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A study on the dynamic and multi-parameter responses of Yanbaru Underground Powerhouse

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ABSTRACT: The Yanbaru Pumped Storage Power Station is the unique hydro-electric power station utilizing seawater, located in Okinawa Island, Japan. The construction of underground house was completed in 1999 and it is located at a depth of about 132 m below the ground surface. This underground powerhouse provides a unique chance to monitor its dynamic and multi-parameter responses during earthquakes and long-term period. The authors installed three accelerometers in the underground powerhouse and one accelerometer at the ground surface to observe its acceleration response during earthquakes. In addition, some displacement gap sensors, AE sensors at the adjacent connection tunnel, rock temperature and environmental parameters such as temperature, humidity and CO2 sensors in the powerhouse and ground surface were installed to monitor its multi-parameter responses. In this study, the authors describe this instrumentation, some numerical analyses and the results obtained so far.

1 INTRODUCTION

The Yanbaru Seawater Pumped Storage Power Station is the first experimental hydro-electric power station utilizing seawater, located in Okinawa Island, Japan (Fig. 1). The construction was completed in 1999. The underground powerhouse is located at a depth of about 132 m below the ground surface (Fig. 2).

This underground powerhouse provides a unique chance to monitor its dynamic and multi-parameter responses during earthquakes and long-term period. The authors initiated a collaborative research since July 2017. Four accelerometers were installed in the underground powerhouse to observed its acceleration response during earthquakes. Specifically, one accelerometer at the bottom level, two accelerometers at the mid-level and one accelerometer at the ground surface at an elevation of 132 m were installed. Furthermore, micro-tremor measurements were carried out in the powerhouse, access tunnel and the ground surface.

Some displacement gap sensors, AE sensors at the adjacent connection tunnel and environmental parameters such as temperature, humidity and CO2 sensors in the powerhouse and ground surface were installed to monitor its multi-parameter responses. Recently, some temperature sensors installed to observe the temperature of rock mass in relation to the temperature variation in the powerhouse.

Besides this monitoring program, 2D and 3D finite element dynamic and Eigen-value analyses have been performed to evaluate the dynamic response of the powerhouse as well as its close vicinity and vibration amplification in the powerhouse as well as at the ground surface. Furthermore, some rockanchors and rockbolts installed in surrounding ground in the powerhouse and the adjacent tunnels were selected and their responses to shock waves were measured with the purpose of evaluating their

Figure 1. An aerial view of the Yanbaru pumped-storage power station.

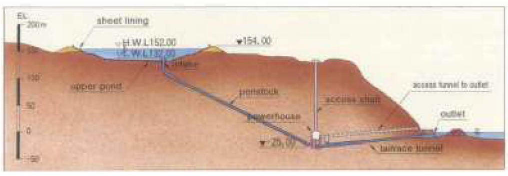

Figure 2. A cross section of the Yanbaru pumped-storage power station.

soundness since the beginning of the construction. The authors would explain the details of this unique instrumentation and the outcomes obtained from the monitoring program and numerical analyses and discuss their implementations.

2 DESCRIPTION OF POWERHOUSE

2.1 *Geological characteristics*

Powerhouse is located within the Kunikami zone of Nago Metamorphic rocks and it is regarded as the southern extension of Shimanto zone (Sato et al. 1994). Rocks are subjected to pressure metamorphism rocks and the overall schistosity plane dips at angle of 40-50 degrees to SW. However, the rocks contain numerous micro-folds (Fig. 3) and thrust-type faults of different scale. Fig. 4 shows cores of a borehole in the powerhouse. The boring was done about 30 years ago and the disintegration of cores along the schistosity (foliation) planes are observed. In the cores, some fracture zones are also noticed perpendicular to the schistosity plane.

2.2 *Rockmass characteristics*

The observation of the outcrops, cores of a borehole indicated that the rock mass has more than two discontinuity sets. The rock mass according DENKEN classification system is generally classified as CH with CM type zones, occasionally. The rock mass was classified using the new rock classification system called "Rock Mass Quality Rating - RMQR). Table 1 gives some rating of outcrops.

Figure 3. Views of rock mass conditions outside of the powerhouse.

Figure 4. View of cores of a borehole drilled about 30 years ago.

