



Seismic stability analysis of a large underground cavern adjacent to slope - Case study in Taiwan

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Abstract

There are four cases of seismic stability analysis for large underground caverns collected firstly. Secondly, as a cases study of Zengwen Reservoir Sediment Sluicing Tunnel, the design change from a single large-span cavern to double caverns due to the conditions of adjacent to slope and shallow cover is explained. The design of seismic analysis for the caverns under design earthquake is illustrated. Finally, the seismic response of the caverns under earthquake in Mar. 20, 2018 is used in-situ monitoring and 3D numerical simulation to investigate. And evaluate the seismic stability of the caverns by in-situ inspection.

Keywords: underground cavern, seismic response, in-situ monitoring, 3D numerical simulation.

1 Introduction

Large underground caverns in Taiwan are mostly built for hydroelectric power needs, such as Zengwen, Minghu, Mingtan, Zhuolan, Guguan and Qingshan Hydroelectric Power Plants. When designing, sites with better environmental conditions are usually selected.

Due to limited hinterland and operational considerations, the construction and operation of the Zengwen Reservoir Sediment Sluicing Tunnel (ZRSST) project has faced many challenges, particularly when the tunnel's plunge pool and outlet section are adjacent to slope and the span of cavern is large. In addition, Taiwan is located on the boundary of two tectonic plates, which is an area with active orogenic movement, leading to frequent seismic activities. The Chi-Chi Earthquake on September 21, 1999 caused serious damage to the lining of 49 tunnels in Taiwan (Wang *et al.*, 2001), suggesting that the operation of underground caverns may face the test given by strong earthquakes.

This paper first collected the cases of seismic stability analysis for underground caverns, and then took the sediment sluicing tunnel of Zengwen Reservoir in southern Taiwan as an example to illustrate the considerations in designing the seismic force for the outlet of the tunnel with large underground cavern. Finally, in-situ monitoring and numerical simulation were adopted to investigate the response of the cavern under earthquake, assessing the seismic stability of the large underground cavern.

2 Cases of seismic stability analysis for domestic and foreign underground structures

The cases of seismic stability analysis collected for large underground caverns are summarized in Table 1. It can be seen from Table 1 that many countries have started paying attention to the issue of seismic stability for underground structures, and began to use numerical analysis to carry out related investigation and design. The numerical analysis methods include: Finite Element Method, Finite Difference Method, and Spectral Element Method, etc.; and their dynamic input method is mostly based on the actual acceleration duration of a certain earthquake.

Table 1: Case study of seismic analysis of large underground caverns

Country	Italy	Iran	Italy	China
Name	Giaglione Cavern	Masjed Soleiman Dam Cavern	Venaus Powerhouse Cavern	Dagangshan Hydropower Station Cavern
Overburden	—	320 m	250 m	530 m
Geology	Calc schist, RMR > 65	Siltstone	UCS = 72.3 MPa	Granite
Dimension	Length = 50 m, Span = 22 m, Height = 46 m	Length = 112 m, Span = 30 m, Height = 50 m	Length = 50 m, Span = 23 m ; Height = 49 m	Length = 226 m, Span = 30 m ; Height = 74 m
Numerical analysis method	Spectral Element Method	—	Finite Element Method	Fast Lagrangian Analysis
Dynamic analysis software	GeoELSE	—	Midas/GTS	FLAC 3D
Schematic diagram	Fig. 1 (a)	Fig. 1 (b)	Fig. 1 (c)	Fig. 1 (d)
References	Barla, 2007	Balideh <i>et al.</i> , 2009	Lu <i>et al.</i> , 2012	Zhang <i>et al.</i> , 2018

