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BEHAVIOR ANALYSIS OF THE UNDERGRAOUND POWERHOUSE BASED ON PRECISE DISPLACEMENT MEASUREMENT

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1. INTRODUCTION

An adequate management of an aging underground powerhouse is recognized to be a mandatory issue through the experience of which significant damages were happened in a few support members of approximately 40-year old cavern for the powerhouse. The studies have been made to verify the soundness of the cavern by arranging two diffused laser range finders at the generator sections for monitoring the convergence, in-situ stress measurements of major concrete structures of the cavern and lift-off tests of pre-stressed (referred to as PS) anchors. Based on these results, the present soundness of the cavern was confirmed with the interpretation by the structural calculation using the simple frame model of the underground powerhouse. The management criterion was updated by applying the future scenarios of the deterioration of the cavern supports to its present structural condition [1], [2], [3].

Following updated management criteria at the above-mentioned underground powerhouse, seven-year convergence data at two generator sections has been accumulated so far. While one is stable, however another section has been shortened gradually, but does not touch the maintenance criteria. In this paper, the convergence behaviors are examined from the standpoint of the structural response of the cavern.

2. OUTLINE OF AN UNDERGROUND POWERHOUSE STUDIED

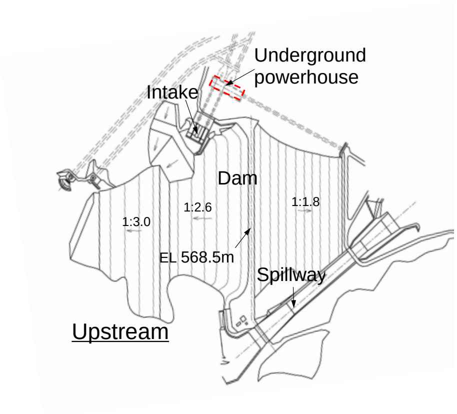
The underground powerhouse studied in this paper, is located in the central part of Japan, includes output of 220 MW, two generator units and discharge of 266 m^3/s, with completion in 1968. It has the dimension of 23 m wide, 42.25 m high and 70.2 m long. Due to the existence of the reservoir above 100 m of its location, the underground powerhouse was constructed with grouting as the watertight structure. The surrounding weak geological zone caused excessive displacement of the cavern and imposed the additional structures to strengthen the stability of the cavern, such as additional arch structures and thicker side wall and slab during the construction. Its characteristics are shown in Fig. 1.

A few damaged PS anchors were identified in 2008, which was 40 years after the completion of the cavern, while no other deterioration in the cavern was found. These are shown in Fig.2. PS anchors arranged in the cavern are a type of un-bond with applying the bituminous coating around the tendon and mortal grouting in the boreholes. It is considered that a few damaged supports did not affect the stability of the cavern. However additional monitoring, which involves measuring the tension stress of existing anchors and monitoring the cavern convergence and major structural beams, was planned to clarify its long-term performance.

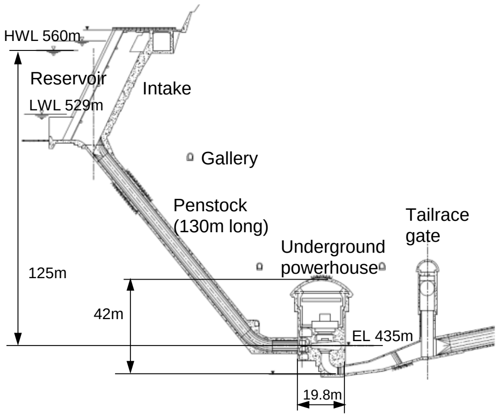
The monitored convergence performed in seven years is only examined in this paper from the mechanical view point of the cavern behavior.

