INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 11th International Symposium on Field Monitoring in Geomechanics and was edited by Dr. Andrew M. Ridley. The symposium was held in London, United Kingdom, 4-7 September 2022.

11th INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

Distributed optical fiber systems for monitoring the serviceability strain response of an Italian concrete arch dam and its foundation

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Abstract

Concrete arch dams are large constructions aiming at producing hydroelectricity, providing water for irrigation and controlling flooding. Although the maximization of the water level of the basin allows to optimize the management of the dam, an accurate monitoring of such large structures must be carried out carefully to evaluate the deformations in operational conditions. Traditionally, the monitoring of the dam body as function of the environmental temperature and reservoir water level is performed through visual inspections, periodic manual surveys or topographical measurements. Nevertheless, this monitoring is complex and time consuming due to the considerable spatial extension of dams. Recently, both traditional survey and innovative techniques for field monitoring have greatly improved, making these checks faster and more complete. In this context, the use of Distributed Optical Fiber Sensors (DFOS) as detector of strain and temperature can be considered a very attractive option, allowing the measurements of spatially dense and distributed data along large distances and with high resolution. The paper deals with the monitoring of a concrete double arch dam, namely Ponte Cola dam, located in Valvestino (BS) in North Italy. Between December 2020 and February 2021, two different types of DFOS both in the foundation and along the crown of the dam were installed. The DFOS are one for strain and one for temperature measurement. Several measurement campaigns were carried out. These measurements have been compared with the ones obtained from traditional monitoring techniques, to estimate the reliability and potentiality of such an innovative system in monitoring the very low strains developed in this type of structures.

Keywords: Distributed Optical Fiber Sensor, Low Strain, Structural Monitoring, Temperature strain

1. Introduction

It is estimated that 19% of world energy is produced by hydroelectric power stations. All over the world there are 45’000 dams higher than 15 m, and their number is constantly increasing, due to the need for more and more energy. Moreover, in Europe and in other economically developed countries there are many dams constructed more than 60-80 years ago and now have to be carefully monitored in order to check their possible deterioration.

Although dams are large, very robust and apparently stable structures, they exhibit significant displacements during their useful life. These displacements, consequence of the environmental load variations, mainly due to the water level and temperature fluctuations during the year, must be carefully controlled and monitored in order verified their compatibility with the structure limit state serviceability. The data can reflect the trends in variables such as deformation, cracking, seepage and concrete deterioration over time and are important information for managers to understand the operational status of a dam. In literature, data analysis methods are largely available (Li et al., 2019; Bukenya et al. 2014) and are considered very important for monitoring dam safety. As reported by Li et al., 2019, dam monitoring data analysis methods look for existing correlation between environment variables such as air and water temperature, water level and other environmental conditions, considered as independent variables, and effect variables (deformation, cracking, seepage, etc.), considered as dependent ones. The study of the interactions among these variables and the evaluation of the trends of effect variables can be used for the prediction and optimization of the dam activity. Based on the monitoring activity, a monitoring index can be determined as threshold to denote warning, extreme dangerous values or abnormal values, to rapidly detect any abnormal changes in the dam state.

The traditional procedure for assessing the structural integrity and deformation state of dams is through visual inspections and manual detection of localized deformations. The inspections are conducted periodically by experienced workers, who record the condition of the dam and possibly recommend actions to be taken to solve the identified problems. This type of procedures has various shortcomings such as high manpower demand, prolonged times for the control of large dams, often insufficient frequency and inaccessibility of critical parts of the structure under surveillance (Bukenya et al. 2014). For example, it is difficult to observe damage developing on the upstream side, under water level or in correspondence of the contact between dam and foundation rock. The resulting lack of information relating to the structural condition can lead to an incorrect assessment of the conditions and therefore uninformed decisions regarding the maintenance of the structure.

The dam monitoring data can be collected using GPS technology (Taşçi, 2008), pendulums, thermometers, flow meters (Chouinard et al, 2006) or other instruments installed on or inside the dam. The aim of monitoring data is to collect measurements that allow to show correlations between the variations in environmental variables and effect variables, that reflect the comprehensive state of the dam. The recent development of monitoring systems has made it possible to gradually implement the technologies available for dam safety control to obtain automatically and in real time measurements, increasing the number of variables collected and the spatial density of the information. Moreover, intelligent monitoring allows to analyse the data in near real time so as to allow any timely interventions in the event of alert situations, but also to optimize the management of energy production itself in normal working conditions of the dam, according to the environmental variables present.

