INVESTIGATION OF DYNAMIC BEHAVIOR VARIATIONS OF THE ENGURI ARCH DAM

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Abstract. *The primary objective of this study is to investigate the dynamic variations in the displacement of the Enguri Arch Dam foundation in relation to periodic fluctuations in the reservoir's water level. The analysis is based on a comprehensive dataset spanning the period from 1974 to 2021. In this work, we applied several modern nonlinear analytical techniques to examine these dynamical changes, with a focus on the highly effective* ***Multifractal Detrended Fluctuation Analysis (MF-DFA)*** *method. Our findings indicate a clear connection between the displacement dynamics of the dam foundation and the overall behavior of the structure. Notably, one of the key factors influencing these dynamics is the variation in the water level of the reservoir behind the Enguri high dam.*

Key words*: Dynamical changes, nonlinear analyses, datasets.*

Introduction

The initial phase of our research involved an in-depth review of existing literature relevant to our topic. This review revealed numerous references highlighting the significant environmental impact of constructing and operating large water reservoirs. Among the documented effects are increased local seismic activity, alterations in regional climate patterns, and the triggering of landslides. These findings underscore the importance of addressing the issue through a multidisciplinary approach, warranting further and more detailed investigation.

Our study focuses on the Enguri Dam area due to its prominence as one of the tallest arch dams in the world, with a height of 271 meters. Located in western Georgia, the Enguri Arch Dam is an integral part of the Enguri Hydropower Plant (HPP), situated within the Enguri River Gorge. Since the commencement of its construction, a comprehensive geodynamical and geophysical monitoring system – advanced for its time – was established in the area to track various physical and structural processes [1–3].

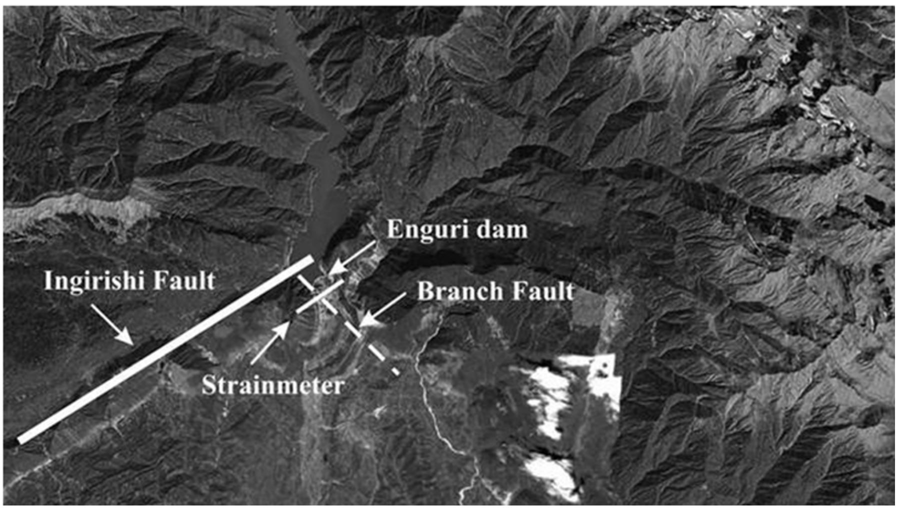


Fig. 1. Enguri dam and reservoir area with locations of the main Ingirishi fault and the branch fault.

Geological surveys have revealed that a branch of the major active Ingirishi Fault intersects the right abutment of the Enguri Dam foundation. The presence of an active or potentially active fault beneath a large dam represents a serious risk to its structural integrity and overall safety [1,4,5]. Given this risk, continuous monitoring of the fault zone began well before the construction of the dam and the subsequent filling of the reservoir.

The branch of the Ingirishi Fault (Fig. 1) that crosses the dam foundation is a significant geotechnical concern, making this site particularly valuable for studying the interaction between tectonic processes and anthropogenic influences. In fact, the Enguri Dam region serves as a natural large-scale laboratory for investigating the deformation behavior of fault zones under the combined effects of tectonic forces, human activity, and environmental factors.

Two key influences on the fault zone behavior were identified. The first, **tectonic strain**, results in a piecewise linear displacement, which we interpret as the **trend component** of the deformation. The second influence is associated with **quasiperiodic oscillations**, which modulate this trend and are likely linked to cyclic environmental or operational factors.

The dataset used in our research covers the period from **1974 to 2021** and is particularly valuable due to its inclusion of critical parameters such as high weir foundation and body tilt measurements, foundation deformation data, internal temperature of the dam body, and water level variations in the reservoir. Portions of this dataset have already been published in peer-reviewed journals [2–6]. In this study, we focus specifically on the **displacement of the dam foundation** recorded over the full observational period (Fig. 2).