2.3 *Geometry and characteristics of powerhouse*

The crown of the powerhouse at 0 m elevation and it is 31.8m high, 16.4 m wide and 40.4 m long (Fig. 5). There is an access shaft next to the powerhouse for materials transport and accessible through an elevator and a stair from the ground surface. The cavern was supported through the use of rockbolts, rock anchors and 300 mm thick shotcrete with a wire mesh.

3 INSTRUMENTATION AND INSTALLATION

3.1 *Strong motion instrumentation*

The first author has developed a portable accelerometer, which can be used under 4 different modes. For strong motion observations during earthquakes, every accelerometer should have a triggering level to start and stop recording for a given time interval, sampling rate and store in a digital format. The minimum sampling rate is 1Hz. The device is named as QV3-OAM-XXX and it has the ability with a storage capacity of 2 GB. The power of the accelerometer can be an internal battery, external

Table 1. RMQR rating of outcrops.

Parameter	Description	Natural	Description	Disturbed
DD	Fresh	15	slight-weathering	11
DSN	1-3	12-16	DSN (3sets+)	4-8
DS	0.3-1.2m	8-12	DS	1-4
DC	rough	15-22	Rough	15-22
GWSC	Wet	5	drip	3
GWAC	Highly-absorptive	5-6	H. Absorp-tive	4-5
RMQR		60-76	RMQR	38-53

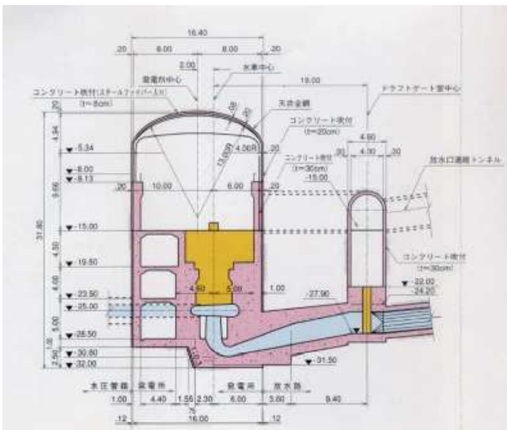

Figure 5. A cross-section of the powerhouse.

battery, solar energy or ordinary 100-240 V electricity. In case solar energy or ordinary electricity, the power is stored into an external battery through an adapter from a power supply such as solar panels or electricity. The system adopted at the powerhouse is designed to utilize the ordinary electricity (100V) or two external batteries. Currently, the system utilize electricity available in the powerhouse.

We installed four accelerometers. Three accelerometers installed in the powerhouse as illustrated in Fig. 6. One accelerometer is at the Underground 4F, which is at the bottom of the powerhouse, two accelerometers at Underground 1F, which is the mid-level of the powerhouse. One of the accelerometer is fixed to the sidewall at the penstock side and the other accelerometer is fixed to the middle of the end-wall of the cavern. The fourth accelerometer is installed at the surface. Fig. 7 shows some views of the installed accelerometers. The main purposes of the installation is to observe the seismic response of the cavern during earthquakes and to evaluate the ground motion amplifications as pointed out by previous pioneering researchers (Nasu 1931; Komada and Hayashi, 1980).

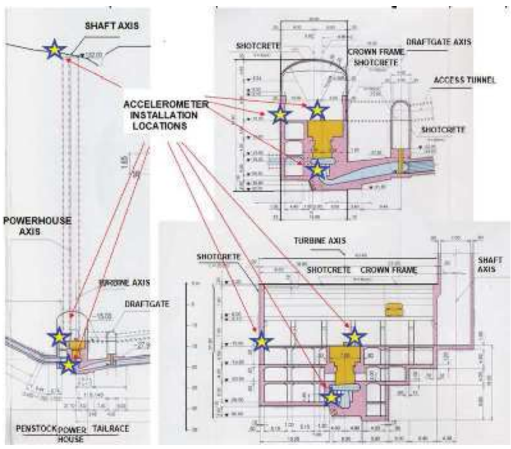

Figure 6. Installation locations of accelerometers.

Figure 7. Views of installed accelerometers.