In this context, sensors based on the Fibre Optic technology, and, particularly, the Distributed Fiber Optic Sensors (DFOS) here presented, allow the measure of strain and/or temperature with high spatial resolution over a long-range. The operating principle of DFOS is based on the injection of a light wave in an optical fiber and on the analysis of the back reflected light signal generated by the scattering effects in the silica composing the fibre. Various optical sensing techniques are used for interrogating the fibres (Schenato, 2017). This technology, already used in many geotechnical applications (e.g., Soga, 2014, Cola et al., 2019), offers the possibility of obtaining information at high spatial frequency, continuously over time. In particular, in this application, the use of DFOS allows to obtain measurements even in positions of the dam that are difficult to reach through inspections or traditional sensors. Focusing on the application at the Ponte Cola dam, each installation of sensors included two optical fiber cables, one for strain measurement and the other for temperature compensation. The two cables have been interrogated in loop configuration using a Brillouin Optical Frequency Domain Analyzer (BOFDA) from FibrisTerre (Germany), with a maximum sampling and spatial resolution of 5 and 20 cm, respectively, and a strain and temperature measurement accuracy of 2 με and 0.1 °C.

2. Case study

2.1 Ponte Cola concrete double arch dam

The hydroelectric power station (Figure 1), known as Ponte Cola dam, is located in the valley of the Toscolano torrent in S. Maria Valvestino, about 9 km from its outlet in Lake Garda (North Italy). The dam, built between 1960 and 1962, has the purpose of storing the energy that can be drawn from the basins of the Toscolano and S. Michele streams and has a reservoir corresponding to an energy reserve of 45×10^6 kWh. The dam extends from an altitude of 124 m a.s.l., corresponding to the lowest point of the foundation, up to an altitude of 505 m a.s.l. corresponding to the crown, whose length in development is equal to 282 m.

Figure 1: a) Aerial view of the dam and the Valvestino lake; b) Valley facing of the dam.

Since the thermal variation is very relevant for the estimation of deformations, 10 thermometers were installed during the construction of the dam on the downstream face, 4 on the upstream one and 18 thermometers were drowned in the concrete casting to monitor the temperature of the dam body. The dam was also equipped with 65 removable strain gauges, 29 distance dilatometers and 124 thermo-extensometers. More recently, the owner company has installed an automatic topographic survey system capable of detecting the position of about 30 targets positioned on the downstream face. Performing manual inspections and measurements on such a large number of sensors requires the workers present in the dam long daily control operations. The topographic measurements, collected automatically, provide more rapid and precise information on the displacement of the dam body as the environmental conditions vary.

In summary, Figure 2 shows an example of the trend of temperatures that characterize the environment around the dam and the dam itself. In particular, in the plot there is reported the air temperature measured by a probe located on the downstream face at 490 m a.s.l., which shows the high variability both in the night-day cycle (ΔT=20°C) and in the seasonal cycle (ΔT=25°C). The water temperature is also reported, measured upstream of the dam at an altitude of 440 m a.s.l., a position which is always located below the water level, which never dropped below 440 m a.s.l. in the considered period. Although the trend is consistent with the measurement of air, it is evident that the temperature fluctuates very little in the short term (day-night variation ΔT<2°C), and, in the long term, it presents a lower amplitude (ΔT=15°C) respect the external air: moreover, it responds to the ambient temperature variation with a slight delay. The temperatures of the dam body are then reported through two sensors, installed at 490 and 440 m a.s.l. respectively. The lower altitude sensor is characterized by approximately constant temperatures in the short term, and shows little variable temperatures (ΔT=7°C) even in the summer-winter cycle. On the other hand, the dam temperature at 490 m a.s.l. is more variable, where the smaller thickness of the dam allows the concrete to be more affected by environmental conditions. The thermal response is similar in amplitude and shape to the response provided by the probe in water.

