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Design, construction and mechanical behavior of relics of complete large Longyou rock caverns carved in argillaceous siltstone ground

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Abstract: This paper presents a comprehensive summary of data, analyses and findings from the investigations over the past twelve years about the relics of large Longyou rock caverns carved about 2 000 years ago at shallow depths in argillaceous siltstone. The paper presents the typical features associated with the rock caverns. They include structures, large spans, portals, extreme shallow-buried depths, imprints, drainages, inclined ceiling, inclined sidewalls, slender rock pillars, rock staircases, site and strata selections, caving lighting, carving method, and underground construction surveying. They are used to reconstruct and highlight the design and construction methods adopted by the ancients. The paper further demonstrates that the relics of the complete large rock caverns are a consequence of coincidental combinations of ancient human effort and natural factors. The full occupation of water with weak acidity in the large rock caverns with the soft surrounding rocks of weak alkalinity is found to be the main factor ensuring and preserving the caverns to have been stable and integral over 2 000 years. However, the five unwatered complete rock cavern relics have been experiencing various deteriorations and small failures including cracks, seepage, small rock falls and delaminating ceiling rocks. Although these deteriorations have been repaired and stabilized effectively, the paper demonstrates that an entire roof collapse failure is highly possible in the near future to each of the five unwatered rock cavern relics. The findings presented in this paper are also invaluable both to the long-term protection and preservation of the large rock cavern relics of national and international interests and importance, and to extend and enrich our experience and knowledge on the long-term stability and integrity of man-made underground rock cavern engineering projects.
Key words: rock cavern; rock mechanics; rock engineering; long-term stability and integrity; argillaceous siltstone; environment

1 Introduction

The relics of Longyou rock caverns are a group of large rock caverns at shallow depths purely carved in argillaceous siltstone of Cretaceous age by ancient people about 2 000 years ago. They are located in a small hill site on the northern bank of Qujiang River in Longyou County in the middle of Quzhou—Jinhua Basin, Zhejiang Province, East China (Figs.1 and 2).

1.1 Unearthing the relics

The relics of the complete rock caverns were unearthed by local farmers in June 1992. In their village on a small hill, there were many small water pools. An example of the pools is shown in Fig.3. The farmers used the water in the pools for their daily life.

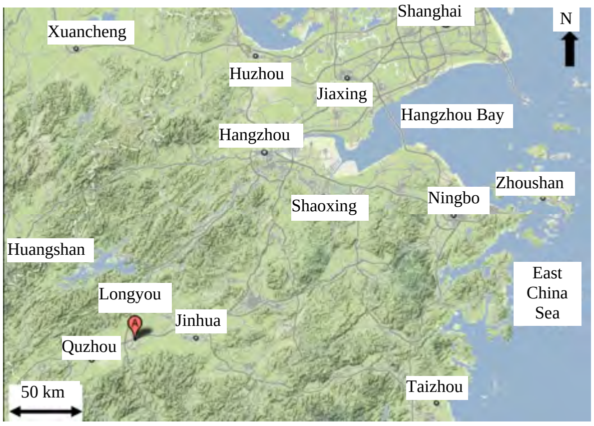

Fig.1 Location and topography of Longyou County in the middle of Quzhou—Jinhua Basin, Zhejiang Province, East China (drawn on topographical base of Google Map 2011).

They observed that some of the pools had fishes but the others not, which attracted their curiosity.

Eventually, on June 9, 1992, four farmers decided to investigate the pools. So, they used water pump to

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Fig.2 Longyou rock caverns in a small hill with uneven ground elevations of 47 to 60 m, and comprising argillaceous siltstone of Cretaceous age on northern bank of Qujiang River with elevation of 36 m near Longyou County (drawn on satellite image of Google Map 2011).

Fig.3 A small water pool of 12 m long and 2 to 5 m wide for vertical portal of the immersed rock cavern No.7 on the small hill.

pump the water out of one pool. After 17 days of continuous pumping, a large rock cavern was eventually unwatered and shown up in front of their eyes.

After cleaning up the mud sediments, they found that the cavern had a regular underground space, a rock staircase, several rock pillars and regular curved imprints on the rock surfaces of the pillars, near-vertical sidewalls and inclined rock roof (see Fig.4 for example). The regular underground space, the rock staircase and the rock imprints told them that it was manually carved in the ground rock.

So, they were excited and continued to pump water out of other four adjacent pools. Again, four similar individual rock caverns were unwatered one by one.

Fig.4 Unwatered rock cavern No.2 with four rock pillars, one rock staircase, one vertical portal with sunlight and curved imprints on the rock surfaces of sidewalls, three pillars (P21, P22 and P23) and inclined roof in argillaceous siltstone of Cretaceous age.