3.2 *Multi-parameter Instrumentation*

The monitoring of underground caverns is essential for the long-term performance and stability of the underground powerhouses. Aydan et al. (2005) have initiated multi-parameter monitoring system to observe the behaviour of structures during excavations as well as during their service life. The multi-parameter system fundamentally covers all measurable quantities such as displacement, acoustic emissions, electric potential or electrical resistivity, water level changes, climatic parameters such as temperature, humidity and CO2, temperature changes of rock. In this study, a thoroughgoing open crack at the access tunnel next the powerhouse cavern was selected to monitor its movement (displacement), acoustic emissions (AE) together with climatic changes (temperature and humidity) (Fig. 8). The power supply is fundamentally battery operated.

The locations of climatic parameters such as temperature, humidity and air pressure (THP) are measured at the ground surface (132 m elevation). Two CO2 sensors are installed at the ground surface and Underground 1F. The monitoring of CO2 is to check the air quality as well as the condition for the carbonation environment for concrete. Recently, two temperature sensors are installed in a short borehole to monitor rock temperature and air temperature around its vicinity. This measurement is expected to yield some information of cyclic thermally induced deformations of the powerhouse.

3.3 *Micro-tremor measurement*

The vibration characteristics in the powerhouse and ground surface are essential to assess the seismic response and stability of underground as well as surface structures. Micro-tremor measurements using

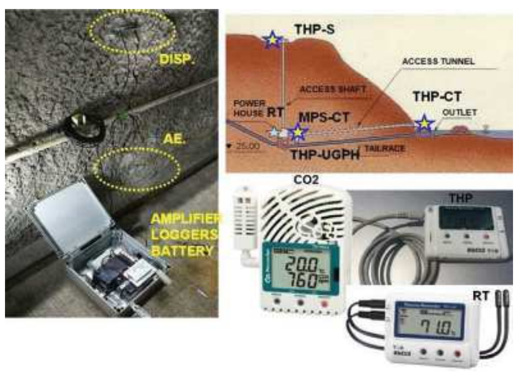

Figure 8. Views and locations of installed multi-parameter monitoring system.

SPC51A micro-tremor device produced by TOKYO-SOKUSHIN was utilized and vibration characteristics in the powerhouse (UG1F, UG4F, Access Tunnel and ground surface were evaluated (Fig. 9). At each location, at least, 3 records for 100 second periods were taken.

3.4 *Impact tests on rockanchors and rockbolts*

The non-destructive testing of support members such as rockanchors, rockbolts (Aydan 2017, 2018) are essential for the maintenance of underground and Surface rock engineering structures from time to time. With this in mind, rockanchors and rockbolts installed in the penstock side of the powerhouse and the access tunnel were selected for non-destructive testing. Three rockbolts in the access tunnel and two rockanchors were tested using a non-destructive testing device produced by IMV. The device is quite compact and a single person can apply the impact force and record the acceleration/velocity wave and its Fourier spectra. The sensor can be easily attached to the rockbolt/rockanchor head using a magnet. We essentially utilize one of three sensors with the consideration of the testing object. Particularly, the STD-S sensor produced by IMV is quite suitable for non-destructive testing of bar-type rockbolts and rock anchors.

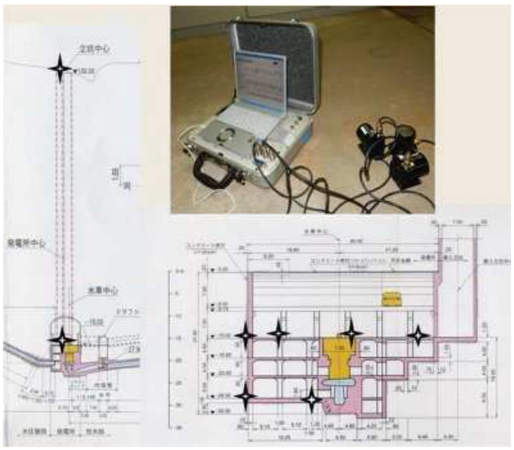

Figure 9. A view of micro-tremor measurement in the powerhouse.

