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Primary Temporal Analysis of Enguri Dam Displacement of Foundation under Loading

[1]Ekaterine V. Mepharidze, [1,2]Aleksandre I. Sborshchikovi, [1]Tamaz L. Chelidze

[1]M. Nodia Institute of Geophysics of the I. Javakhishvili Tbilisi State University, Georgia
[2]Business and Technology University, Tbilisi, Georgia
ekamep@gmail.com

ABSTRACT

The main aim of our research was the analysis of time distribution characteristics of the Enguri dam foundation displacement according to the periodic variation (loading) water level in the lake around the Enguri Arch Dam. The primary temporal analysis was carried out in 1974-1981 period. Modern methods of nonlinear analysis DFA (detrended fluctuation analysis), and MF-DFA (multifractal detrended fluctuation analysis) were used.
The results of our research are important and from investigation we can conclude that dynamic changes of dam foundation displacement, assessment of dam behaviour and water level change in the reservoir of the Enguri high dam. The analysis of the dynamics measures of the Enguri dam displacement shows us the pattern of nonlinear dynamics of the normal regime with start loading.

Key words: *Enguri Dam, displacement, temporal analysis*

Introduction

The location of the Enguri Dam was selected based on extensive engineering research. The influence of the dam and changes in the reservoir's water level on both the structure and the surrounding environment was studied. Construction began in the last century, and the 271-meter-high Enguri arch dam is one of the tallest dams of its kind in the world. Since construction began, state-of-the-art interdisciplinary geodynamic and geophysical monitoring has been organized in the dam area. Geological studies have documented that a fault branch of a major active fault beneath the Enguri Dam, the Ingirishi Fault, intersects the right wing of the dam's foundation. The presence of an active (or potentially active) fault at the foundation of a large dam is known to pose a serious threat to dam safety. It is logical that monitoring of the fault zone began long before construction of the dam and filling of the reservoir [1-5]. The main Ingirishi fault (Fig.1, Fig.2) crosses the foundation of the Enguri dam and, thus, poses a significant hazard to the dam.

The study area effectively serves as a natural large-scale laboratory for examining the effects of tectonic activity, anthropogenic influences, and environmental factors on fault-zone deformation. The combined impact of these processes is captured in the time series of fault-zone strain. The observed fault dynamics clearly reflect the interaction of two principal components: a tectonic strain component, which produces piecewise linear temporal displacements and is interpreted as the long-term trend, and a secondary component that generates quasiperiodic oscillations superimposed on this underlying trend.

Strainmeters and demographs are located in the dam body and tunnels, which measure the displacement of the dam when the water level in the reservoir varies.

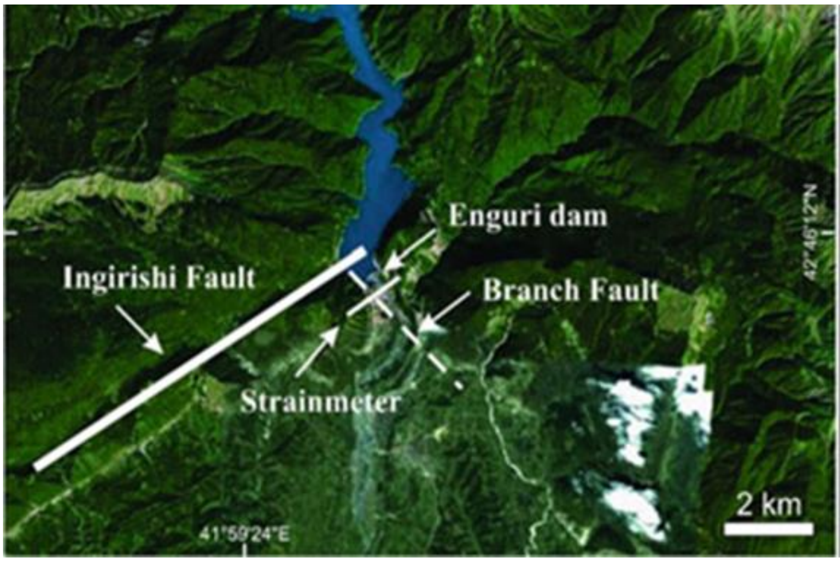


Fig. 1. Satellite image of the Enguri dam and reservoir area, locations of the Ingirishi fault and crossing the dam foundation.