They cleaned up the mud in the rock caverns and used the five caverns for tourism business. At present, about 600 000 tourists visit the cavern relics annually.

1.2 Authors' endeavors

The news of this discovery was slowly spread in China. The first author of this paper got to know this news and immediately went to the site in December 1998. He was amazed and excited at what he saw. The five unwatered cavern spans are between 18 and 34 m and heights between 10 and 20 m. Each cavern has its distinctive shape, unusual pillars and remarkably curved and shaking imprints with high regularity. How could a group of large ancient rock caverns be carved in and preserved just beneath this small hill that has uneven ground elevations between 47 and 60 m and a plane area of about 350 m × 280 m? He believed that the relics are natural wonders with numerous unknowns and questions. They are invaluable in culture, engineering and science.

Since then, he and his fellows have carried out many investigations on the rock caverns. Many of the research results and findings were published in Refs.[1–13] and a book [14] in Chinese although a few in English [15–18]. Therefore, this paper presents an updated executive and yet comprehensive summary on the essential data, analyses, findings and issues of the twelve years-long investigations.

2 Background

2.1 Underground spaces and essential issues of long-term stability and integrity

Human beings have constructed and used a large amount of underground spaces at different depths for various activities such as hydropower houses and oil and gas storages. At present, the sciences and technologies for construction and utilization of underground spaces have been thoroughly and rapidly developed. There are many publications and literatures documenting the state-of-art of modern rock mechanics for rock cavern engineering [19–21]. These documents cover many modern theories, methods and technologies.

When more and more and larger and larger rock caverns are constructed and utilized, human beings are facing one of the most challenging and difficult issues. This issue is the prediction and assurance on the long-term stability and integrity of underground projects for the coming hundreds or even thousands years. This issue is due to the fact that the surrounding rocks of underground projects always experience various loads, including in-situ tectonic stresses, gravitational force, groundwater pressures, and various chemical reactions and environmental changes. These natural loads cannot be completely controlled by human beings. They can cause deteriorations and physicochemical weathering in the surrounding rocks, which may cause malfunction or even failure of underground projects. Therefore, current design life for the serviceability of underground cavern projects is only 50 to 100 years, which is short for some important projects, including permanent storage of heat-emitting highly radioactive wastes [22–25] and hydrocarbon gas [26–28] in deep rock formations.

It is difficult to find the right answers in the many successful cases and research findings of modern rock mechanics and cavern engineering projects for the histories of modern rock mechanics and rock engineering are younger than 100 years. We have to find suitable and alternative cases to further advance our experience and knowledge of modern rock mechanics and rock engineering.

2.2 The alternative approach to the issues

One of the suitable and alternative approaches to attack the issues is to undertake the in-depth investigations on existing ancient man-made large underground rock caverns with the methodologies of modern rock mechanics and rock engineering. In ancient times (or specifically before commencement of the Industrial Revolution in the second half of the 18th century), people manually constructed underground rock caverns with simple equipments.

Such investigations can enlighten our thoughts, extend our experience and give us confidence. Each of such actual cases is in fact a long-term in-situ experiment with one to one scale (or actual size) on the behavior and performance of an underground rock cavern project. What we need to do are to describe these actual cases with the languages of modern rock engineering, to examine them with the theories of modern rock mechanics and then to discover new science or new natural laws from them. Consequently, we can find the right solutions to the prediction and assurance of the long-term stability and integrity of modern underground rock caverns for next hundreds or even thousands years.

However, it is not easy to find the actual cases of ancient man-made and large underground rock caverns due to at least four reasons: (1) the opportunity for large caverns to encounter adverse geological conditions is high; (2) the rock roof can experience great settlements and even collapse; (3) science and technology for building large rock caverns are limited in ancient times; and (4) there are difficulties in long-term preservation. It is of great interest and historical value to reveal and recognize the highlights from the actual relics. Such highlights can also be able to re-educate us and to make us further respect our ancestors (it is noted herewith that a large rock cavern is defined by its span over 20 m).

2.3 Known relics of large ancient rock caverns abroad

Results of our literature review indicate that among various underground caverns made by ancient people outside China, at least three cases of ancient man-made large rock caverns can be confirmed. They are the bell-shaped quarry caverns of Beit Guvrin in central Israel, the Wieliczka salt mine in southern Poland, and the Basilica Cistern caverns beneath the city of Istanbul in Turkey.

The Beit Guvrin caverns were carved in soft chalk with horizontal beddings during the early Arabic period (the 7th–11th centuries) as stone quarries. An extensive testing program was carried out to provide the required input data for the stability analyses [29, 30]. It is noted that such bell-shaped caverns for stones are similar to those ancient caverns for quarrying stones in Jurassic tuff in Sanmen County of Zhejiang Province, East China [31].

