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Hydrology

Geodynamic Monitoring for Assessing Stability and Hydrodynamic Conditions of Enguri High Dam Foundation Rocks

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Enguri Dam can be considered to be a high risk structure because it is located in a seismically active zone, has one of the highest walls (271 m) and the water level of the reservoir has extremely high annual changes of more than 100 m. The first permanent multi-disciplinary geodynamical-geophysical monitoring network was installed in the area of Enguri dam well before its construction with the aim of studying possible reservoir-triggered activity. The hydrostatic pressure of the reservoir acts on the dam mass and affects various geodynamic processes in the body of the dam and the surrounding rocks. To study the development of hydrodynamic processes with time, changes in pressure, temperature and electrical conductivity of water in the pores of rocks have been measured in numerous wells in and around the dam. This enabled to study the hydrodynamic connection between the wells and the reservoir. Electrical, acoustical and video logging surveys were carried out in the wells in order to study the physical conditions of the wells, the intensity of fracturing of the surrounding rocks and the state of stress. In order to determine the genesis of underground and surface waters and their ratio, their chemical and isotopic analyses were carried out. Stable isotope values confirm the existence of a mixture of "young"- atmospheric and "old" groundwater. In case of repeated video recording in the wells, it will be possible to inspect the size and frequency changes of fracturing at different depths in the wells with time and thus also the change of potential water pathways around Enguri Dam. *© 2023 Bull. Georg. Natl. Acad. Sci.*

fault zone, dam foundation, hydrodynamic time series, strain, fracture density

The studies included the organization of permanent monitoring on adjacent territory of the dam "in order to assess the reactivation potential of "Ingurishi fault". These studies were started in order to research the geodynamic condition of Enguri Dam and to assess its safety.

Inguri réservoir is known to have great economic importance for Georgia (irrigation and potable water supply, flood protection, renewable energy, energy independence). Therefore, it is rather important to ensure its safety and longterm stability.

The Enguri Dam in Georgia was designed and built in 1977 according to the modern technologies available at that time, according to safety standards. Together with filling the reservoir with water, seismic monitoring was carried out. Due to the large value (100 m) of water level differences in the Dam and its location in a seismically active zone, it belongs to a high-risk structure.

The German project "Technologies for the Protection and Safe Operation of Reservoirs 2019-2022 ("DAMAST") is dedicated to the safety of Enguri dam, which aims at studying the processes responsible for induced seismicity due to activation of seismic faults on Enguri Dam territory. In the framework of the DAMAST project further seismic and geodynamic monitoring network has been installed to ensure the safe and efficient functioning of the energy supply system in Georgia. Thus, we used the possibility of combining observations, caused by the coincidence of two projects in time in order to analyze the geodynamic situation and assess possible risks.

Materials and Methods

The permanent multi-disciplinary geodynamical-geophysical monitoring network was organized in the dam area [1-3] in order to control the stress–strain state in the foundation of dam according to existing standards. A Seismic network with xxx stations was installed in the area of Enguri dam well before its construction with the aim of studying possible reservoir-triggered activity. Monitoring of FZ strain began in December 1974, 4 years before the start of reservoir filling in April 1978.

The tiltmeter monitoring system of Enguri Dam and its foundation includes 10 stations for geodynamic monitoring which are installed in the body and foundation of the Dam. Three stations were installedin in sections 12, 18 and 26 of the dam at the benchmarks of 360 m, 402 m and 475 m., the 7 stations at the base of the dam on the left bank of the river in tunnel No. 160, totally 10 stations. Observation data are transmitted to Tbilisi every hour. In addition, data from a meteo-station and from awater level gauge for monitoring water level in the lake are also transmitted.

In addition, to the tiltmeter stations, a 22.5 m long Quartz extensometer (deformograph) has been installed in the Tunnel №3413 in the right embankment of the river Enguri in the lower bief. This instrument recorded horizontal displacements and widening of the so-called branch fault continuously since 1974, deformation processes are registered by an extensometer using a laser device, the data are automatically transferred to Tbilisi State University for analysis every hour.