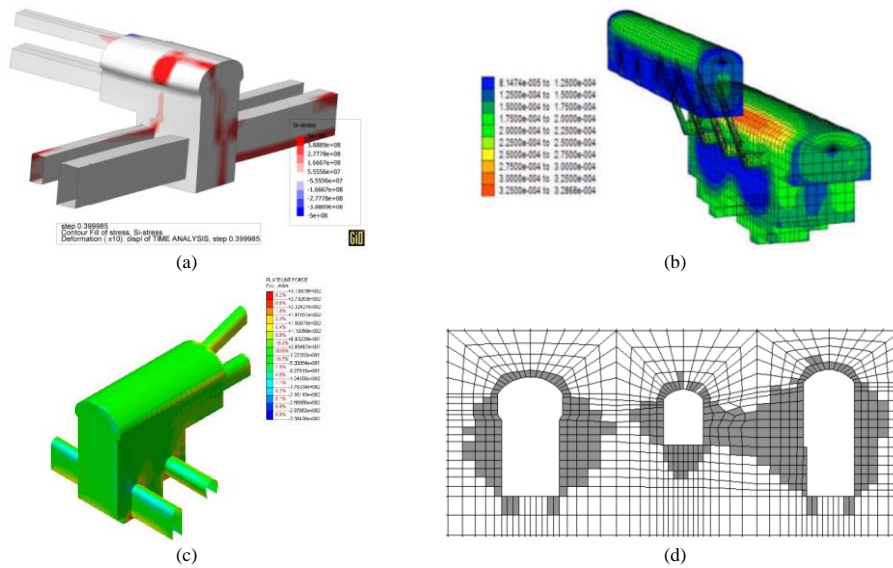


Figure 1: Case study of seismic analysis of large underground caverns. (a) Giaglione Cavern (Barla, 2007); (b) Masjed Soleiman Dam Cavern (Balideh *et al.*, 2009); (c) Venaus Powerhouse Cavern (Lu *et al.*, 2012); (d) Dagangshan Hydropower Station Cavern (Zhang *et al.*, 2018)

3 The outlet section design of the ZRSST project

3.1 The design concept of outlet section

Due to the space of Zengwen river for the outlet section of ZRSST (Figure 2) is limited, the plunge pool with a length of about 100.5 m in the outlet section must be constructed inside the mountain. However, since the clearance span requirement for the plunge pool was 20 m, and the structure was adjacent to a slope and it is difficult in achieving the arching effect after excavation; therefore, the original design was to reduce the span of the plunge pool by double arch with a 10-m span for each arch. The shape is look like a seagull, and the middle needs a reinforced concrete column with thickness of 4 m. The shape also looks like a glasses. The construction sequence is first carried out the excavation and supporting for the 4-m thick middle column, and then for the two sides. In addition, due to the position of the outlet forming an oblique configuration with the slope nearby, in order to reduce the bias effect on the stability of the cavern, the techniques of piles and side wall combining with backfill covering were used in the basic design, first stabilizing the bottom of slope and at the same time reducing the bias effect before excavation the cavern (UGI, 2012).