The Wieliczka salt mine is situated in the town of Wieliczka and within the Krakow metropolitan area in southern Poland [32, 33]. The mine caverns were excavated 700 years ago and continuously produced salt until the end of the 20th century when the commercial salt mining was stopped due to both of low salt prices and mine flooding. It was approved as one of the first world heritages by the United Nations Educational, Scientific and Cultural Organization in 1978.

The Basilica Cistern is the largest of several hundred ancient cisterns that lies beneath the city of Istanbul, Turkey [34]. It was built in 532 A.D. during the reign of Byzantine Emperor Justinian I. The surrounding rock is limestone.

In addition, Hatzor and Benary [35] carried out a back-analysis of the stability of an ancient underground cavern for water reservoir. The cavern was excavated in horizontally bedded chalk with vertical joints about 3 000 years ago. Its roof collapsed probably during the time of construction. The roof failure left a dome shaped loosened zone, with a span of 7 m and a height of 2.5 m.

2.4 Relics of large ancient rock caverns in China

In China, there are numerous ancient rock caverns for the purposes of stone quarry, underground tomb, water drainage tunnel, military tunnel, storage room, and carved religion statues. Among them, the authors have examined the relics of eight ancient man-made large rock caverns in Zhejiang and Anhui provinces of East China [2, 14]. The relics of Longyou rock caverns are the subject of this investigation.

3 Relics of ten complete rock caverns

As shown in Fig.5, there are at least 24 individual rock caverns in the small hill site. They were formed with similar manual carving methods in thick argillaceous siltstone. Ten of the 24 rock caverns were complete while the others failed.

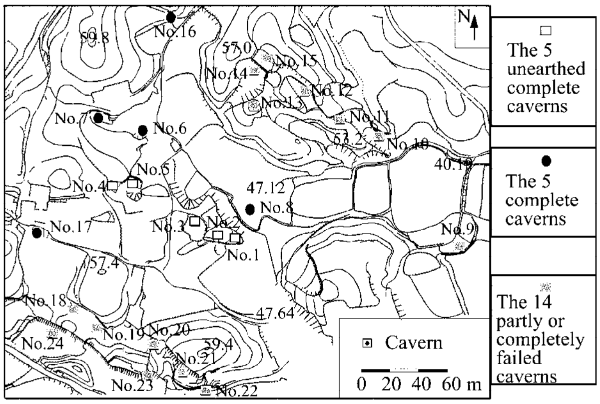


Fig.5 Topography and location plan of 24 Longyou rock cavern portals on the small hill in argillaceous siltstone (unit: m).

The complete rock caverns were defined by their special properties as follows: (1) the rock caverns were stable and kept their original man-made geometries; (2) they did not have any visible collapses and damages in their surrounding rocks; (3) the carved or chiseled imprints on the rock surfaces of their interior spaces including ceiling, walls and pillars were fresh, sharp and regularly patterned; (4) almost none of cracks on the rock surfaces was observed; and (5) a layer of mud sediments was on the rock base of each cavern when water was pumped.

The exact locations and plane areas occupied by the ten complete rock caverns are shown in Fig.6. The five complete caverns No.1–5 were unearthed or unwatered by pumping water out of their small water pools in 1992. The small water pools were actually the vertical portals marked in Fig.5. The other five complete rock caverns No.6–8, 16 and 17 are still occupied with water. Their vertical portals are the small water pools designated with WP6, WP7, WP8, WP16 and WP17, respectively. Except the cavern No.1, the small portal of each cavern is situated on its southern boundary.

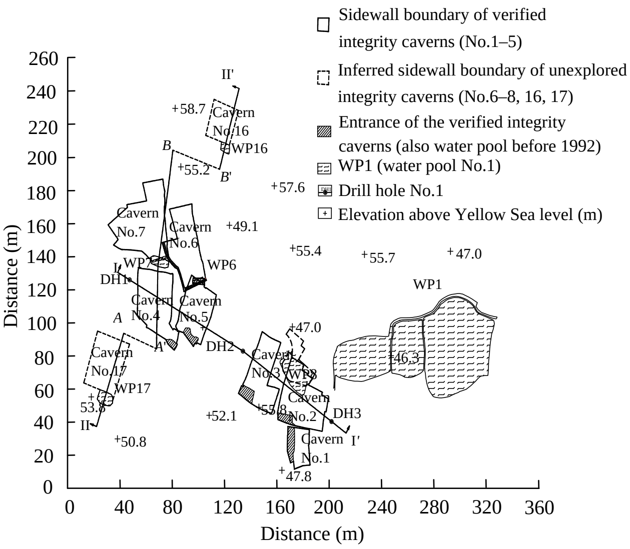


Fig.6 Plan boundaries of ten complete caverns and their vertical portals with small water pools.