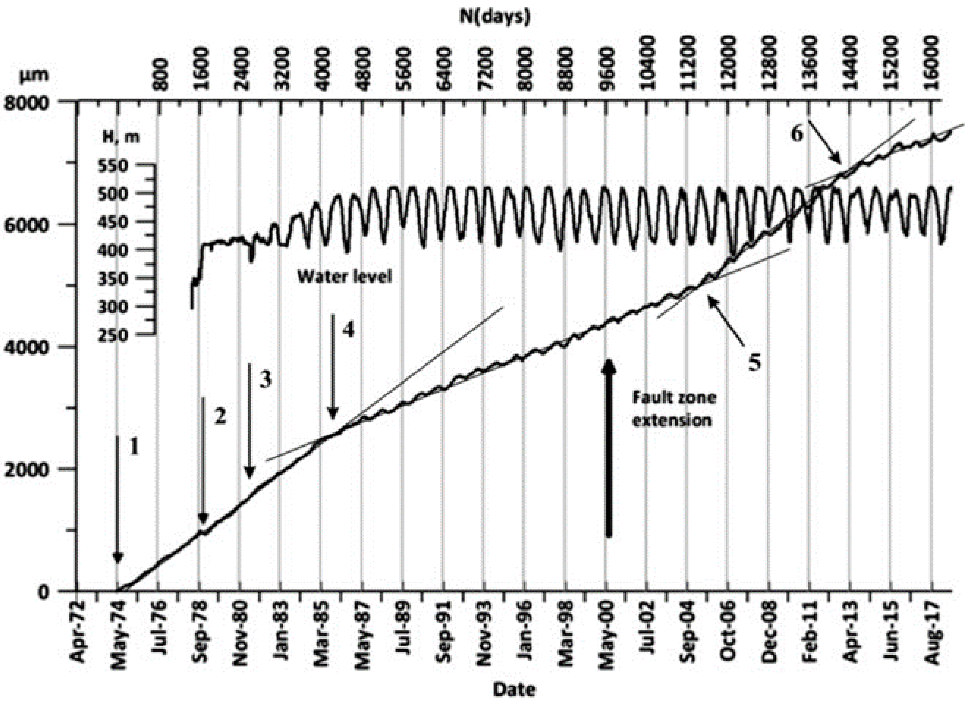


Fig. 2. The upper curve shows the variations of water level height at the Enguri lake from 1978 to 2017; the lower curve shows data from the strain-meter. Data are from 1974 to 2017 versus time. Arrows 1, 2, 3, 4, 5, 6 correspond to the start of 6 periods of fault zone extension, see Table 1 for details. We can see of fault compaction by approximately 90 microns, as a consequence of a quick, 100-m increase in water level in 1978. The upper horizontal axis shows the number of days after the start of the strainmeter monitoring. The thin, straight lines show six periods of the fault's main trend with different extension rates

The data (Fig. 2) also show that the water load reduced the initial displacement rate recorded before the lake refill, since the total accumulated deformation value in 2017 was only 7000. The decrease in accumulated deformation is explained by the orientation of deformation caused by the water load, which is favorable for the compaction of faults.

Table 1. Subdivision in periods of fault zone extension

Number of periods	Periods	Number of days in the period; in brackets the same from zero day (May 1974) to the end of a given period	Tectonic component of strain rate α μm/year	Pattern of lake impounding (man-made component of strain)
1	May 1974–Apr 1978	1500 (1500)	230	Before lake impounding
2	May 1978–Jan 1981	1300 (2800)	250	WLinthelakeraisedto100m
3	Feb 1981–May 1985	1400 (4200)	250	Irregular load-unload regime
4	Jun 1985–Sep 2004	7000 (11200)	160	Regular quasi-periodic regime
5	Oct 2004–Feb 2013	3200 (14400)	230	Regular quasi-periodic regime
6	Apr 2013–Mar 2018	2000 (16400)	150	Regular quasi-periodic regime

Methods.