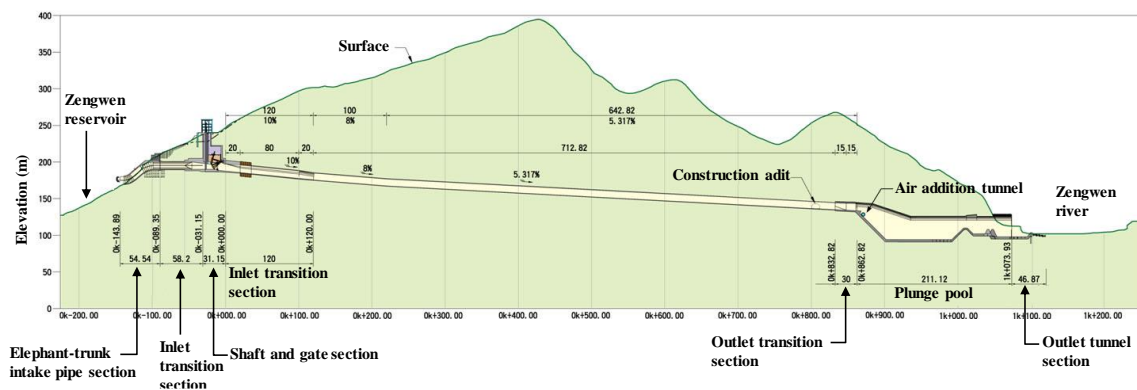


Figure 2: The longitudinal diagram of ZRSST project

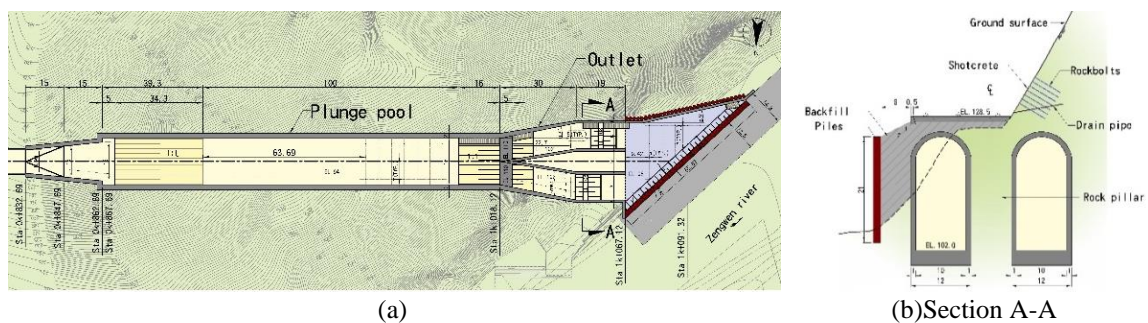


Figure 3: The schematic diagram of the outlet section of the ZRSST

To be cautious, the basic design consulting company invited a senior consultant from an engineering consulting company in Switzerland to review the basic design. After carrying out in-situ investigation, core analysis and discussion, the foreign consultant

recommended dividing the outlet section from one to two, and increasing the distance between the two caverns, as shown in Figure 3 (a). The consultant also recommended modifying the size of the plunge pool in accordance with the results of the hydraulic modeling test. The design of the outlet section on the other hand followed the spirit of the original basic design, adopting the techniques of piles and side wall combining with light concrete backfill to first stabilize the bottom of slope and at the same time reducing the bias effect before excavation the cavern. Details are shown in Figure 3 (b) (UGI, 2012).

3.2 Seismic analysis and design

3.2.1 Seismic design

The seismic design of the outlet section of the ZRSST is based the rules and regulations of the Southern Region Water Resources Office (2012). After performing the earthquake hazard assessment, three seismic scenarios were defined, namely the Operating Basis Earthquake (OBE), Design Basis Earthquake (DBE) and Maximum Credible Earthquake (MCE). Table 2 shows the peak ground acceleration and coefficient values for the seismic design of the ZRSST.

Table 2: Peak ground acceleration and coefficient of the design earthquake

Design earthquake		OBE	DBE	MCE
Horizontal direction	Acceleration (g)	0.49	0.53	0.62
	Seismic coefficient	0.159	0.168	0.192
Vertical direction	Acceleration (g)	0.33	0.35	0.41
	Seismic coefficient	0.106	0.112	0.128

3.2.2 Lining design

The lining design of the outlet section of the ZRSST was analyzed according to the load combination of the concrete structure design specifications. The seismic force is considered based on the corresponding response spectrum as shown in Table 2. According to the analysis of the specified load combination, force distribution of the underground tunnel lining structure was obtained. The results were used to determine the concrete lining thickness and the number of steel bars required.

4 Cavern seismic analysis and inspection

4.1 Cavern seismic response monitoring

4.1.1 Installation of 3D accelerometer

Figure 4 shows the layout of three-dimensional (3D) accelerometer for the outlet section of the ZRSST. There were five 3D MEMS (Microelectromechanical System) accelerometers installed in the outlet section of the ZRSST, which were located on the north side of the lining trail. The measurement range of the accelerometer is ± 2 g and the frequency range is 0~500 Hz, with sampling frequency set at 100 Hz.