Two geological cross-sections are constructed and shown in Figs.7 and 8. The cross-section I-I′ in Fig.7 connects the caverns No.4, 5, 3 and 2 and shows their transverse profiles of regular underground cavern space in the argillaceous (or pelitic) siltstone covered with a thin mantle of superficial soils. The cross-section II-II′ in Fig.8 connects the caverns No.17, 4, 7 and 16 and shows their longitudinal profiles of regular underground cavern space.

3.1 Complete rock caverns No.1–5

Figures 9–23 give much more details of the structures of the unwatered rock caverns No.1–5. Table 1 lists their dimensions, including the cavern geometries, the portals, the rock staircases, the rock water traps, and the rock pillars. Except the mud sediments, all of the five caverns are made of the in-situ argillaceous siltstone. The ceiling surfaces are inclined and curved. The sidewalls are usually inclined and their inclination

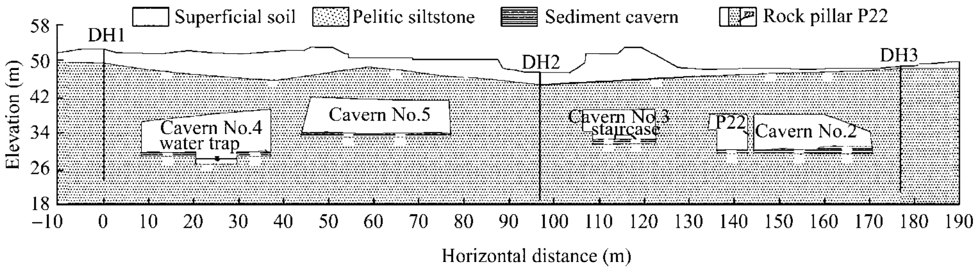


Fig.7 Geological cross-section I-I′ in Fig.6 for the complete caverns No.2–5.

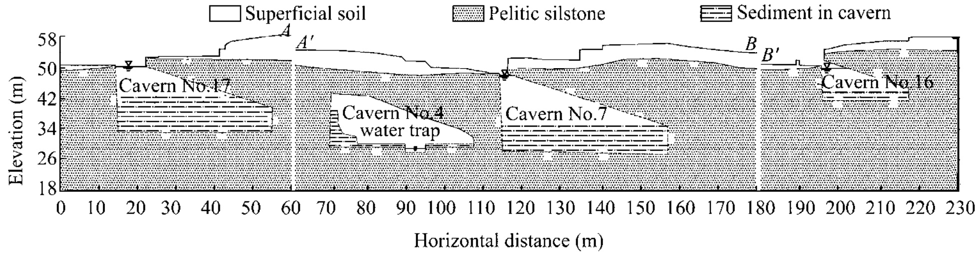


Fig.8 Geological cross-section II-II′ in Fig.6 for the complete caverns No.2–5.

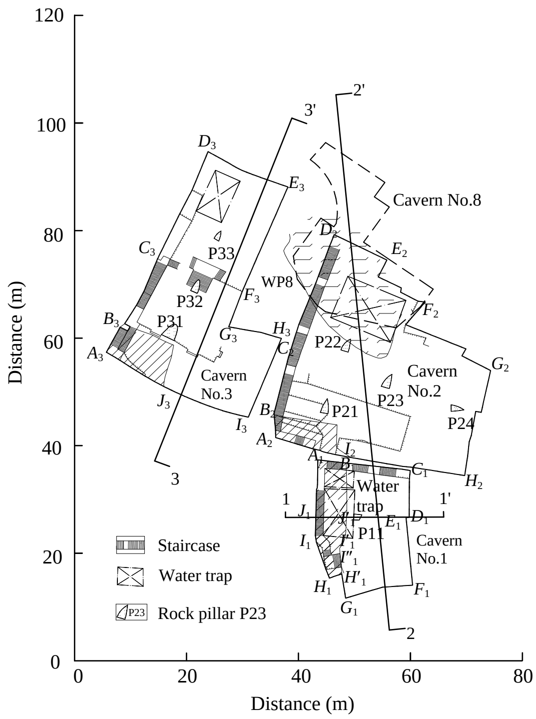


Fig.9 Plan view of the complete rock caverns No.1–3 showing their staircases, water traps and pillars.