3. CONVERGENCE OF THE CAVERN

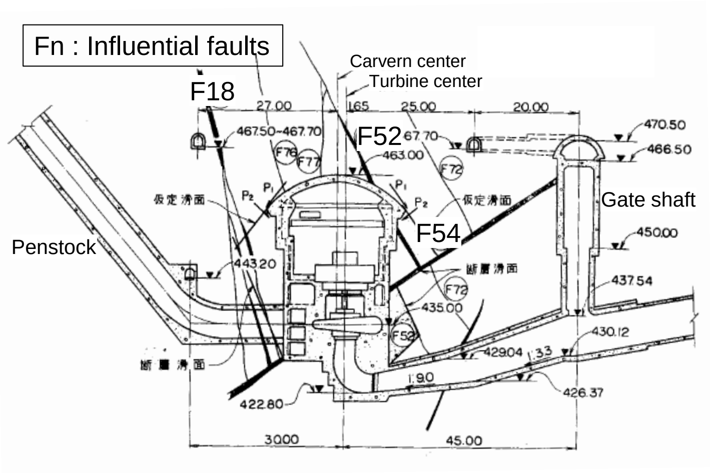
Monitoring plan is shown in Fig. 3. The convergence is monitored at the middle elevation of two generator sections of No. 1 and No. 2 in the machine room using a new device using the diffused laser beam, referred to as the diffused laser range finder (DLRF) [1], which consisting the laser transmitting and receiving unit and the reflecting board. The distance between the unit and the board is continuously measured in a precision of 0.1 mm with any interval. The overview of DLRF is shown in Fig. 4. The circumstance conditions of the reservoir water depth and the ambient temperature of the cavern are simultaneously measured.



(a) Layout of powerhouse



(b) Longitudinal section of waterway



(c) Geological condition

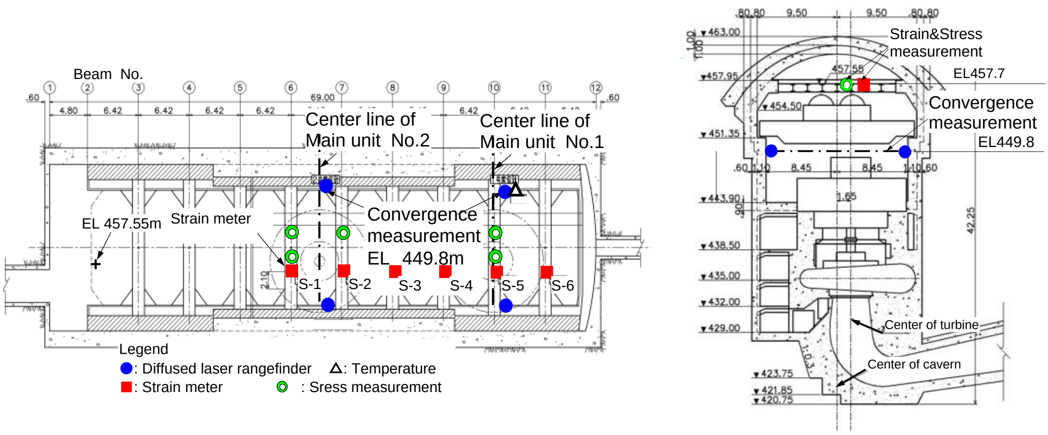
Fig.1
Situation of underground powerhouse

(a) Broken tendon of PS anchor

(b) Borehole and the broken tendon remained

(c) Broken tendon of PS anchor, which was drawn

Fig.2
Damaged PS anchors



(a) Plan of underground powerhouse

(b) Section of underground powerhouse

Fig. 3
Underground powerhouse and monitoring arrangement

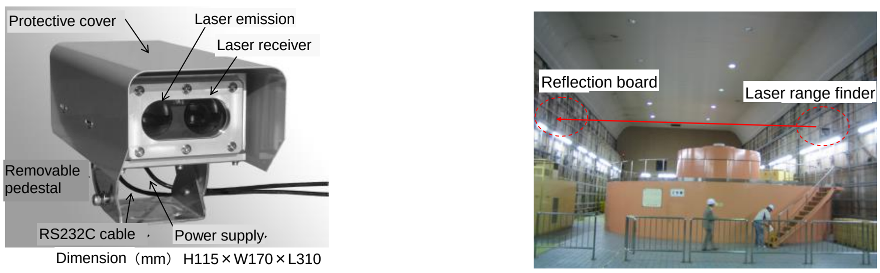
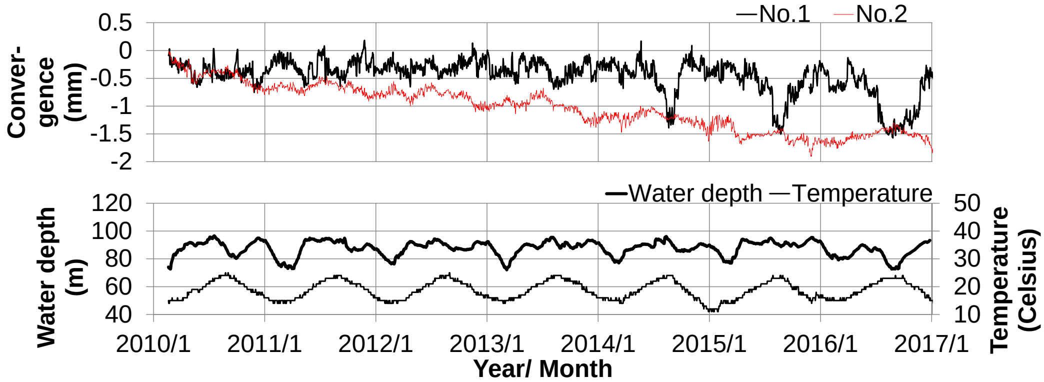