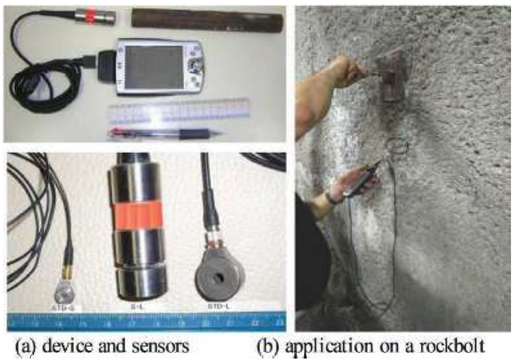

Figure 10. Non-destructive test device and its utilization on a rockbolt in the access tunnel.

4 NUMERICAL ANALYSES

The use of numerical analyses is essential for evaluating and understanding behaviour of underground structures for their dynamic and long-term performance. In this study, the fundamental modes of underground powerhouse with the consideration of the surface topography were analyzed using 3D MIDAS-FEA software. In addition, 2D response analyses of the powerhouse were carried out using FEM (Kashiwayanagi 2018). Material properties used in this study are given in Table 2. One of the main purposes of the 3D analyses was to see the effect of mountain configuration (Fig. 11). For that purpose, Eigen value analyses were carried out for the domain with and without underground opening and shaft (Figs. 12 & 13). Table 3 gives the natural frequencies obtained from the mode analysis of

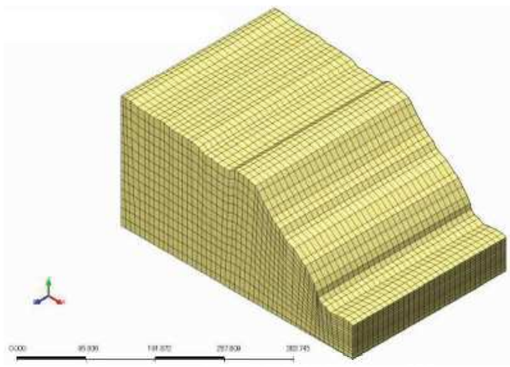

Figure 11. 3D Finite element Mesh

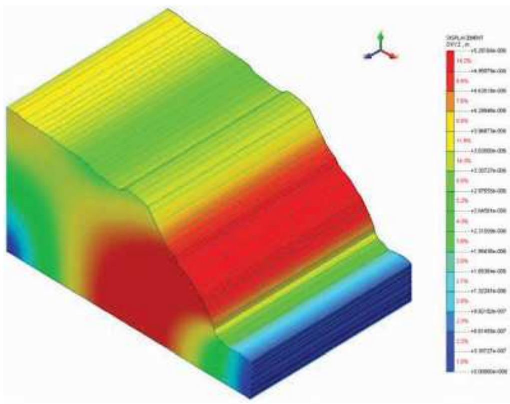

Figure 12. Mode 1 displacement response (no cavern).

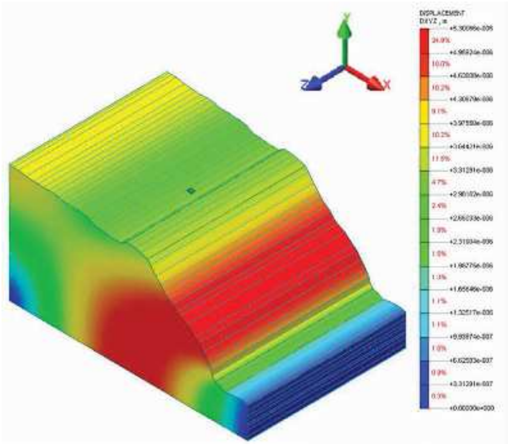

Figure 13. Mode 1 displacement response (with cavern).

Table 2. Material Properties

Material	UW(kN/m^3)	E(GPa)	Poisson Ratio
Rock mass	27.0	4.00	0.25
Concrete	23.5	11.042	0.20

Table 3. Eigen values for each mode

	Mode 1(s)	Mode 2(s)	Mode 3(s)
No Cavern	0.898	0.651	0.646
With Cavern	0.898	0.653	0.646

the numerical model. There is almost no difference for the dominant period due to the existence of the cavern.