4.1.2 Dapu Earthquake (March 20, 2018)

The Dapu Earthquake occurred on March 20, 2018. The epicenter is located in Dapu Township of Chiayi County, Taiwan (23.31°N, 120.54°E), with a Richter magnitude scale of 5.3, and a maximum seismic intensity of V (80~250 gal) in Dapu Township.

In this earthquake, a total of four 3D accelerometers were used to record the acceleration response, while accelerometer D had no record due to poor signal. Figure 6 shows the acceleration record of accelerometer C in the north-south and east-west direction. The maximum acceleration values for all accelerometers are summarized in Table 3. Table 3 shows the maximum acceleration values of each accelerometer. The directions of maximum acceleration for accelerometers A, B and C are all in the north-south direction; the east-west direction has less acceleration; and the vertical direction has the smallest acceleration. In contrast, the direction of maximum acceleration for accelerometer E is in the east-west direction; the north-south direction has less acceleration; and the vertical direction has the smallest acceleration. From the acceleration value of each accelerometer, it can be seen that the larger the span of cavern, the greater the acceleration.

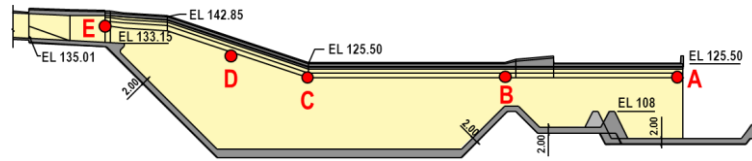


Figure 4: The setup of five 3D accelerometer in the outlet section of the ZRSST

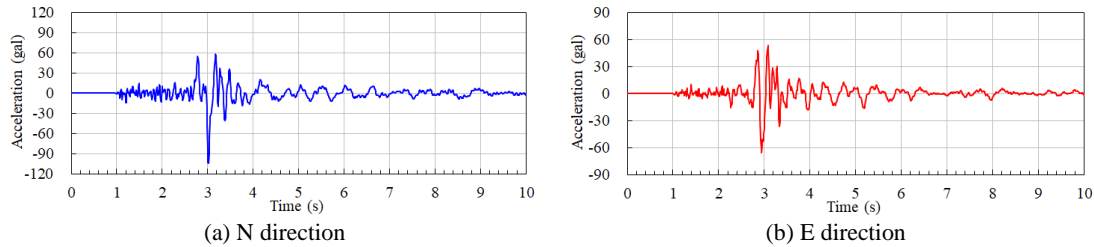


Figure 6: Acceleration record of survey station C in N and E direction

Table 3: Maximum acceleration of each survey station A to D

NO.	Direction		
	N (gal)	E (gal)	U (gal)
A	88.05	72.50	56.84
B	97.86	66.10	64.91
C	104.32	65.68	58.84
E	65.92	76.44	48.58

4.2 3D Numerical simulation

4.2.1 Model information

In this paper, the 3D numerical simulation based on the MIDAS GTS NX program of finite element method was used to carry out non-linear dynamic time history analysis.

Figure 7 shows the 3D numerical model and its boundary conditions. Table 4 shows the mechanical parameters of the numerical model.