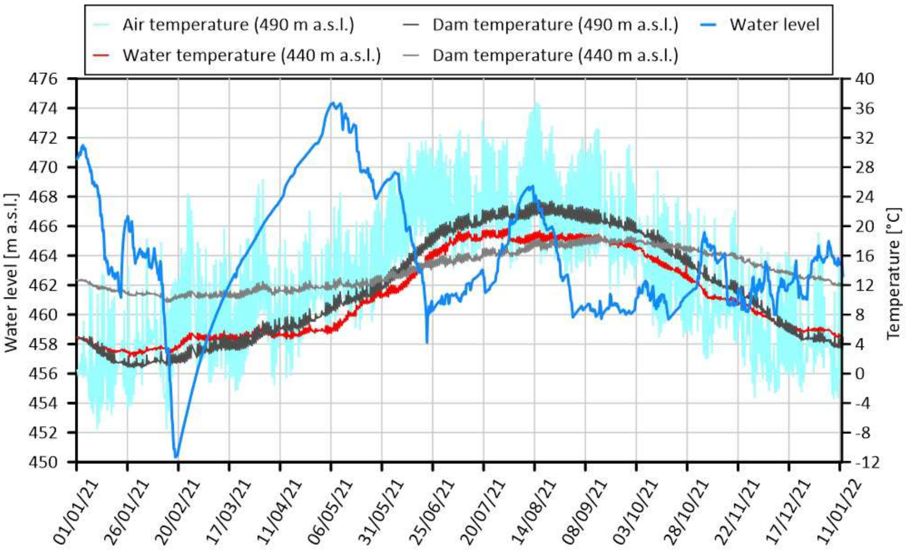

Figure 2: Measurements of temperature and water level in the reservoir for the period 01/2021 – 01/2022.

2.2 Fiber optic installation

Between January and February 2021, two installations of fiber optic sensors were carried out at the dam, the first at the dam foundation, the second at the crown. Each installation involved drilling a borehole in the concrete or in the foundation rocks to embed the fiber optic cable. The borehole is cemented (Figure 3) to guarantee an efficient coupling between the fiber and the material to be monitored. Particularly in the dam foundation two parallel boreholes are executed up to 330 m a.s.l., crossing about 40 m of concrete and 40 m of calcareous rock forming the dam foundation. One borehole contains the DFOS here presented, in the other 5 rod extensometers with continuous interrogation are installed at different depths, in order to have a reference for the DOFS measurements.

Particular precautions have been followed to ensure that the fiber is not damage during the installation and fixing phases. Both in the foundation and the crown two different fibers were positioned, one for strain and one for temperature measurement. Each fiber makes a two-way path and therefore, at each depth, two measures are available, in the follow named "up-down" and a "down-up", referred to the descending and ascending portion of cable, respectively. Two armored corrugated optical fiber cables for strain measurement (BruSens® V9, Solifos), approximatively 200 m and 600 m long each, were installed in the dam foundation and crown, respectively. In addition, two cables for temperature measurement (BRUSens® DTS STL PA, Solifos) of the same lengths were installed. The temperature cable is specifically designed to be almost insensitive to mechanical strain; to this aim, it is composed by a fiber hosted in a gel-filled stainless-steel loose tube. Temperature measure is very important to study the behavior of the dam, but also to evaluate the thermal-optical effects on to the strain cable for a correction of the strain recorded by the strain DFOS and isolated only the mechanical fraction of strain.

The fibers allow a measurement of deformation and temperature with high spatial density (one point every 20 cm), so as to allow a complete interpretation of the deformation state of the dam. In this preliminary installation, only two measurement cables are available, but the implementation of this type of sensors can lead to the collection of information distributed throughout the structure.