To study geomechanical and hydrodynamic processes in time, it was planned to record changes in pressure, temperature and electrical conductivity of water in the pores of rocks. Wells were drilled for this purpose. In total, 2 deep and 3 shallow wells were drilled. In October 2020, drilling of the wells Shtolna, KIT-1, KIT-2, KIT-3 and KIT-4 was completed, the depths of which are as follows: Shtolna-15 m, KIT1-229 m, KIT2-307 m, KIT-3-25 m and KIT-4 70 m.

After completion of drilling and arrangement of wellheads, acoustical and video logging surveys were carried out in the wells.

From these measurements the orientation of the principal tectonic stresses at the well site could be deduced by checking the wells for fractures and stress-induced borehole breakouts.

After these studies, in part of the wells seismometers have been installed, in others pressure and temperature sensors for hydrodynamic omonitoring. In particular, at the end of June 2020, hydrodynamic observations were organized in front of Enguri Dam on the left (KIT-2 well) and right embankment (KIT-1 well) of the river Enguri. The wells are located in fractured limestone rocks and open the karst water horizon. Special automatic devices manufactured by HOBO were installed in the wells, through which data on the level and temperature of the water at an interval of one hour is recorded. Processing of data are carried out regularly. Also, since March 2021, t temperature and electrical conductivity at the newly drilled well KIT3

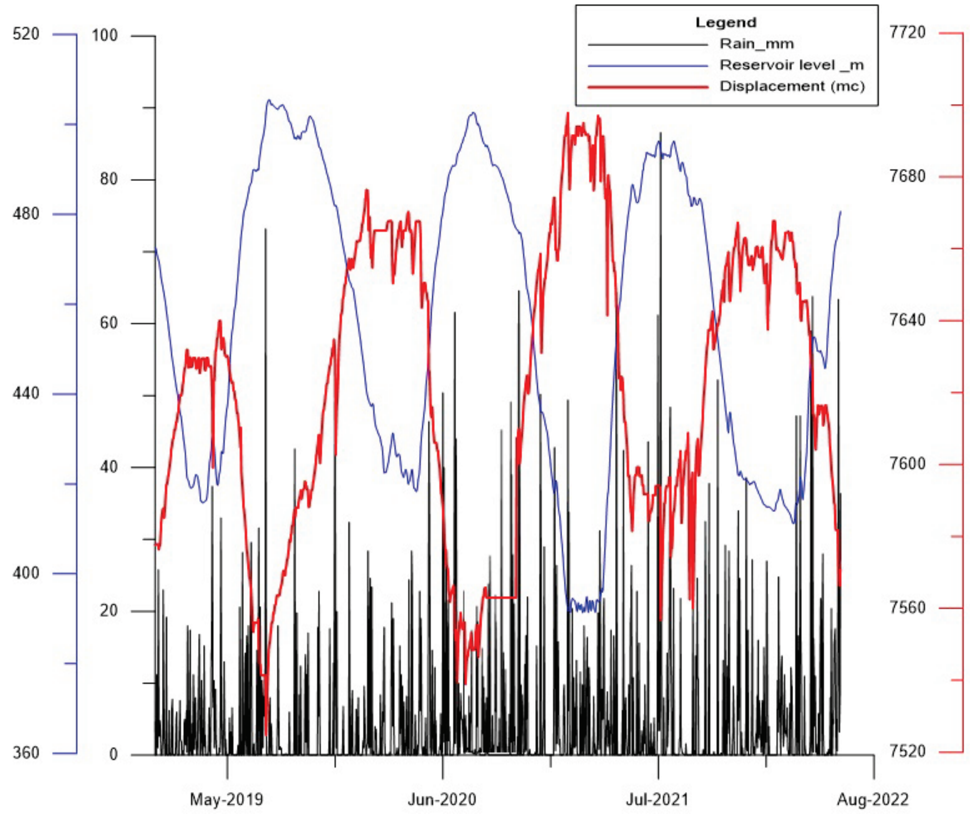

Fig. 1. Graphs of the relative horizontal displacement of the right-bank blocks collapse of the river Enguri, obtained with an extensometer (1), as well as graphs of changes in the amount of precipitation (2) and the water level in the Jvari reservoir (3) 2019-2022. The extensometer measures the displacement in a xxx direction, such roughly parallel to the Enguri dam and perpendicular to the Enguri valley. It is located across the so-called branch fault.

was installed using an automated device equipped with a GPRS information transmission system.