For estimating long-term correlations of the dam strain time series during load-unload of reservoir we used the methods DFA (detrended fluctuation analysis), and MF-DFA (multifractal detrended fluctuation analysis).

In time-series analysis, detrended fluctuation analysis (DFA) is a technique used to assess the statistical self-similarity of a system's components. The DFA scaling exponent encapsulates comprehensive information about temporal correlations and is particularly effective for identifying long-term correlations in non-stationary time series. DFA has been widely applied across numerous disciplines, including geophysics, geodynamics, meteorology, biology, bioinformatics, and economics. This scaling approach yields a straightforward quantitative measure of a signal's correlation structure and, compared with many conventional methods, offers the distinct advantage of reliably detecting long-range correlations in non-stationary data [6–9].

DFA consists of two steps:

(1) the data series B(k) are shifted by the mean B and integrated (cumulatively summed), $y(k) = \sum_{i=1}^{k}[B(i) - B]$, then segmented into windows of various sizes Δn;

(2) in each segmentation the integrated data is locally fit to a polynomial $y_{\Delta n}(k)$ (originally, and typically, linear) and the mean squared residual $F(\Delta n)$ (''fluctuations''):

$$F(\Delta n) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(y(k) - y_{\Delta n}(k))^2} \ ,$$

where N is the total number of data points. Note that $F(\Delta n)$ can be considered as the average of the summed squares of the residual found in the windows. The n-th order polynomial regressor in the DFA family is denoted as DFAn, with unlabeled DFA often referring to DFA1.

Multifractal detrended fluctuation analysis (MF-DFA) is used to detect variability and uncertainty in empirical time series data.

MF-DFA is the most effective method for detecting multifractality in time series. It takes the mean of the time series in each interval as a statistical point, which is then used to calculate volatility functions. It then determines generalized Hurst exponents based on the power law of the volatility functions. A key advantage of MF-DFA over other approaches is its ability to detect long-term correlations in non-stationary time series. The reaserch describes the key steps and formulas underlying the analysis.

The first step of the MF-DFA is to construct the "profile", $Y(j)$ by integration after subtracting from the time series, $R(i)$ its average, $\bar{R}$:

$$Y(j) = \sum_{i=1}^{j} (R(i) - \bar{R}), i = 1, \dots, N.$$

The second step of the MF-DFA is to divide the profile $Y(j)$ into $N_s = int\left(\frac{N}{s}\right)$ non-overlapping segments of equal length s.

The exponent *h(q)* is called a generalized multifractal Hurst exponent and is related to the classical monofractal Hurst exponent *H*.

For the MF-DFA analysis we use the generalized Hurst exponent, which has no upper limit and expressed as:

$$H = \begin{cases} h(q) & - \quad for\ stationary\ time\ series \\ h(q) - 1 & - \quad for\ non-stationary\ time\ series \end{cases}$$

The estimation of H represent fundamental base, as we want to know the long-term dependence of a time series.

Results.

For our primarily research of Enguri dam foundation displacement under compare with water variation the second period (May 1978–Jan 1981) was investigated (which shows on Fig.2 (arrow 2, 3)).

Nonlinear DFA analysis of Enguri dam foundation displacement data for 1978-1981 was carried out. The results of DFA analysis of displacement, show the long-range correlation of scaling features, changes in dynamical structures, and the regularity of the system. DFA analysis was carried out for polynomial fitting p=2, 3, 4, 5 (see Fig. 3).