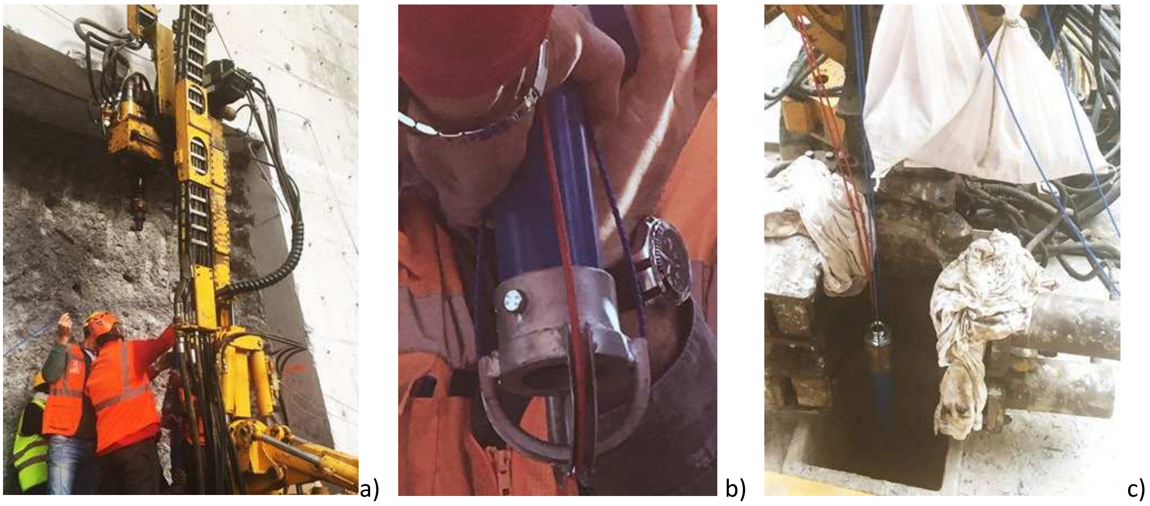

Figure 3: a) Installation phase of the fibers in the dam foundation; b) detail view of the terminal element opportunely designed to support the cable curvature; c) Ultimate positioning of the fibers at the final stage of their installation in the dam foundation.

3. Measurement campaigns

Some preliminary manual measurement campaigns were carried out after the installation of the sensors (Figure 4). Subsequently, two long period surveys with automatic interrogation of DFOS was performed in August 2021 (26 days) and in November-December 2021 (27 days), once the sensors fibers were connected, through standard communication cables, to a single central measurement station located in the control house of the dam. From here with the interrogator can interrogate all the 4 fibers, two for the strain and the other two for the temperature measurements, each requiring two channels of the interrogator, in double-ended configuration. In this way, it was possible to automatically record the data on a digital memory, without interruptions and without the need for the presence of an operator.

In the present work, only the data acquired are presented and briefly commented. Analysis of the data are still in progress and are not here reported.

The data of the fibers in the foundation are shown in Figure 5. For ease of interpretation, only 4 measurements are reported, two for each period. The information is obtained as relative measurement with respect to a first reference one, carried out on 27/5/2021. In fact, the measurement allows to express the strain with respect to a measurement considered as a reference. As anticipated, the measures are reported in "up-down" and "down-up", which generally show a great consistency one with each other. The graph on the left allows to immediately confirm the higher temperature measured in July and August, compared to the May reference, while it shows a general cooling of about 2-3 degrees in the winter period if compared to the reference taken in May. The upper 5 meters of fiber are strongly affected by the external temperature, while from 30 m downwards we observe an almost constant temperature, approximately for all the measurements. The deformation measurements, on the other hand, show a very low strain (less than 10^{-4}) along the entire depth investigated by the sensor, but due to this low level of strain a clear trend is barely identified.

Figure 4: a) Position of the niche with respect to the dam body; b) preliminary measures in the fibers installed in the dam foundation; c) Localization of the crowning fibers; d) preliminary measures of the crowning fibers.