In order to identify the influence of exogenous factors (atmospheric precipitation and pressure) and geodynamic components on the aquifer, Enguri hydroelectric power station systematically provided us with information from the weather station at the dam and on the water level in the Jvari Reservoir as well as the amount of precipitation.

As we mentioned above, geodynamic observations are carried out using 22,5 long Quartz extensometer (deformograph) installed in Tunnel №3413 on the right embankment of the river Enguri. The data of the changes in water level in the reservoir and the data on the amount of precipitation for the same period together with the data of the Quartz extensometer. It has been established that the total displacement of blocks A and B correlates with changes in the water level in the reservoir. Also, the connection of low-amplitude changes in the movement of blocks with the amount of precipitation is recorded.

The extensometer shows on one hand extension across the fault zone due to the tectonic stress, which summarizes during almost 40 years to xxx mm (please provide a number here). In addition there is a quasi-periodic displacement which indicates maximum extension in the periods of low water level and minimum extension in the periods of high water level. This is an indication of the response of the rocks formation of Enguri Valley to activities (changes in water level) in reservoir operation (Fig. 1).

The anomaly in the determinism of fault zone strain recurrence due to a transition from the initial (natural) state to the quasi-periodic regime of reservoir exploitation.

It is clear that the hydrostatic pressure of the reservoir on the dam mass determines the geodynamic processes in the body of the dam and the surrounding rocks. The study of the hydraulic pressure heads acting on this unstable geodynamic system (rocks surrounding the dam) and their mutual influence is important in determining the stability of the dam.

In order to study the distribution of hydrodynamic pressures in the dam and its surrounding system, surveys were carried out in the wells in this area. The wells are drilled both inside and outside the dam body. The studies included the determination of the condition of wells, the determination of fracturing in them and the hydraulic connection of the system as a whole. For the future regular monitoring is planned.

During the current monitoring in standard wells, variations in water level, temperature and electrical conductivity were observed, which are due to both exogenous (atmospheric precipitation, fluctuations in groundwater pressure and tidal variation) and endogenous (earthquakes) factors.

Thus, the well observations made it possible to assess the hydraulic and related geodynamic changes in the entire system. Wells drilled in front of the dam on the slope surrounding it drain groundwater from karst sedimentary rocks that have a high conductivity and quickly respond to incoming precipitation. Thus, the effect of precipitation in wells is more immediate and precedes the change in the water level in the dam [4].

In addition, due to the location of the dam body in karst rocks, a close hydrodynamic connection between the wells and the dam reservoir is also recorded. The change in the water level in the dam over the same period is reflected in the change in the water level in the well. For example, the process of emptying the Enguri dam (January-April 2021) immediately affected the drop in the water level in the wells, which proves their superficial connection. At the same time, the water level respond to the water level in the reservoir is retarded which can be explained by hysteresis in the water saturation-drying cycle in the pores of rocks.

In order to determine the genesis of underground and surface waters and their ratio, their chemical and isotopic analyzes were carried out. The chemical composition of the water of the Enguri River is typical for fresh water with calcium, magnesium, sulfate, hydrocarbonate mineralization of 2.07 g/l and is almost identical to the chemical composition of the dam reservoir with mineralization of 2.9 g/l. However, in the latter, the values of phosphorus and sulfate are increased, which is explained by the relative immobility of the water in the reservoir, the biological processes occurring in it, as well as the removal of groundwater from the mountain slopes in the reservoir.

Depending on a geological structure, the wells xx, KIT-2, KIT-3 differ from each other in their chemical and isotopic composition. In particular, in all three wells calcium remains the leading cation, which is the characteristic of karstic waters, but in the second place instead of magnesium, the sodium cation is observed. Sulfide remains the dominant component in the anions, the value of which is the highest in KIT #3 well (2059 mg/l).

Stable isotope values confirm the existence of waters of “young” atmospheric genesis in rivers and reservoirs (18O-10.3, 2H -72). A relatively “heavy” isotopic composition is observed in KIT#1 and KIT#2 wells (18O-9.35; 2H-66.6), which shows the existence of mineralized ground waters in these wells. The “heaviest” value was observed in the KIT #3 well, which indicates the existence of relatively deep underground water components.