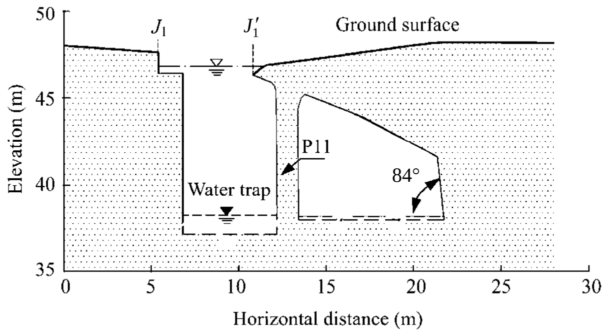


Fig.10 Geological cross-section 1-1′ in Fig.9 for the complete cavern No.1.

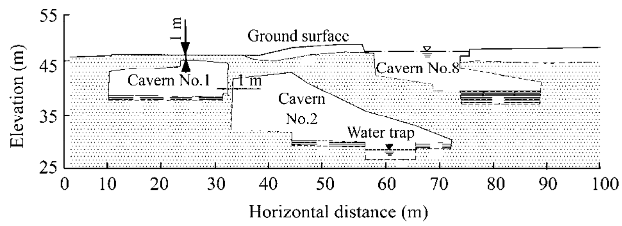


Fig.11 Geological cross-section 2-2′ in Fig.9 for the complete caverns No.1, 2 and 8.

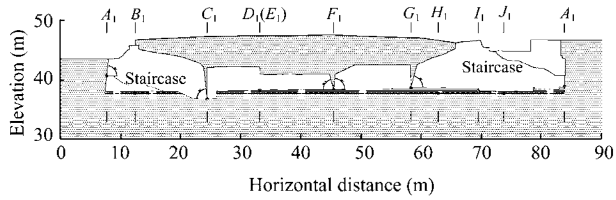


Fig.12 The vertical profile of the four interior near-vertical walls for complete cavern No.1 with the corner locations A_1 to J_1 in Fig.9.

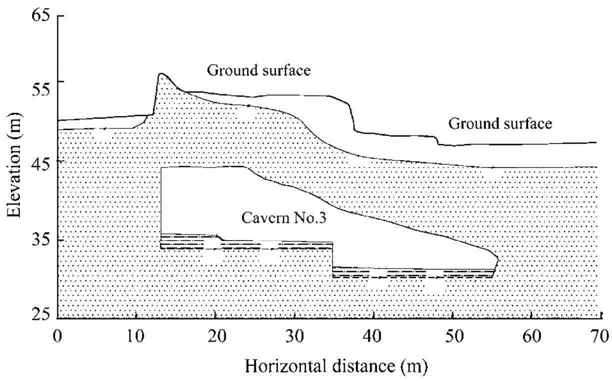


Fig.13 Geological cross-section 3-3′ in Fig.9 for the complete cavern No.3.

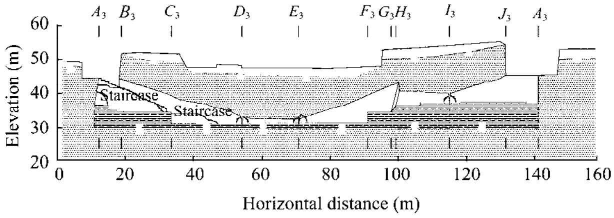


Fig.14 The vertical profile of the four interior near-vertical walls for complete cavern No.3 with the corner locations A_3 to J_3 in Fig.9.

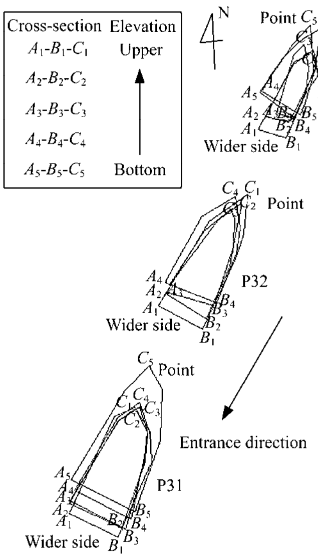


Fig.15 Detailed horizontal cross-sections of three rock pillars P31, P32 and P33 at five different heights in the complete cavern No.3 in Fig.9.

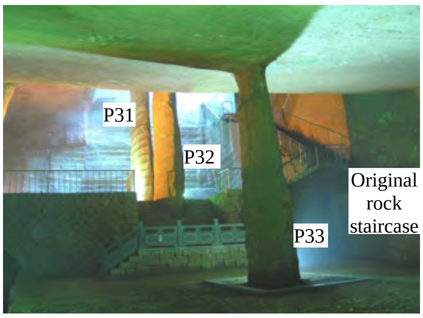


Fig.16 Site photograph showing three rock pillars (P31, P32 and P33) in the interior of the complete cavern No.3.