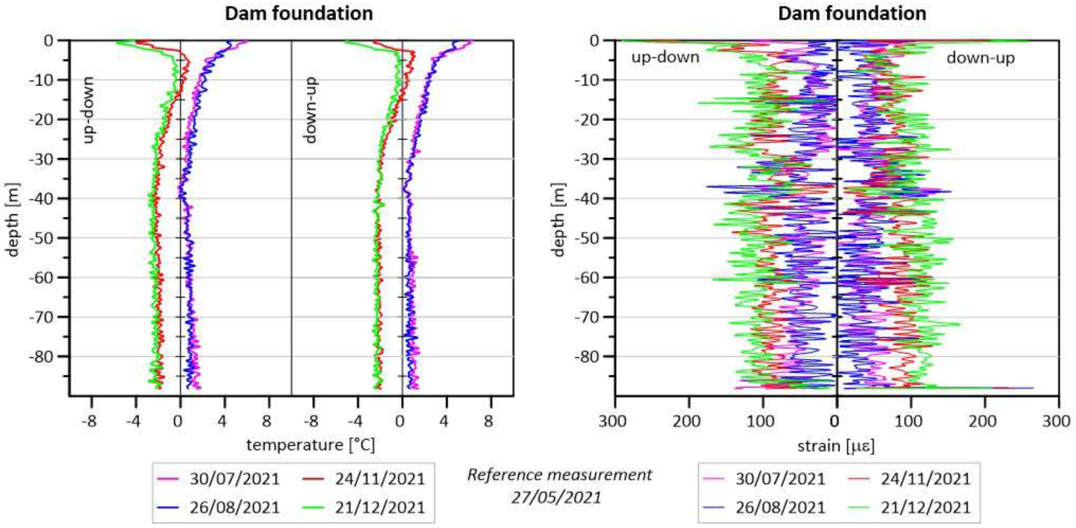

Figure 5: Measurements of temperature and deformation measured for the fibers in the dam foundation.

The fibers at the crown (Figure 6) show an approximately constant temperature along the entire extension (a little less than 300 m) of the fiber, for each date considered. In this case, the increase in temperature of about 7 °C and 12 °C in the two summer days is even more evident compared to May 2021, while a decrease of 8 °C and 11 °C in the winter measurements is observed. Although the measurement is approximately constant, small peaks are noted with an interspace of about 10-12 m. Some of these peaks are also found in the strain profiles, and they are located at the thermal dilatation joints present in the concrete structure. Globally it appears that the strains of the crown are much more significant than those in the foundation, confirming a greater effect of environmental loads in this dam portion. The summer measures show greater dilatations, concentrated especially at the dilatation joints, which are then reduced in the winter campaign, as it can be expected.

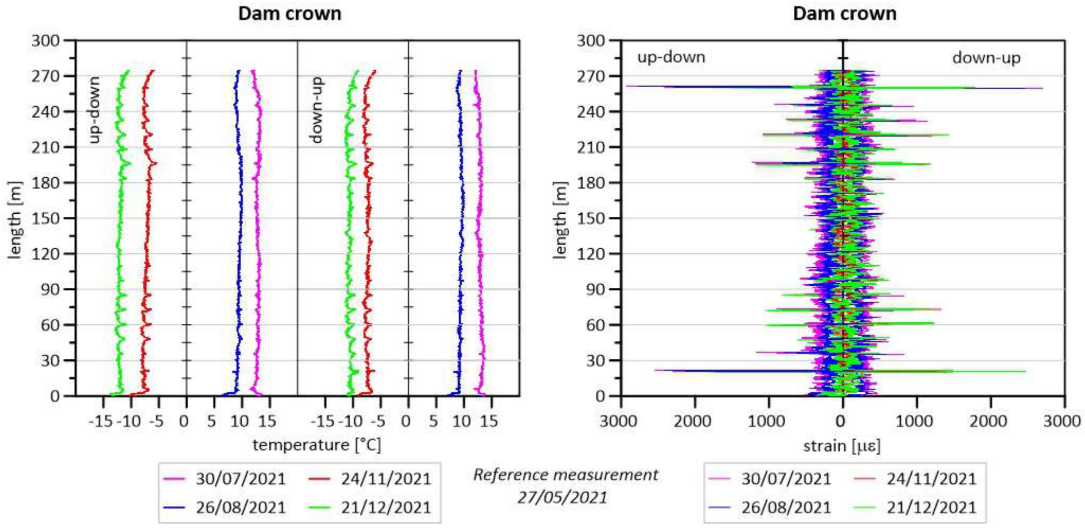

Figure 6: Measurements of temperature and deformation measured for the fibers in the dam crown.