Fig. 4
Diffused laser range finder (DLRF)

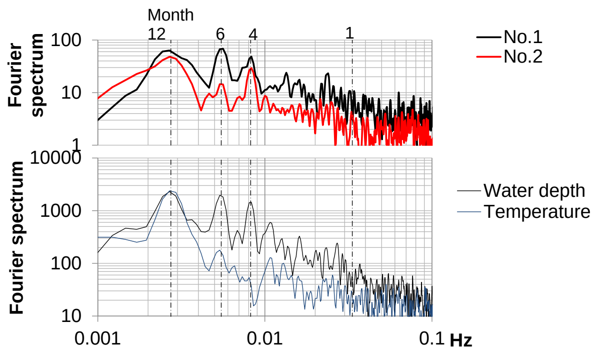
The seven-year convergence histories of the cavern are shown in Fig. 5 with the reservoir water depth (referred to as the water depth) and the ambient temperature in the machine room (referred to as the temperature, simply). The data are compiled as daily ones. The water depth is measured from the top of the cavern (EL 463 m) to the reservoir surface. Fourier spectra are shown to identify the frequency characteristics of the data.

The water depth shows several cyclic fluctuations a year, while the temperature in the powerhouse fluctuates once a year. The convergences of both sections (referred to as No.1 section and No.2 section) show gradual shrinkage with higher frequency fluctuation, which are approximately 1 mm and 1.5 mm for No. 1 and No. 2 sections respectively and still less than the maintenance threshold of 2.5mm [1].

The frequency of the data is characterized with the peak of the Fourier spectrum. The water depth has significant peaks at 12, 6 and 4 months which are considered corresponding to the yearly reservoir operation and seasonal precipitation fluctuation. The temperature spectrum in the cavern shows the peak at 12 months, corresponding to the yearly temperature cycle. The frequencies of both convergences have significant peaks at 12, 6 and 4 months. This figure implies that the cavern convergence could behave under the influence of the water depth and the temperature in the cavern.