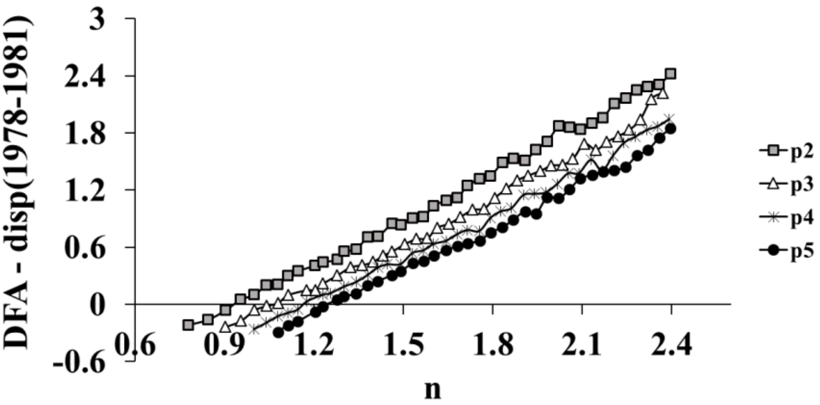
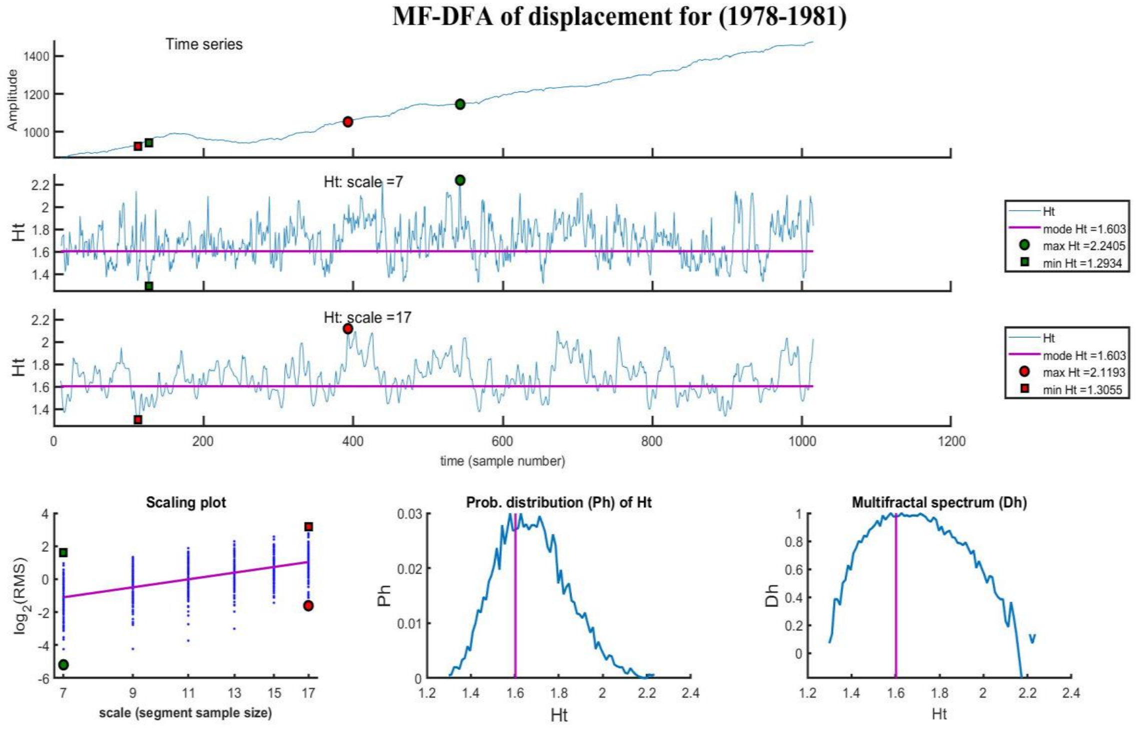


Fig. 3. DFA analysis of Enguri dam foundation displacement for 1978-1981.