5 MEASUREMENTS AND DISCUSSIONS

5.1 *Strong motion measurement*

The measurements have been continuing since 2017 July 26. All devices were set to the trigger value of 19 gals. Except some man-made vibrations, no accelerations recorded due to earthquakes. We recently reduced the trigger value of accelerometers to 4 gals, which is the lowest level of triggering for the accelerometers. The three devices recorded one event at 13:39 on 2018 March 23. Fig. 14 shows the acceleration records. Although the event was due to man-made activity, it was interesting to note that three devices were triggered.

5.2 *Micro-tremor Measurements*

Micro-tremor measurements were carried out at several locations as shown in Fig. 8. Fig. 15 compares the H/V spectra of micro-tremor measurements at different locations. The dominant frequency for the surface is about 0.976Hz, which implies that the natural period of the ground surface is about 1.025s.

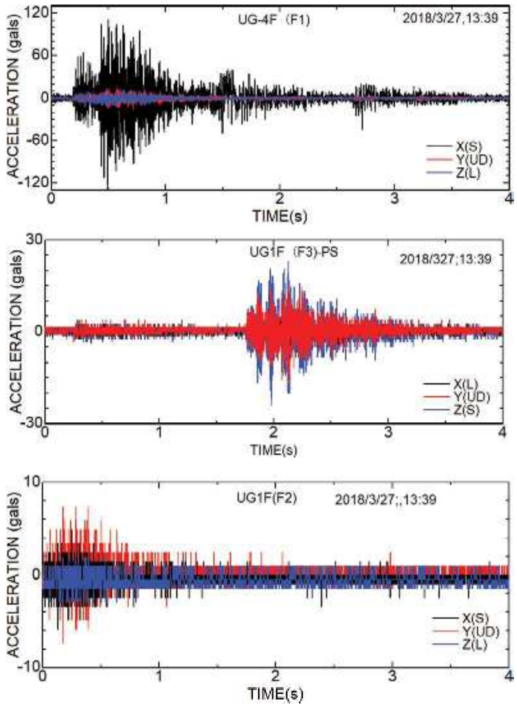

Figure 14. Acceleration records of three accelerometers.

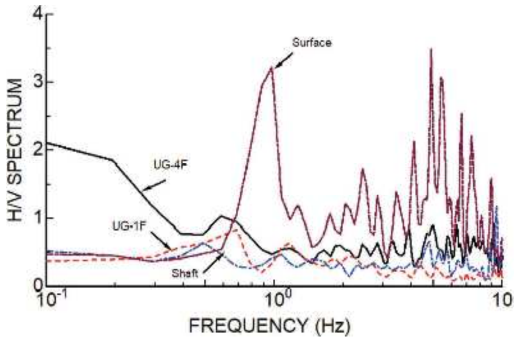

Figure 15. Comparison of Micro-tremor measurements

Although this value is slightly different from the eigen value analyses, it may be said that the computational results may estimate the vibration characteristics of the Yanbaru Sewater Pumped Storage Power Station.

5.3 *Multi-parameter Measurements*

In this subsection, the multi-parameter measurements, specifically, the responses of crack displacement, acoustic emissions and climatic response of the cavern, access tunnel and ground surface are presented. responses of crack displacement, AE, Temperature, Air Pressure, CO2 concentration, and rock temperature are shown in Figs 16 to 21.

As noted from Fig. 16. residual crack displacement occurs after one year, implying that some time-dependent deformation taking place. The AE response also confirms the time-dependency of the deformation behaviour of the crack. Figs. 18 & 19 show that temperature and air pressure fluctuates and their amplitude depends upon the location. Similarly, CO2 concentration and temperature response of rock mass (20cm from sidewall) and inner temperature of the powerhouse varies with time. Particularly the rock temperature implies some thermal stress variations as reported by Aydan et al. (2013).