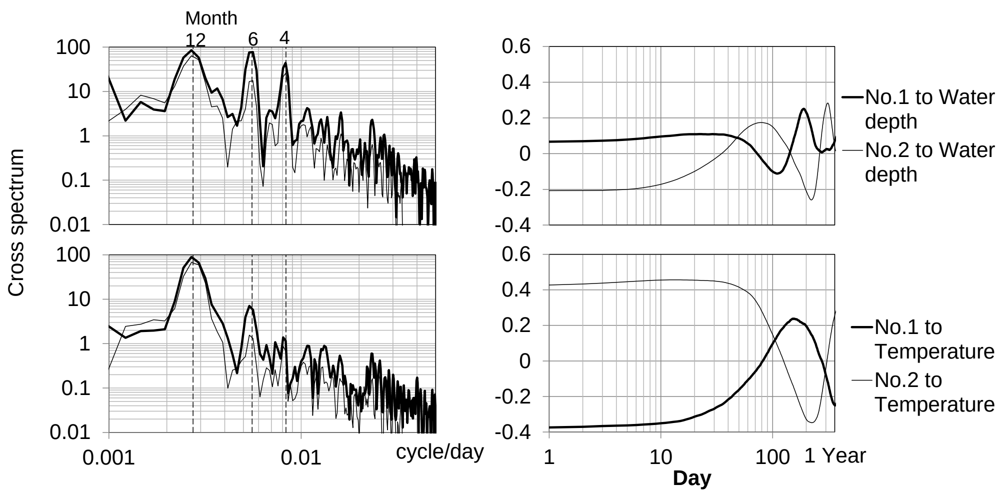


(a) Convergence and related records



(b) Frequency characteristics

Fig. 5
Convergence records of the cavern



(a) Cross spectrum

(b) Cross correlation

Fig. 6
Correlation among convergence, water depth and temperature

The relations among them are examined deeply with cross spectra and cross correlation coefficients (referred to as CCCs) as shown in Fig. 6, the water depth in the above and the temperature in the below. The cross spectra show the similar peaks described above. The convergences of the cavern are affected strongly by the water depth and the temperature in the cavern. The CCCs within one year lag shows low values to the water depth and the temperature. It is considered that the cavern behaves promptly corresponding to the fluctuation of the water depth and the temperature. This paper focuses the relations between the convergences and their circumstances of the reservoir water depth and the ambient temperature of the cavern numerically in the following sections.

4. STUDY OF THE CAVERN BEHAVIOR

4.1. EXAMINATION OF CAVERN BEHAVIOR WITH THE SIMPLIFIED CONVERGENCE

The cavern convergences are processed by eliminating the long term trend and higher fluctuation than ones of the water depth and the temperature. The filtering techniques are applied in the processing using Trifunac method and low-pass-filter of 0.033 cycle/day (ie, once in a month). The processed results are shown in Fig. 7 for the convergences, the water depth and the temperature. The convergences fluctuated in the amplitude of 0.3 mm approximately. One of No.1 section began the wider fluctuation corresponding to the peak of the temperature at most in 0.8 mm from 2014.

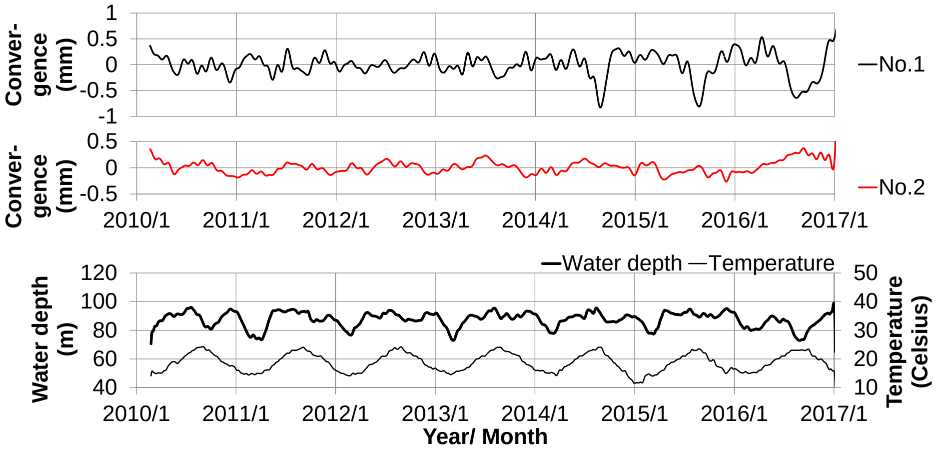
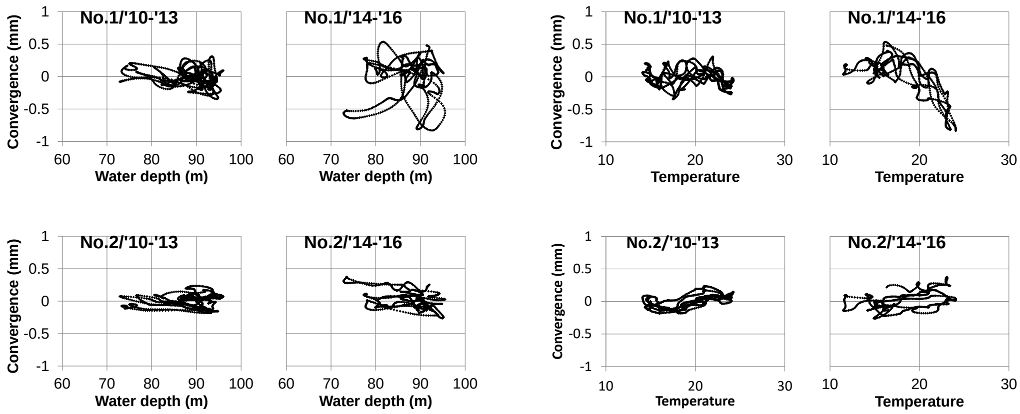


Fig. 7
Processed convergence records

The simple correlations between the convergences and the water depth or the temperature are examined in the durations of (1) 2010 to 2013 and (2) 2014 to 2016 as shown in Fig. 8. The convergence of No. 2 section shows consistent behavior to the water depth and the temperature in both durations. One of No. 1 section shows relatively complicated manner and has not been consistent in a whole duration. Due to the location of the monitored section of No.1, the three-dimensional behavior may predominate. The further study is necessary to explore the convergence behavior at No. 1 section.