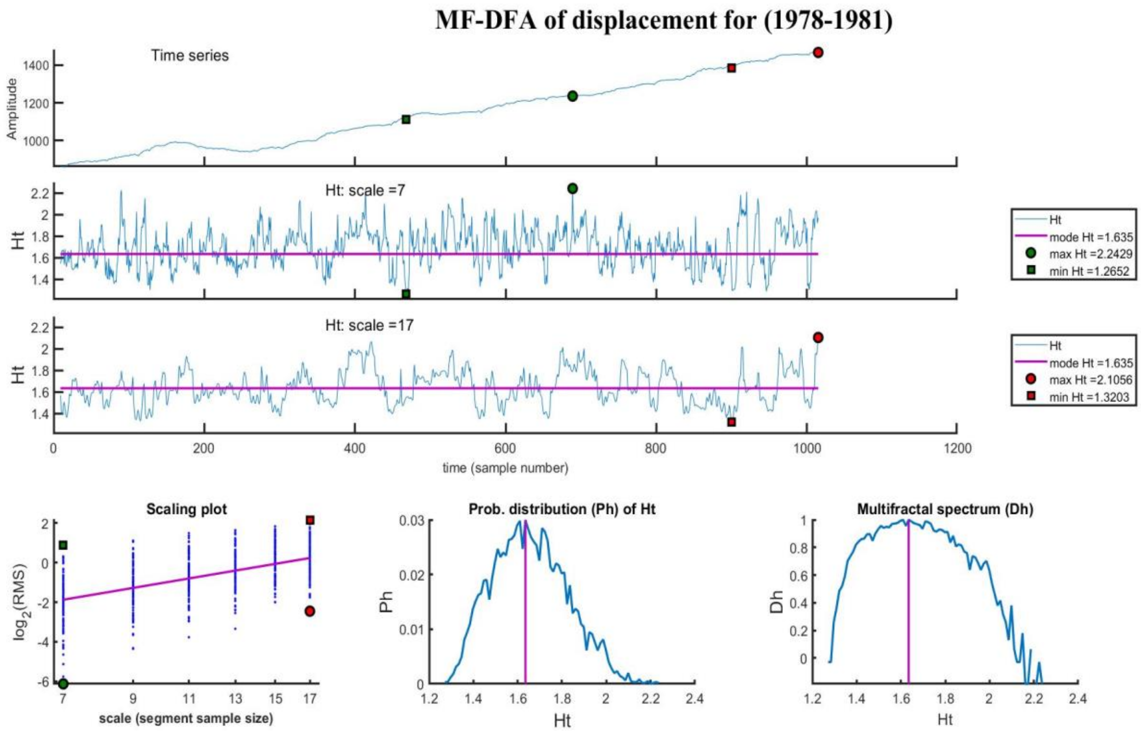
From the DFA analysis of Enguri dam data sets, we can see how the structure of the dynamics changes with increasing polynomial approximation, order is disrupted, and mutual correlation weakens.

Multifractal Detrended Fluctuation Analysis (MF-DFA) of long-term correlations of the power law of non-stationary Enguri dam foundation displacement data in 1978-1981 was carried out. The variation of the multifractal characteristics was carried out for polynomial fitting with p=2, 3, 4, 5 (Fig. 4)

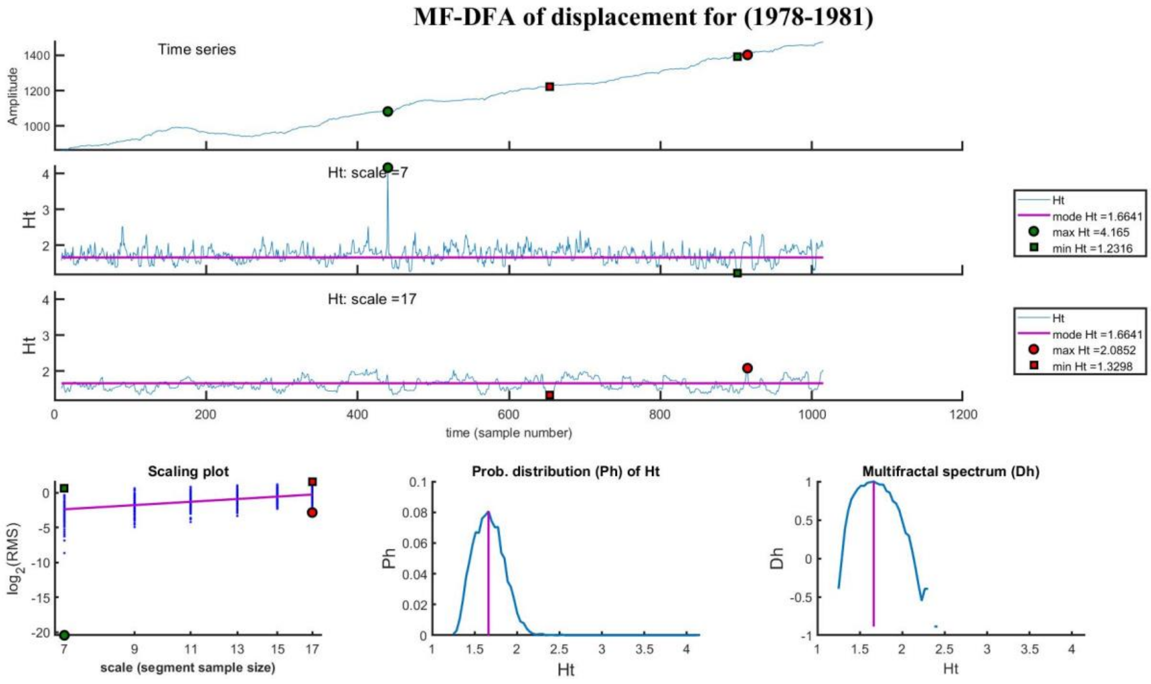
Values of Ht, the q-order of generalized multifractal Hurst exponent time signal, were calculated. The local generalized multifractal exponent (Ht) can now be computed from the local fluctuation of real time series signal (Fig. 4) estimated as well as the logarithmic function (Ht). From Fig. 4 we can see a non-stability, that under variation at the orders of scale s =7 and s =17 changed maximum and minimum of Ht, but Ht mode is constant ($mode\ Ht \approx$ 1.6). This changes in dynamic structure of time series clearly observed, where the plot of Ph-probability distribution of Ht and Dh- multifractal spectrum represents the relationship in the form of parabola and shows an increase in the thresholds at the $mode\ Ht \approx 1.6$.