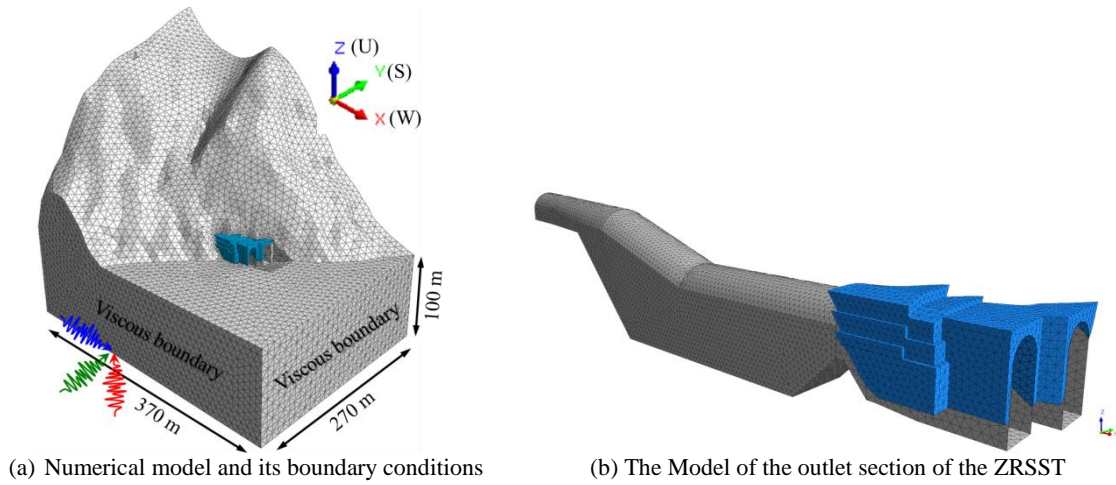


Figure 7: The 3D numerical model and its boundary conditions

Table 4: Mechanical parameters of numerical model

	Elastic modulus (GPa)	Poisson ratio	Unit weight (kN/m ³)	Shear wave velocity (km/s)	Compression wave velocity (km/s)
Rock mass	0.759	0.18	23.93	0.363	0.581
Concrete lining	29.127	0.20	23.54	-	-

4.2.2 Input motion

Figure 8 shows the response recorded by the free-field observation station about 1 km northeast of the ZRSST during the Dapu earthquake. Considering that the seismic wave transmitting from the bedrock to the surface will be amplified, the SHAKE program was used to deconvolute the ground acceleration in the north-south and east-west direction to a depth of 100 m. The resulting acceleration time history was inputted into the model.

4.2.3 Analysis of results

Figure 9(a) shows the maximum acceleration distribution diagram of the lining after carrying out the seismic analysis of the outlet section of the ZRSST. It is obvious that the maximum acceleration value of the lining near the slope is large while that near the tunnel is small. Compared with Table 3, the analysis results and the results from in-situ monitoring results are consistent. However, the acceleration response of the analysis is not correlated to the span of the cavern.

Figure 9(b) shows the seismically induced axial force and bending moment interaction diagram of the lining of the outlet section of the ZRSST. The red line represents the allowable stress line (or envelope curve) for the lining, while the points represent the seismically induced axial force and bending moment increment. The seismically induced axial force and bending moment increment of the lining under earthquake is

much smaller than the envelope curve, suggesting that the impact of the earthquake on the lining of the outlet section of the ZRSST should be minimal.