(a) Simple correlation between convergence and water depth

(b) Simple correlation between convergence and temperature

Left law: 2010 to 2013（4 years）,Right law:2014 to 2016（3years）

Fig. 8
Simple correlation among convergence, water depth and temperature

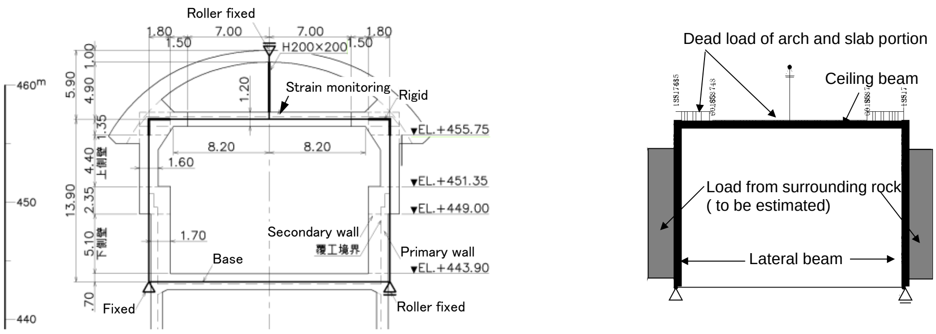
4.2. REGRESSION OF CONVERGENCE

Regression formula is examined for the convergence of the cavern in terms of the water depth and the temperature change in the cavern. A simple physical model of the cavern is introduced as shown in Fig. 9 referred to [1]. The load due to the water depth acts mostly laterally on the model. Considering the physical behavior of the model due to both loads, it will be deformed linearly to the water depth and the temperature changes. The regression formula of Eq. [1] is assumed.

$$u = A + B(p_0 - p) + C(t_0 - t) \qquad [1]$$

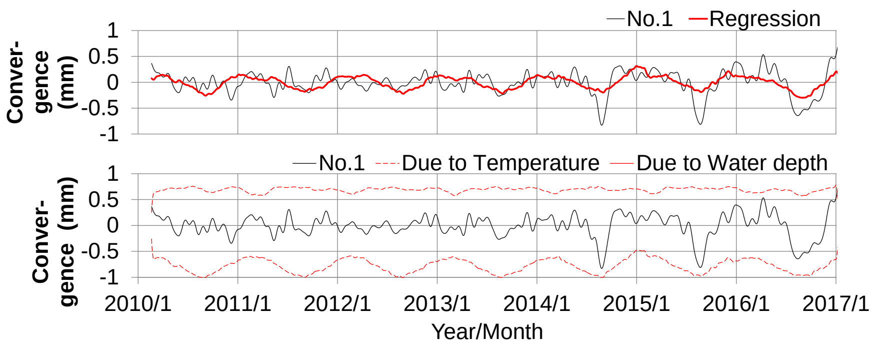
Where, u: convergence, p: water depth， p_0: reference water depth， t: temperature, t_0: reference temperature, A,B,C：constant

The histories of the water depth and the temperature, p and t are examined by ignoring p_0 and t_0. The constants of A, B, C are estimated by multiple correlation study for the processed data as shown in Fig. 7. The results are illustrated in Fig. 10 and Table 1. The multiple correlation coefficients are 0.54 and 0.59 for the convergence of No.1 and No.2 sections. These indicate a certain degree of the correlation of the convergence to the water depth and the temperature in the cavern. The standard partial regression coefficient indicates the degree of the correlation among the parameters. The convergence of No.1 section behaves inversely by almost the temperature change. The change of the water depth and the temperature comparably induce the convergence of No. 2 section in an inverse and a proportional manner, respectively. These manners are consistent to the characteristics shown in Fig. 8. The estimated convergences for both sections by Eq. [1] provide reproducible results as a whole, although the wider fluctuation of the No. 1 section since 2014 is not followed. The fluctuations of the convergences are the amplitude of 0.5 mm and 0.2 mm approximately for the yearly changes of the water depth and the temperature, respectively.