This fact is also proved during the observation process on KIT #3 well, when during the increased precipitation period the share of surface water in its composition, the values of specific conductivity in it decreased, and when in the opposite case – the conductivity increases at the expense of deep mineral water (Fig. 2).

In the same time increasing water level triggered decreasing of water temperature and vice-versa.

This fact is explained by the inflow of atmospheric relatively cold, fresh and low-mineralization water into the well, which causes the temperature to drop and to decrease of the mineralization.

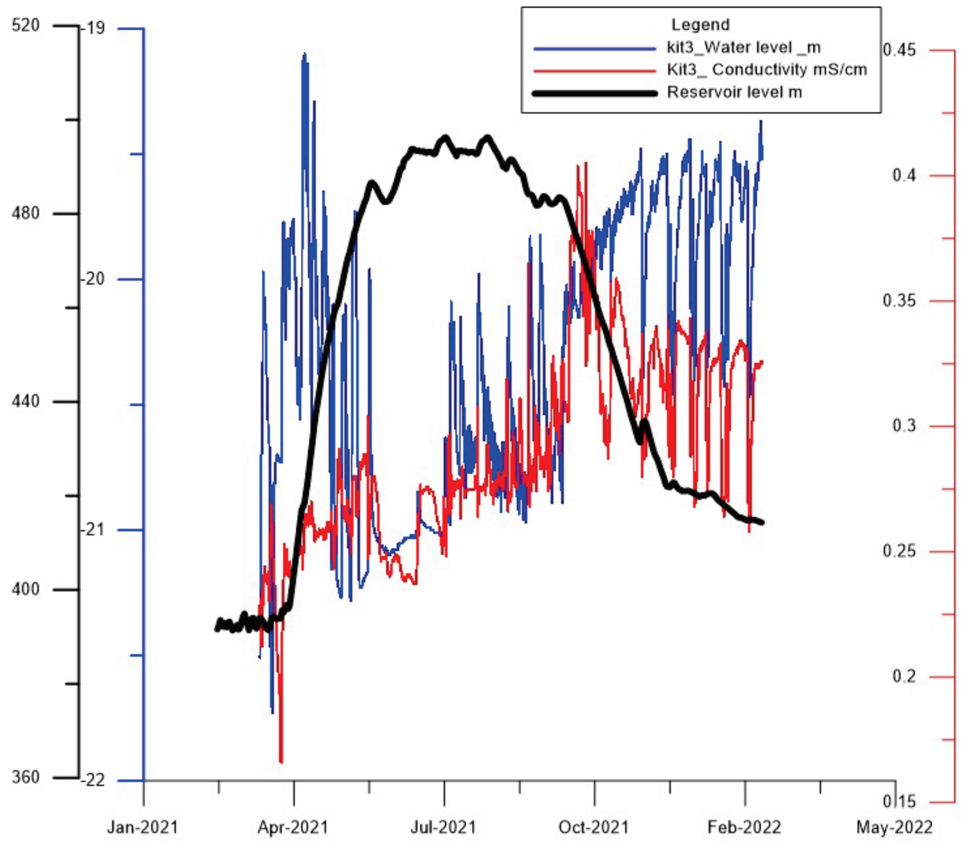

Fig. 2. Variation of water level, conductivity in borehole KIT3 and water level in reservoir.

In order to explain the hydraulic relationship between the dam body and adjacent rocks, an inspection of concrete and rock integrity in the wells was implemented, for which video inspections in the old and new wells were conducted. Fig. 3 shows examples of the video recordings from 6 wells at different locations and at different depth levels.

First, Dam-TOP 1 and Dam-TOP 2 wells drilled in the dam body were studied, it was concluded that the condition of the concrete in the upper part is good. In depths, the limestone layer under the concrete is fractured and water leakage is taking place. There is a similar situation in the well drilled in the tunnel on the right bank of the dam-„Shtolna, where the condition of the concrete in the upper part of the well is good and walls of broken limestones are observed below 11 meters. A video inspection in two galleries in the left side of the dam body was conducted, which revealed the strong fracturing and leakage of water from the well. For example, in the well which is located in the tunnel LC 3-2 and LC 5-5. Intensive fracturing on the left bank must be related to the strong dynamic loading, as evidenced by the strong grinding nature of taken cores in the drilled wells in this territory. Well KIT-1 located on the right bank of the river in front of the dam is also infectively fractured.