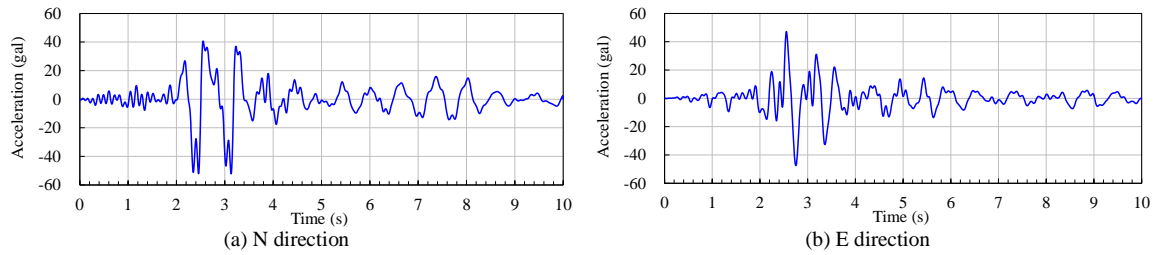


Figure 8: Acceleration time history of input motion

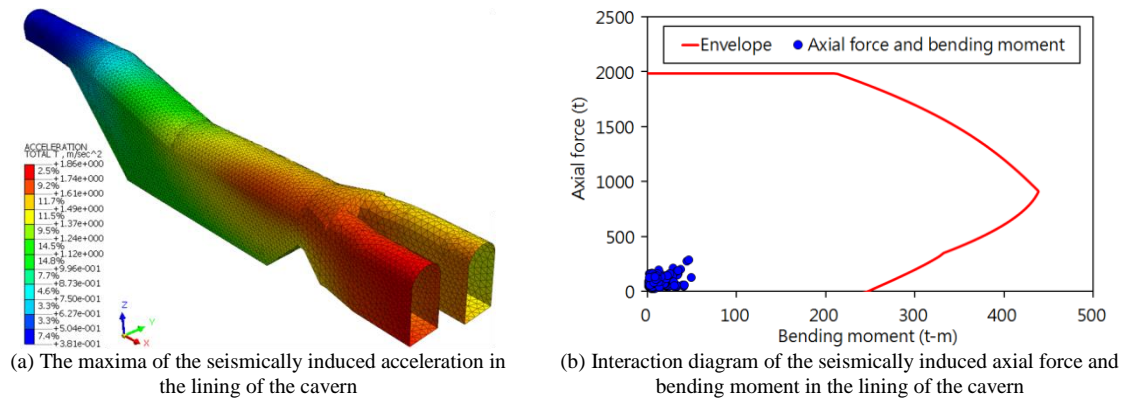


Figure 9: Results of numerical simulation

4.3 In-situ inspection of the cavern

In this study, inspection for the entire tunnel was conducted from 2 days after the earthquake. Figure 11 shows the condition of the outlet section of the ZRSST. By comparing the images of the lining of the cavern before and after the earthquake, it is apparent that there is no abnormality in the lining of the cavern after the earthquake, suggesting that the cavern is in good condition and is safe. The results show that the earthquake has little impact on the outlet section of the ZRSST.

5 Conclusions

This paper first collected the cases of seismic analysis for underground caverns, and then took the sediment sluicing tunnel of Zengwen Reservoir as an example to illustrate the reduced bias effect by changing the outlet section of the tunnel from a single large-span cavern to double caverns and adopting the thick foundation covering. In addition, the considerations in designing the seismic force for the water outlet of the tunnel were illustrated. Finally, in-situ monitoring and numerical simulation were adopted to investigate the response of the cavern under earthquake, assessing the seismic stability of the structure. This case study can be a reference for similar projects in the future.

The large underground cavern is a highly statically indeterminate system. The surrounding environment can have a huge impact on the stability of the structure.

Although several domestic and international cases of seismic design for underground caverns have been investigated, the behavior of underground cavern under earthquake is not fully understood. Therefore, the seismic response of underground caverns needs to be studied in order to facilitate the seismic design of underground caverns in the future.

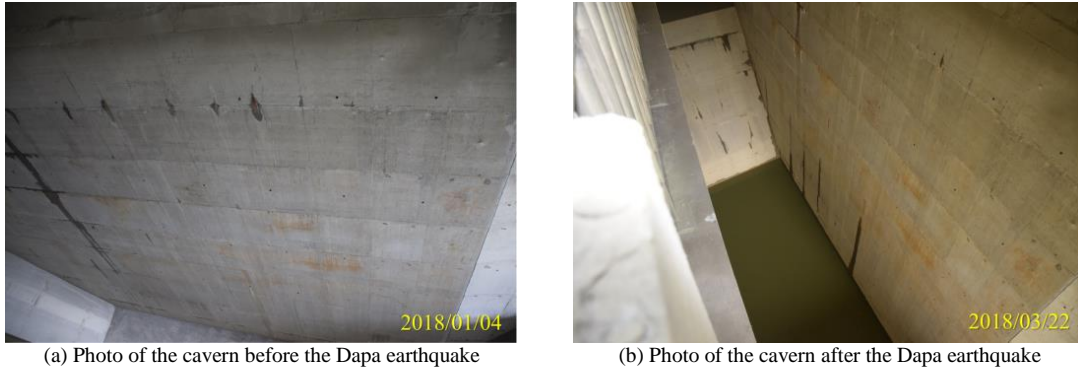


Figure 11: Appearance of the lining of the cavern

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