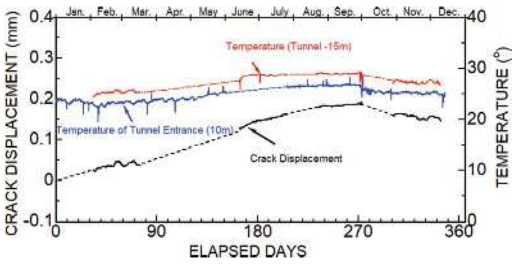

Figure 16. Displacement and temperature responses of the crack

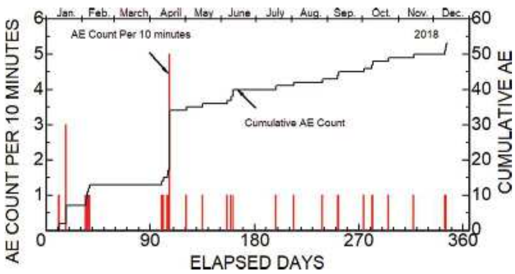

Figure 17. Acoustic emission response of the crack

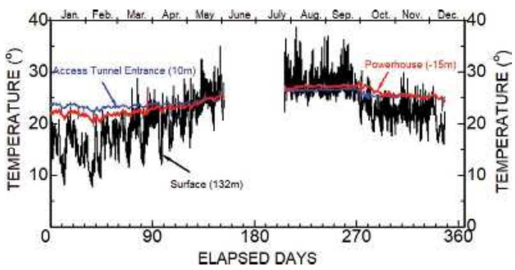

Figure 18. Temperature variations at various locations

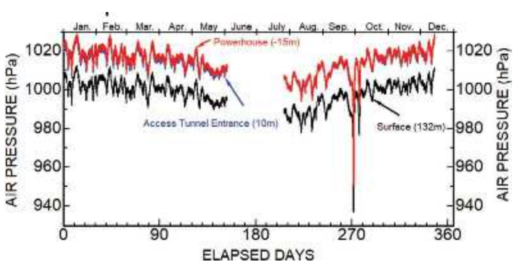

Figure 19. Air pressure variations at various locations

5.4 *Non-destructive tests on rockanchors and rockbolts*

The non-destructive tests on rockanchors and rockbolts are essential to evaluate the performance of support members and their maintenance. Three rockbolts in the access tunnel and two anchors at the penstock side of the powerhouse were selected for non-destructive testing and some non-destructive tests were carried out. Fig. 22 shows one example of acceleration response together with computed response using the procedure proposed by Aydan (2017, 2018). These non-destructive tests and computations have been continued.

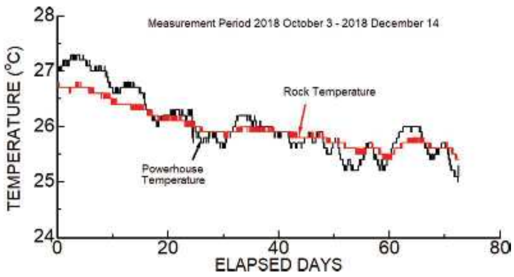

Figure 20. Temperature response of rock mass to powerhouse temperature.

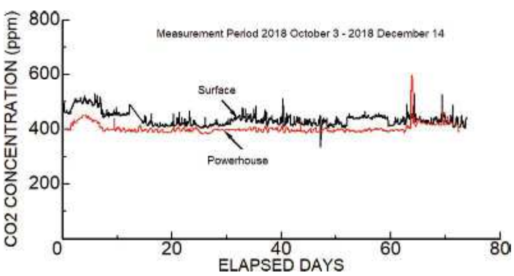

Figure 21. CO2 variations in the powerhouse and ground surface.

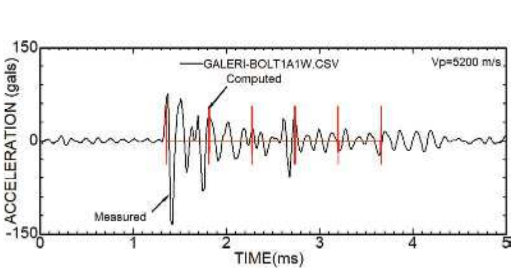

Figure 22. Temperature variations at various locations

6 CONCLUSIONS

The authors explained the strong motion instrumentation and multi-parameter monitoring system at the Yanbaru underground powerhouse. In this study, the authors described this instrumentation, some numerical analyses and the results of monitoring obtained so far. Altough the recorded and monitored results are not that so long, it still provides some insight views on the vibration and multi-parameter responses of the underground powerhouse. It is expected that the continuation of this observation and monitoring system would be quite valuable for the dynamic response of large underground structures and their long-term performances.

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