properties of the tilt process.

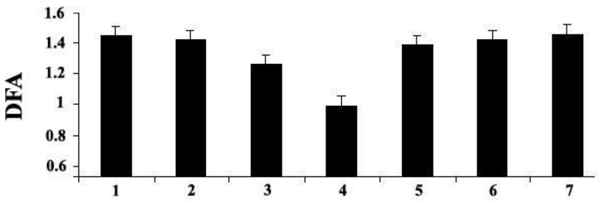

Fig. 4. Variation of detrended fluctuation analysis (DFA) scaling exponents for different time periods of observation. Numbers in abscissa correspond to periods of observation.

After, we have analysed data sets of tilt measurements of dam body. These data have been measured in consecutive 10 minutes throughout the year 2011. Exactly, in Fig. 5, results of DFA calculation of increment series of tilt data, along and transversely to the dam, are presented. We clearly see, that tilt process transversely to the dam body undergoes seasonal quantifable changes (black circles in Fig. 5).

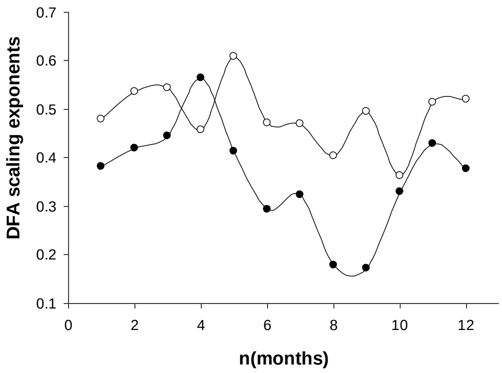

Fig. 5. DFA scaling exponent of dam body tilt increments data sets.

In March and April DFA exponents of increments variation was close to 0.5 indicating randomlike behavior. Contrary to this, in August, September considered process become clearly antipersistent. Tilt process along dam body do not indicates such clear changes (white circles in Fig. 5). These are results for DFA , p=2. Calculation for DFA p=3, 4, 5 gives similar results and are not shown in Fig. 5.

Thus, results of our analysis show, that methods of dynamic data analysis may help to reveal unknown features of the high dam body behavior and can be successfully used for the purposes of real time monitoring.

4. Conclusions

In present study we analysed data sets of Earth crust local tilts as well as Enguri dam body tilts time series. It was found that tilt dynamics undergoes different changes related with dam construction and operation. It was shown, that these changes may be quantified by modern data analysis methods. This is important conclusion because it provides a basis to advance in detecting and evaluating supposedly high-dimensional changes in the Enguri dam behavior caused by multitude of geotechnical processes which may be or may not be related to the natural tilting of the Earth crust.

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