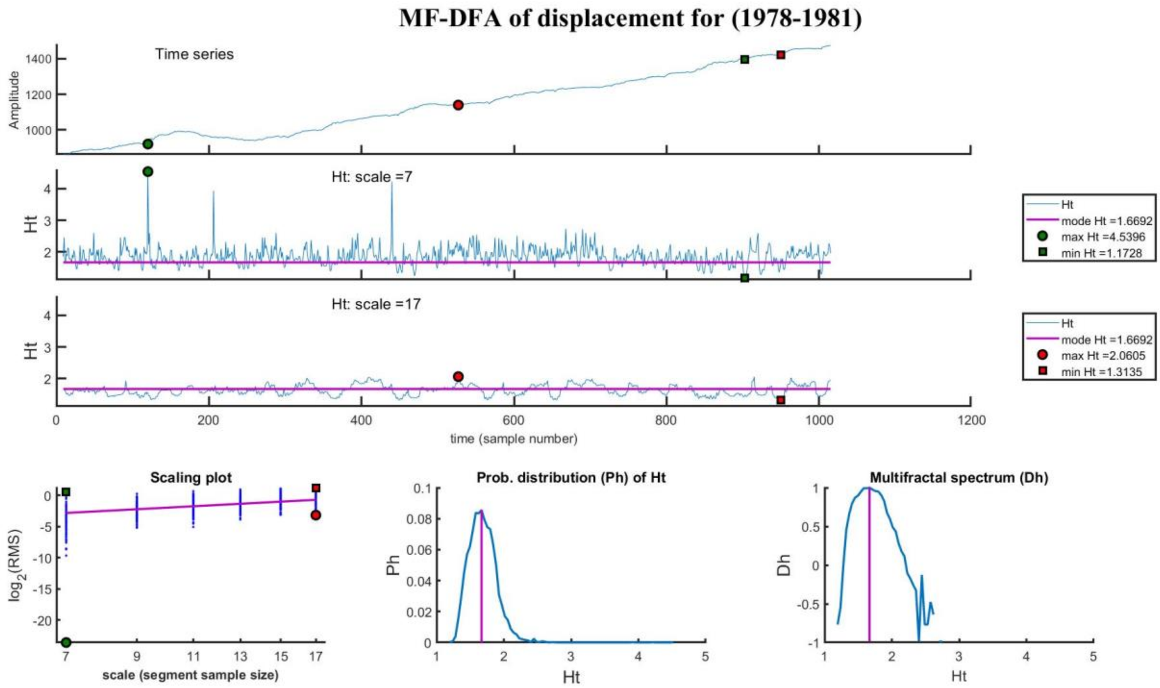
a)



b)



c)



d)

Fig. 4. The MF-DFA analysis of the Enguri dam foundation time series displacement in 1978-1981: a) for polynom =2; b) for polynom =3; c) for polynom =4; d) for polynom =5. Ht: q- generalized multifractal Hurst exponent time signal. Percent of output variable: Ph - probability distribution of Ht, Dh- multifractal spectrum.