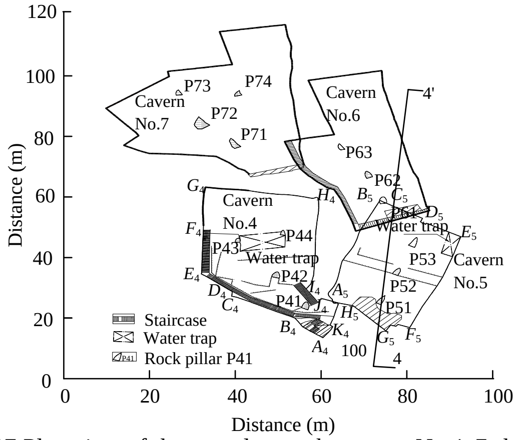


Fig.17 Plan view of the complete rock caverns No.4–7 showing their staircases, water traps and pillars.

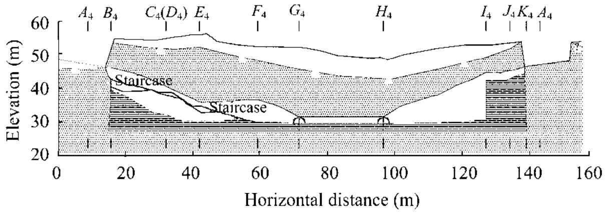


Fig.18 The vertical profile of the four interior near-vertical walls for complete cavern No.4 with the corner locations A_4 to K_4 in Fig.17.

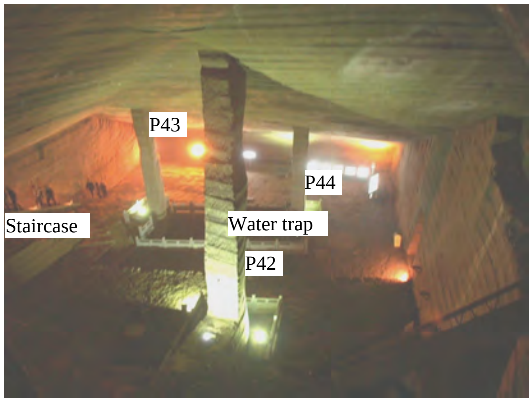


Fig.19 Site photograph showing three rock pillars (P42, P43 and P44) in the interior of the complete cavern No.4.

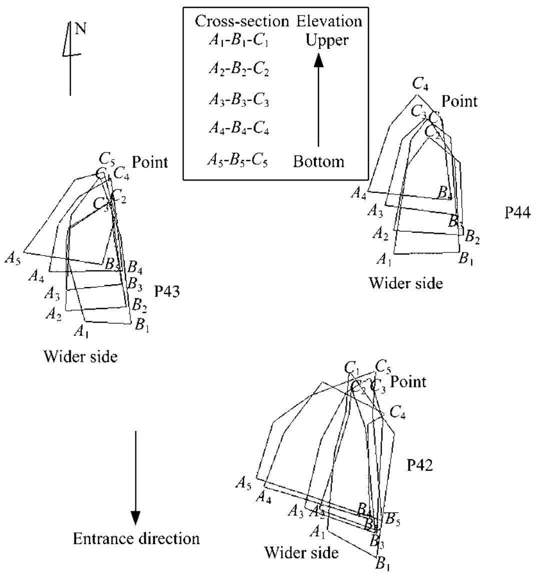


Fig.20 Detailed horizontal cross-sections of three rock pillars P42, P43 and P44 at five different heights in the complete cavern No.4 in Fig.17.

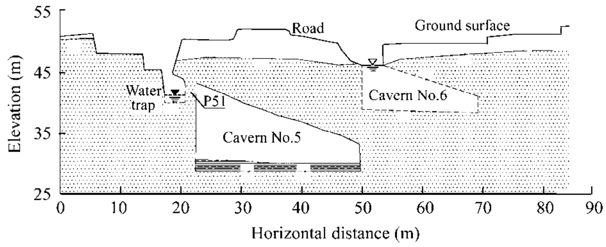


Fig.21 Geological cross-section 4-4′ in Fig.17 for the complete caverns No.5 and 6.

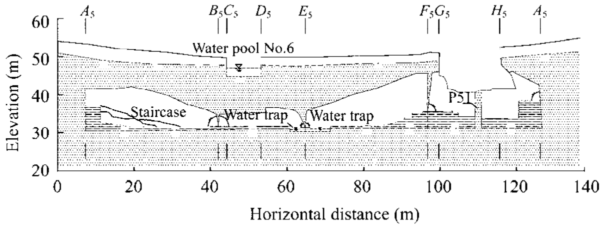


Fig.22 The vertical profile of the four interior near-vertical walls for complete cavern No.5 with the corner locations A_5 to G_5 in Fig.17.