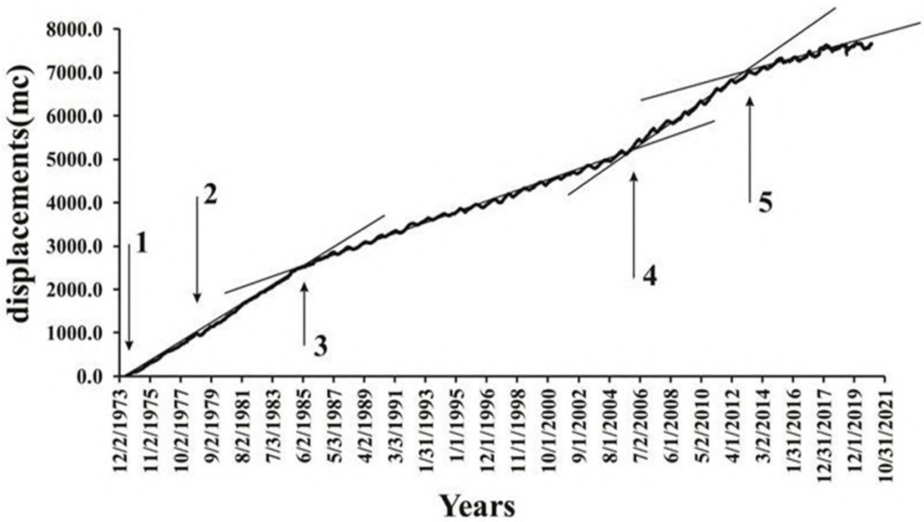


Fig. 2. Dam foundation displacement data sets around Enguri in period from 1974 to 2021. Arrows 1, 2, 3, correspond to the initial periods of fault zone extension.

To enable continuous monitoring of fault zone behavior, a **quartz strainmeter** was installed in 1974 – four years prior to the initial filling of the Enguri reservoir. Positioned across the fault zone, this instrument measures relative displacement of the blocks separated by the fault (approximately 10 meters in width), specifically in the direction normal to the fault plane. As such, the strainmeter captures fault zone **extension and contraction**. The total length of the quartz tube is **22.5 meters**, and the system's **free end** is equipped with a **photo-optical recording device**, now operating in parallel with a **laser-based system**. The strainmeter is designed with its fixed and free ends anchored on opposite sides of the fault, each several meters away from the fault plane. Measurements were recorded daily at the same time, with a system sensitivity of approximately **0.18 micrometers per millimeter**.

The **stepwise filling** of the Enguri reservoir commenced on **April 15, 1978**, and from **1987 onwards**, the water level has exhibited **regular seasonal fluctuations**. Seismic data were collected from a network of monitoring stations installed throughout the Enguri area, with a **magnitude threshold** of **M2.2** for inclusion in the local earthquake events catalogue spanning **1974 to 2021**.

In our study, we utilize the **strainmeter data** to analyze displacement in the **foundation of the high Enguri Arch Dam**. As previously noted, fluctuations in the reservoir's water level appear to influence **local seismic activity**, which in turn may affect the deformation dynamics of the dam foundation.

To examine the **nonlinear dynamics** of foundation displacement, we applied the **Multifractal Detrended Fluctuation Analysis (MF-DFA)** technique. The analytical software used was developed by specialists at the **M. Nodia Institute of Geophysics, Ivane Javakhishvili Tbilisi State University**. MF-DFA is a powerful method capable of revealing **hidden multifractal structures** within non-stationary time series and is an extension of the traditional **Detrended Fluctuation Analysis (DFA)** introduced by Kantelhardt et al. [7].

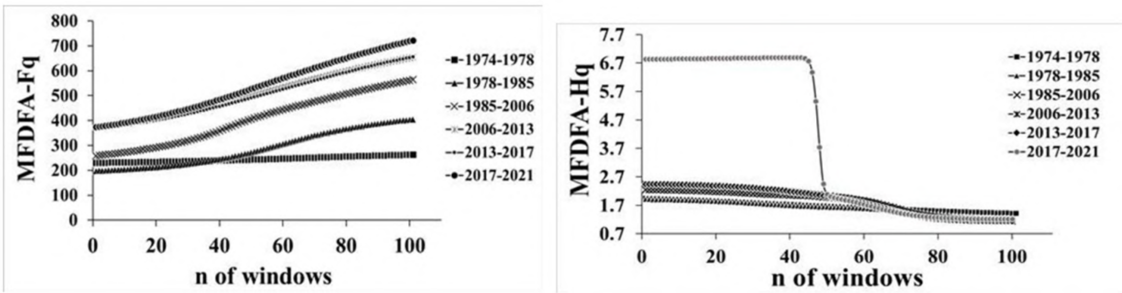
Our analysis explores the **multifractal scaling behavior** of the displacement time series. We examine three key metrics:

- the **generalized Hurst exponent** H(q),
- the **multifractal spectrum dimension** D(q)
- the **fluctuation functions** F(q).