Intense fracturing must be associated with strong dynamic loading, which in turn is caused by continuous deformations of the dam and stresses acting on the slopes next to it.

Changeable dynamic loads (movement of the dam body in various modes (water level drop in the Jvari Reservoir of Enguri Dam, seasonality, etc.) intensively affect the supporting rocks, as a result of which the fracturing becomes more frequent and accordingly, the intensity of washing the concrete and rocks with water increases.

In case of repeated video recording in the wells, it will be possible to inspect the size and frequency

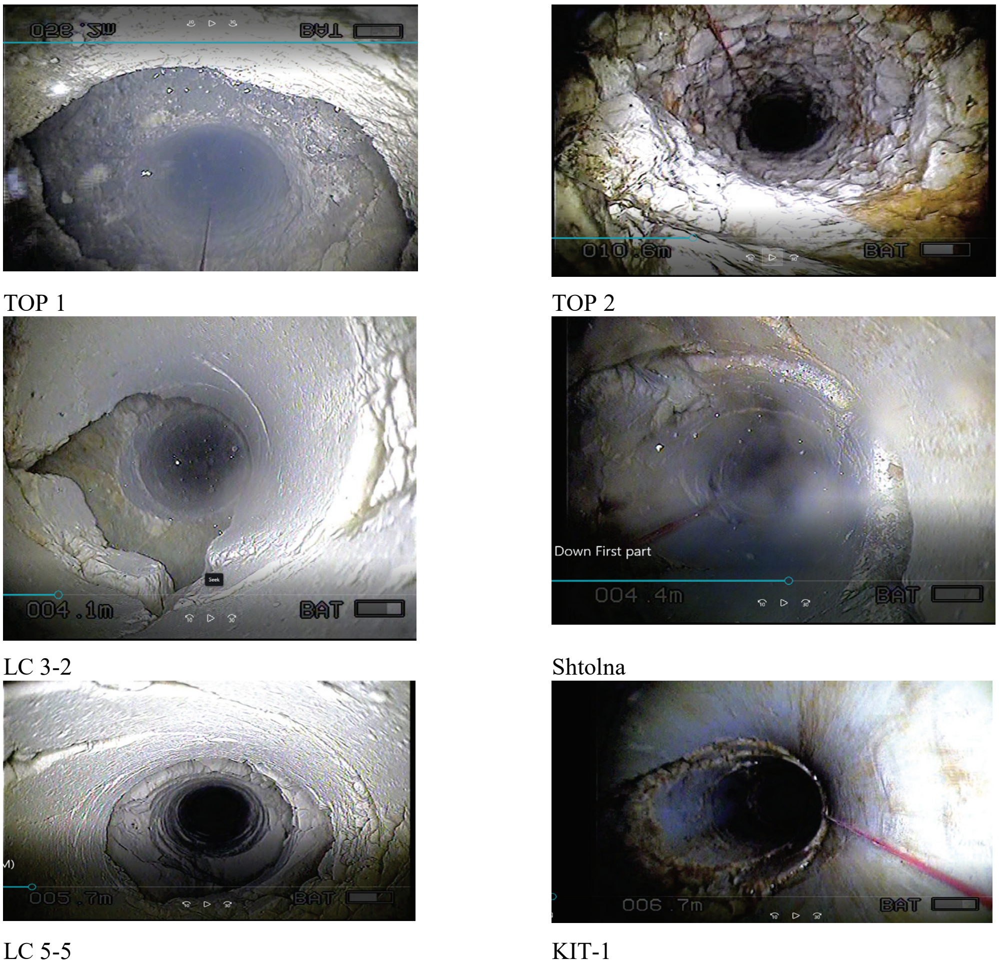

Fig. 3. Pictures of video logging in different borehole. The depth of the log is indicated in the lower left of each photo of boreholes. With this kind of monitoring, the state of the concrete section can be inspected on one hand and fractures and faults can be identified.

changes of fracturing at different depths in the wells and thus, the change of tension in time be analyzed.

During such monitoring in the wells, the density of dam fractures is assessed horizontally and vertically. Below is given an assessment example, where it is shown that fractures of horizontal type are widely common in wells, whereas vertical – occur only at depths from 10 to 20 m.