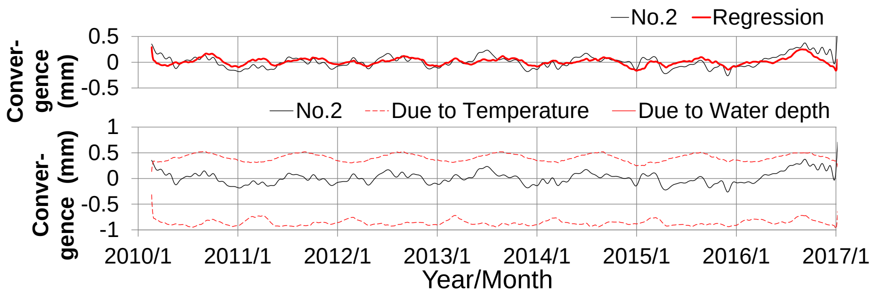


(a) Image of the model (b) Frame model

Fig. 9
Representation of the cavern[1]



(a) Convergence of No.1 section



(a) Convergence of No.2 section

Fig. 10
Regression of convergence
Table 1

Regression formula for the cavern convergence

Parameters		For No.1 section	For No. 2 section
Constant	A	0.0862	0.4709
	B	-0.0416	0.0216
	C	0.00787	-0.00986
Cross correlation coefficient		0.54	0.59
Standard partial regression coefficient	B'	-0.590	0.586
	C'	0.195	-0.469

4.3. CONSIDERATIONS

The safety assessment of the cavern has been conducted by the following manner [1], [2]. The current loading condition was assumed by the in-situ stress monitoring of the ceiling beam shown in Fig. 9(a). The convergence of 2.5 mm of the cavern was estimated by incorporating the risk scenario of the loss of the support effect due to the entire deterioration of supports. As the further risk, higher loading which could cause the damage in the main concrete structures was incorporated for the terminal condition of the cavern. These convergences of 2.5 mm and 6 mm were set as the maintenance criteria of the convergence.

The current convergences are less than the criteria and correlate to the water depth and the temperature with repeatability. The fluctuation amplitudes are smaller enough than the criteria. However, the cumulative convergence is clear in the No. 2 section and larger amplitude has been found in the No. 1 section since 2014. The continuous monitoring of the convergence has been essential from the view point of the soundness assessment of the cavern, taking into account the relationship among the convergence, the water depth and the temperature such as Eq.[1]. When the abnormal behavior would be found in the future, the re-evaluation of the cavern behavior will be indispensable.

5. CONCLUSION

The convergence monitoring has been conducted in the cavern of the hydropower plant since 2010 and these data are examined for the soundness assessment of the cavern. The conclusions are listed as follows.

(1) The convergence monitoring using a DLRF provide the useful convergence data with the high precision of 0.1 mm for the soundness assessment of the cavern without any troubles and missing observation in 8 years so far.

(2) The convergence at the representative two sections behaves corresponding to the yearly and/or the seasonal fluctuations of the reservoir water depth and the ambient temperature in the cavern. One of the center section at No. 2 machine develop the cumulative convergence, while one of another section near the end of the cavern shows less cumulative convergence and wider amplitude especially since 2014.

(3) These are less than the unusual convergence which is designated as the maintenance criteria under the assumption of the entire loss of the support effect as the risk scenario. The convergence behavior is stably reproducible to be consistent with the water depth and the temperature fluctuations. No concerns are found in the current situation of the cavern so far.

(4) The DLRF has been renewed in beginning of 2017. It caused certain discontinuities for the convergence monitoring. The cumulative deformation at No. 2 section and the wider amplitude at No. 1 section will be clarified using the data accumulated in the future.

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SUMMARY

A few damaged pre-stressed anchors were identified in the 40-year aged underground powerhouse, while no other deterioration in the cavern was found. The monitoring of the cavern convergence has been conducted to clarify its long-term performance using a newly developed precise range finder since then. The convergences of two sections during seven years are examined. These have behaved stably reproducible and been consistent with the yearly and/or the seasonal fluctuations of the reservoir water depth and the ambient temperature in the cavern. These are less than the unusual convergence which is designated under the assumption of the entire loss of the support effect as the risk scenario. No concerns are found in the current situation of the cavern so far.