From Fig.4 we can see the scaling functions Ht, Ph, Dh, which are depend on q-order Hurst exponent. The q-order Hurst exponent Ht for the time series is multifractal. MF-DFA analysis consists of several steps: to first convert Ht to the q-order mass exponent and thereafter convert signal to the q-order singularity exponent (Ht) and q-order singularity dimension Dh; The plot of Dh shows us multifractal spectrum.

The initial MF-DFA results indicate that the dynamics of dam foundation displacement began to change with the onset of reservoir impoundment during the period 1978–1981. This analysis enables an assessment of the dam's response to reservoir filling and the influence of this process on foundation displacement, as well as an evaluation of the associated risk of potential damage

Conclusion.

This article presents a preliminary analysis of Enguri Dam foundation displacement data, during the period 1978–1981. Nonlinear analysis methods DFA and MF-DFA revealed a clear pattern of dam deformation dynamics. These results are important for studying the behavior of the Enguri Dam. Analysis of the Enguri Dam displacement time series allows us to establish patterns in nonlinear dynamics under normal conditions and under water loading. Significant deviations from the multifractal characteristics obtained above should be analyzed in detail to determine whether the anomaly is significant for dam stability. The results of this study will form the basis for further research into dam behavior and will help scientists avoid a catastrophe caused by dam failure and foundation displacement.

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დატვირთვის დროს ენგურის კაშხლის საძირკვლის გადაადგილების პირველადი დროითი ანალიზი

ე. მეფარიძე, ა. სბორშჩიკოვი, თ. ჭელიძე

რეზიუმე

ჩვენი კვლევის მთავარი მიზანი იყო ენგურის კაშხლის საძირკვლის გადაადგილების თაღოვანი კაშხლის გარშემო ტბაში წყლის დონის პერიოდული ვარიაციის (დატვირთვის) დროს დროითი განაწილების მახასიათებლების ანალიზი. პირველადი დროითი ანალიზი ჩატარდა 1974-1981 წლების პერიოდისთვის. გამოყენებული იქნა არაწრფივი ანალიზის თანამედროვე მეთოდები DFA (ტრენდმოცილებული ფლუქტუაციის ანალიზი) და MF-DFA (მულტიფრაქტალური ტრენდმოცილებული ფლუქტუაციის ანალიზი).

ჩვენი კვლევის შედეგები მნიშვნელოვანია და შეიძლება გამოყენებულ იქნას ენგურის კაშხლის წყალსაცავში წყლის დონის ვარიაციის დროს კაშხლის საძირკვლის გადაადგილებაში დინამიკური ცვლილებების დასადგენად და მუშაობის შესაფასებლად.

ენგურის კაშხლის დინამიკური გადაადგილების პარამეტრების ანალიზი ნორმალურ რეჟიმში საწყისი და დატვირთვის ქვეშ ავლენს არაწრფივი დინამიკის სურათს.

საკვანძო სიტყვები: ენგურის კაშხალი, გადაადგილება, დროითი ანალიზი.

Первичный временной анализ смещения основания плотины Энгури при нагрузке

Е. Мепаридзе, А. Сборщиков, Т. Челидзе

Резюме

Основная цель нашего исследования заключалась в анализе характеристик временного распределения смещения основания плотины Энгури в зависимости от периодических изменений (нагрузки) уровня воды в озере вокруг арочной плотины Энгури. Первичный временной анализ проводился в период 1974-1981 годов. Использовались современные методы нелинейного анализа DFA (детрендовый флуктуационный анализ) и MF-DFA (мультифрактальный детрендовый флуктуационный анализ).

Результаты нашего исследования важны и на их основе можно сделать вывод о динамических изменениях смещения основания плотины, оценке поведения плотины и изменение уровня воды в водохранилище платины Энгури.

Анализ динамических показателей смещения плотины Энгури показывает нам закономерность нелинейной динамики нормального режима при начальной нагрузке.

Ключевые слова: плотина Энгури, смещение, временной анализ