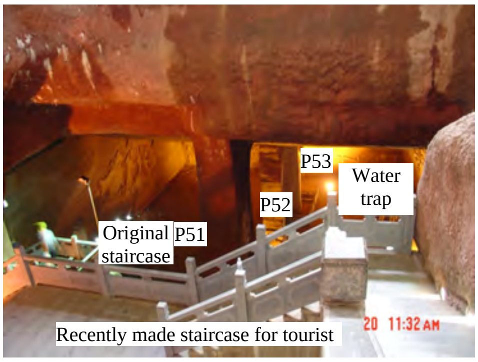


Fig.23 Site photograph showing three rock pillars (P51, P52 and P53), staircase and water trap in the interior of the complete cavern No.5.

Table 1 Dimensions of the complete caverns No.1–5.

Cavern No.	Length (m)	Width (m)	Plane area (m^2)	Ceiling slope (°)	Maximum height (m)
1	23	16	367	21–27	8
2	35	34	1 057	16–26	15
3	42.5	18	852	19–28	12
4	26	37	1 005	16	18
5	34	23	770	17–25	15

Cavern No.	Portal area (m^2)	Roof rock thickness (m)	Number of rock pillars	Area of rock water trap at base (m^2)
1	5.5×11.3	0.6–6.94	1	5×12
2	3.0×13.4	5.7–15.8	4	8×12
3	4.5×11.6	4.5–14.5	3	5×9
4	3.0×7.0	6.5–21.3	4	5×10
5	3.0×7.0	4.0–21.3	3	3×7

angles are also given in those figures. The mud sediments on the rock base of each cavern have not been completely removed so the actual rock base is not completely clear.

3.2 Other five complete rock caverns

The water in the complete caverns No.6 and 7 was pumped out in the 1990s and in September 2008, respectively. Some days later, the two caverns were naturally fully refilled by water from rainfall and seepage. The water in the cavern No.8 was pumped out in March 2004 and refilled naturally soon again. Therefore, some details for the complete caverns No.6–8 are obtained and shown in Figs.6, 8, 9, 17, 21, 24 and 25.

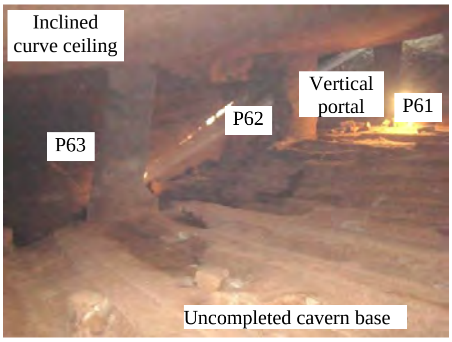


Fig.24 Site photograph showing uncompleted interior space of the complete cavern No.6.

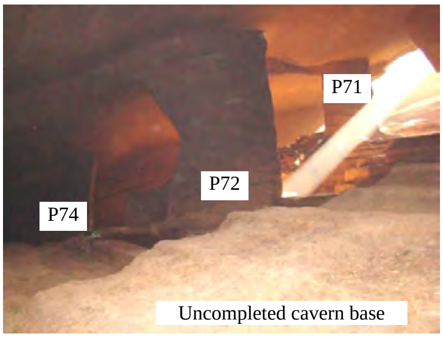


Fig.25 Site photograph showing uncompleted interior space of the complete cavern No.7.

The complete caverns No.6 and 7 have the plane areas of 993 and 1 352 m^2 in a near-rectangular geometry and an irregular geometry, and 3 and 4 rock pillars, respectively, as shown in Figs.6 and 17. From the carved rock surfaces and shapes, they were partially carved, as shown by their site photograph in Figs.24 and 25. Each has a vertical portal, a water trap and a regular rock staircase. Their bases are steeper and more irregular than those of the complete caverns No.1–5. Their portals have a plane area of 7.8×3.4 and 12×3.5 m^2, respectively. Their roof rock thicknesses at the portal are about 1 and 2 m, respectively.

The complete cavern No.8 has a vertical portal of 24 m long and 4–13 m wide, as shown in Fig.9. The roof rock thickness at the portal is about 1 m. The complete cavern No.16 has a vertical portal of 6.0 m long and 3.8 m wide, as shown in Fig.6. The roof rock thickness at the portal is about 2 m. A soil mantle of 1.1 m thick is above the roof rock. The complete cavern No.17 has a vertical portal of 9.5 m long and 6.6 m wide, as shown in Fig.6. The roof rock thickness at the portal is about 2.4 m.