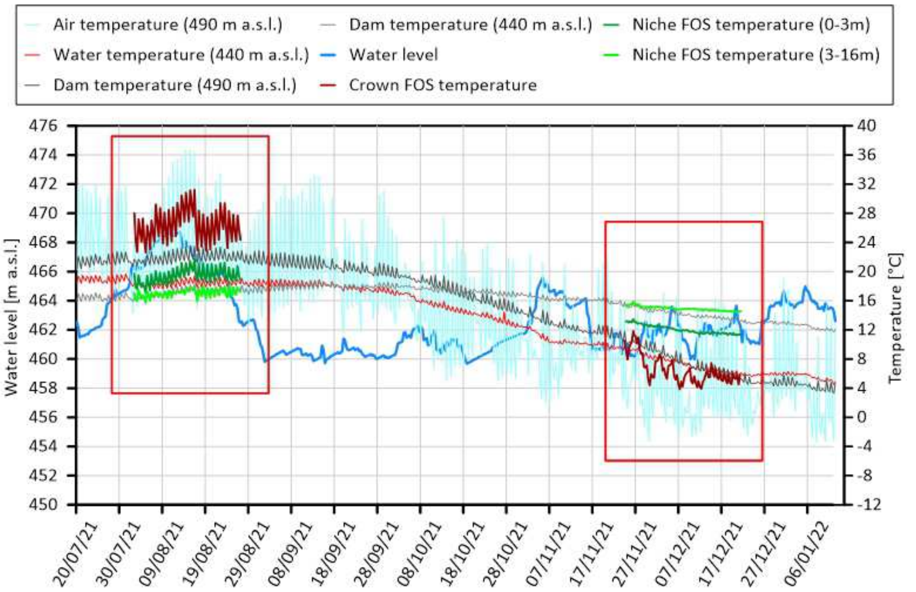

Figure 7: Measurements of temperature obtained by the FOS for the two period 7-8/2021 and 11-12/2021 compared with other sensors results.

Finally, Figure 7 shows a preliminary comparison among the temperature measured with the data of traditional sensors (those already commented in §2.1) and the data acquired by DFOS in the two campaigns. About the strain in the foundation, it is plotted the average value of the first 3 m of depth (L_1, 0-3 m, dark green) and the subsequent 13 m (L_2, 3-16 m, light green). The crowning measurements were instead averaged over the entire fiber length, as the homogeneity of the data was evident. The DFOS measure are translated from the temperature present in the dam on the reference day (27/5/2021), to make them comparable with the traditional sensor measurements. The temperatures acquired in section L_1 show a translation of about 3°C with respect to those of the sensor immersed in the concrete at 440 m a.s.l., more in the summer and less in the winter, testifying how the shallow portion of the fiber is more affected by the external temperature. The deeper part L_2, on the other hand, shows results very similar both in trend and values to those detected by the traditional sensor. The trend of the crown DFOSs data is consistent with that of the traditional sensors. However, with exception of the last period of December, in which the measurements are very similar to those of the concrete sensor at 490 m a.s.l., in the remaining periods the amplitude of the oscillations, which is greater, and the temperature detected becomes intermediate between the data of the sensor in concrete and that in the air. This behaviour can be attributed to the fact that the fiber was installed at a shallower depth than the temperature sensor and is therefore more affected by the outside air temperature.

4. Conclusions

This work presents the installation phases of optical fiber sensors for measurement of strain and temperature in a large concrete dam. Some preliminary acquired data are described and compared with data recorded with traditional sensors. Although the state of activities is still in an initial phase, the outcomes achieved confirm that DFOSs promise very good applicability performance.

Anyway, with the current state of experience in using DFOS for monitoring a large concrete dam, although these sensors have shown a high ability to provide reliable measurements, it is also worth noting some critical issues that have been encountered. The fiber optic cable itself is a fairly delicate sensor and the installation, as well as the activities aimed at performing the measurements, must be carried out with care and caution. In fact, there is the risk to damage the optical fiber, thus reducing the accuracy of the data that can be collected. Furthermore, to ensure greater reliability of the measurement, specific calibration and testing activities should be carried out on the sensors to obtain the specific characteristics of the cables actually installed on site. All things considered, however, the reliability of the sensors is very satisfactory and their applicability is really promising.

The next step in the interpretation of the DFOS results will consist in comparing also the strain measurements collected with the topographic or strain gauge data available, so as to validate the instrument also in this context. In fact, once this is completed, it is believed that DFOS can be widely applied to other dams, with even more extensive applications on the dam body and foundation.

Acknowledgements

This work was co-financed as part of the UNIMPRESA project by the University of Padua and by ENEL Green Power.

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