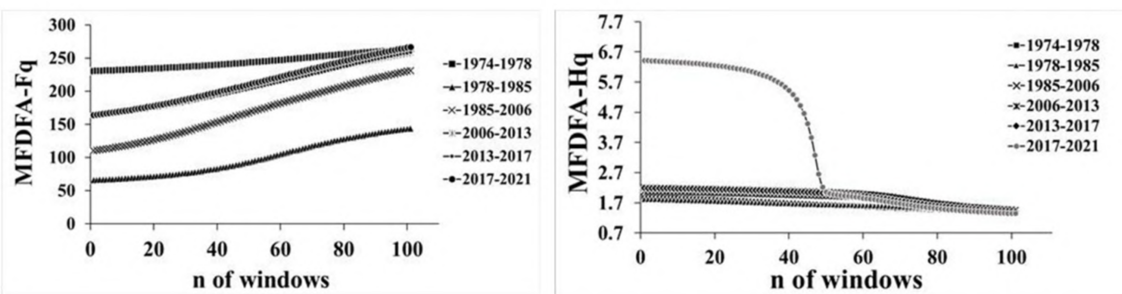
The **Hurst exponent**, originally proposed by Hurst (1951), provides insight into the correlation structure of the time series. If H(q) lies between 0.5 and 1, the data exhibits **long-range correlations**; values between 0 and 0.5 indicate **anti-correlated** behavior, and H(q)=0.5H(q) signifies **uncorrelated or short-memory** processes. Values above 1 are characteristic of **random-walk-like** dynamics.

It is important to note that while MF-DFA accurately determines **positive generalized Hurst exponents**, it may lose precision in the presence of **strong anti-correlations**, where h(q) approaches zero [9,10]. Nevertheless, MF-DFA remains one of the most effective tools for analyzing **multifractal properties of non-stationary geophysical time series**.

The displacement data spanning **1974 to 2021** were affected by various external influences – including **reservoir filling**, **meteorological variability**, and **seismic activity** – necessitating **detrending** prior to analysis. For this purpose, we divided the overall dataset into several distinct sub-periods: **1974–1978**, **1978–1985**, **1985–2006**, **2006–2013**, **2013–2017**, and **2017–2021**, – each representing a phase with noticeably different displacement behaviors. MF-DFA was then applied using **polynomial detrending** of various orders, such as **p = 2** and **p = 5**, to capture both local and global trends (Fig. 3a, 3b).



a.



b.

Fig. 3. MF-DFA (Fq, Hq) analysis of displacements of Enguri Arc Dam foundation (a. polynomial degree =p2; b. polynomial degree =p5).

The results obtained from the MF-DFA analysis reveal the evolution of the three principal characteristics – **Hurst exponent H(q)** and **fluctuation function F(q)** – over the observation period, with particularly pronounced activity during **2017–2021**. The analysis shows that **increasing the polynomial order used in detrending leads to a reduction in F(q)**, indicating a decrease in fluctuation amplitude.

The values of the **Hurst exponent H(q)** were generally found to be in the range **0.5 to above 1**, which signifies a **long-range dependence** or **positive correlation** in the time series of dam foundation displacements.

Our results suggest that **increasing the polynomial degree in the MF-DFA method alters the underlying dynamic structure**, effectively smoothing the series and reducing fluctuations. This behavior points to a strong influence of external factors – such as structural and environmental conditions – on the temporal variability of the displacement data.

Conclusion

In this study, we investigated the **dynamic characteristics of the Enguri Arch Dam foundation displacements** using long-term monitoring data collected between **1974 and 2021**. We employed the **Multifractal Detrended Fluctuation Analysis (MF-DFA)** method, which enabled a detailed examination of the nonlinear and multifractal properties of the displacement time series.

Our findings demonstrate that the dynamics of foundation displacement are significantly affected by both the **construction process** of the arch dam and, more importantly, by **fluctuations in the reservoir water level**. The MF-DFA results provided a clear and quantitative understanding of the system's dynamic behavior, allowing us to assess the **degree and nature of structural changes** over time. These insights are crucial for ensuring the **ongoing safety and stability** of the Enguri high dam, especially in the context of long-term geophysical and environmental influences.

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