According to the observations in numerous wells at Enguri Dam site, a cause-and-effect link between atmospheric precipitation and water level changes in dams and wells, which shows the exogenous nature of these processes could be demonstrated. It is also supported by the fact that the process of releasing water from the Enguri dam was accompanied by a drop in the water level in the wells, indicating the existence of a direct connection between them. The intensity of the connection has to be investigated in future, e.g. with tracer tests.

A video inspection was carried out in the body of the dam and in the old and new wells drilled in its front side – it has been concluded that in the dam body and drilled wells in its front side, the condition of the concrete in the upper part is good, but in separate wells the concrete and Limestones under it are strongly fractured and intensive water leakage is occurring.

All these are due to the dam deformation and stresses acting on its side slopes. Changeable dynamic loads are intensively happening on the slope rocks, due to which the fractures are formed and the intensity of washing the limestone with water increases, which might increase the geo-dynamic risk.

One of the means of controlling this dynamic process and its negative consequences in time is the implementation of repeated video inspection in the wells, controlling the condition of fractures and their sizes and the joint interpretation with deformation monitoring e.g. from the extensometer.

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ჰიდროლოგია

გეოდინამიკური მონიტორინგი ენგურის მაღალი კაშხლის საძირკვლის ქანების სტაბილურობისა და ჰიდროდინამიკური მდგომარეობის შესაფასებლად

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**აკადემიის წევრი, ივანე ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტი, მ. ნოდიას გეოფიზიკის ინსტიტუტი, საქართველო*
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§კარლსრუეს ტექნოლოგიური ინსტიტუტი, გამოყენებითი გეომეცნიერებების ინსტიტუტი – ტექნიკური პეტროფიზიკის განყოფილება, გერმანია

ენგურის კაშხალი, მისი სეისმოაქტიურ ზონაში მდებარეობის, მაღალი რისკის, მისი დამბის მაღალი სიმაღლის (271 მ) და რეზერვუარში 100 მ-ით მეტი წყლის დონის წლიური ცვლილების გამო, მიეკუთვნება მაღალი რისკის სტრუქტურას. რეზერვუარის შესაძლო გავლენის შესწავლის მიზნით, ენგურის კაშხლის აგებამდე, ორგანიზებულ იქნა პირველი მუდმივი მულტი-დისციპლინური გეოდინამიკურ-გეოფიზიკური სამონიტორინგო ქსელი. რეზერვუარის ფიქსირებული ჰიდროსტატიკური წნევა მოქმედებს კაშხლის მასაზე და გავლენას ახდენს კაშხლის სხეულსა და მიმდებარე ქანების სხვადასხვა გეოდინამიკურ პროცესებზე. დროთა განმავლობაში ჰიდროდინამიკური პროცესების განვითარების შესასწავლად, კაშხლის და მის

ირგვლივ არსებულ მრავალრიცხოვან ჭაბურღილში იზომებოდა ქანების ფორებში წყლის წნევის, ტემპერატურისა და ელექტრული გამტარობის ცვლილებები, რამაც შესაძლებელი გახადა ჭაბურღილებსა და წყალსაცავს შორის ჰიდროდინამიკური კავშირის შესწავლა. ჭაბურღილებში ჩატარდა ელექტრული, აკუსტიკური და ვიდეოკაროტაჟული კვლევები ჭაბურღილების ფიზიკური მდგომარეობის, მიმდებარე ქანების ნაპრალიანობის ინტენსივობის და დაძაბულობის მდგომარეობის შესასწავლად. მიწისქვეშა და ზედაპირული წყლების გენეზის და მათი თანაფარდობის დასადგენად ჩატარდა ქიმიური და იზოტოპური ანალიზები. სტაბილური იზოტოპური მნიშვნელობები ადასტურებს „ახალგაზრდა“ – ატმოსფერული და „ძველი“ მიწისქვეშა წყლების ნაზავის არსებობას. ჭაბურღილებში განმეორებითი ვიდეოგადაღების შემთხვევაში, შესაძლებელი იქნება დროთა განმავლობაში ჭაბურღილების სხვადასხვა სიღრმეზე ნაპრალიანობის ზომისა და სიხშირის ცვლილების შემოწმება და, შესაბამისად, ენგურის კაშხლის ირგვლივ წყლის მოძრაობის პოტენციალის ცვლილება.

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