3.3 Typical features and highlights

The typical features can be summarized and highlighted on the design and construction of the complete rock caverns made by the ancient people. A conceptual design sketch is drawn in Fig.26 to show

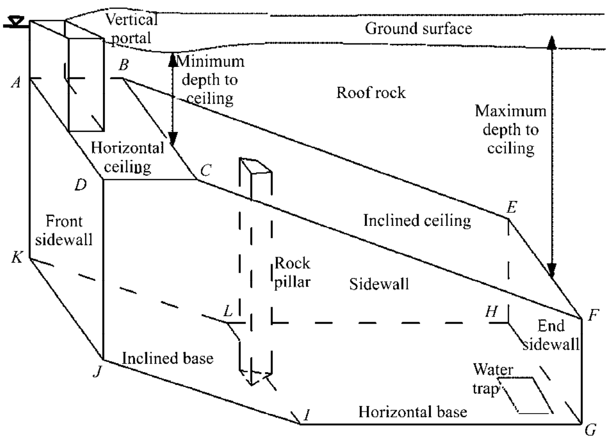


Fig.26 Conceptual design sketch for rock cavern structure with vertical portal (V-type).

the essential structure of the complete rock caverns. Details are further discussed below.

3.3.1 *Cavern depths*

As shown in the above cross-section figures and Fig.26, the depth from the ground surface to the cavern ceiling for each cavern is variable. The minimum depth is at the vertical portal and around the front sidewall. The depth increases along the cavern longitudinal direction to the maximum depth at the end sidewall. The depth is usually constant along the transversal direction.

Table 2 gives the values of the minimum depth and the transversal span width for each of the ten complete rock caverns. The ratio of the minimum depth to the span is far less than 1, which demonstrates that the ten complete caverns are extremely shallow.

Table 2 Ceiling depths and spans of ten complete rock caverns.

Cavern No.	Minimum ceiling depth, *H* (m)	Span, *B* (m)	*H*/*B*
1	0.6–1.5	23	0.03–0.3
2	5.7–7	34	0.17–0.46
3	4.5–8	18	0.25–0.81
4	6.5–8	26	0.25–0.82
5	4–4.5	23	0.17–0.93
6	1	≥7.8	≤0.13
7	1.5–2	≥12	≤(0.13–0.17)
8	1	8–12	≤(0.08–0.13)
16	2.85–3.1	≥6	≤(0.48–0.52)
17	2.15	≥9.5	≤0.23

For the five unwatered complete caverns No.1–5, their maximum depths are 6.94, 15.8, 14.5, 21.3 and 21.3 m, respectively. The ratio of the maximum depth to the span is equal to 0.30, 0.46, 0.81, 0.82 or 0.93 for the caverns No.1–5, respectively, which further demonstrates that the five caverns are shallow. Therefore, the ten complete rock caverns could have been subjected to various failures.

3.3.2 *Inclined ceiling*

It is evident that the ten complete caverns have adopted the inclined ceiling structure. The average dip direction of the ceiling slopes of the complete caverns No.1–5 is N17.6°E and closely equal to the average dip direction of the argillaceous siltstone beddings of N19°E. The average dip angle of the five ceiling slopes is 21.6° and also closely equal to the average dip angle of the beddings of 24°. These data demonstrate that the inclined ceiling design and construction are based on the understanding and utilization of the bedding strata.

A three-dimensional numerical analysis was carried out to assess the stress and deformation fields in two rock cavern models. One is based on the actual rock cavern with an inclined ceiling. The other is an assumed model with a horizontal ceiling. The numerical results show that the inclined ceiling design cannot only improve the stress condition of the surrounding rock but also reduce the settlement of the roof and the lateral deformation of the sidewalls [5, 14].

3.3.3 *Vertical portal*

Each complete cavern has only one portal associated with a vertical shaft. The vertical portal is normally located on the southern boundary of the cavern. The cavern longitudinal directions are usually toward the vertical portal and along the south to southwest direction. This cavern orientation can maximize the portal of the sunlight into each cavern, as shown in Figs.4, 16, 23–25. Besides, the vertical portal can allow rainfall and surface runoff into the cavern and can keep the cavern to be fully occupied with water, as shown in Fig.3. Consequently, a drainage system in each cavern is necessary.

Most importantly, the vertical portal can ensure the caverns to be carved in the thick argillaceous siltstone, which is normally below a soil mantle and some thin argillaceous siltstone strata, as shown in Fig.27. This result can demonstrate that the design and construction of the ten large caverns are based on the understanding and utilization of the rock mechanical behavior of the in-situ rocks. The thicker the rock strata are, the higher the surrounding rock stability is, and vice verse.

3.3.4 *Rock pillars*

Some rock pillars are shown in Figs.4, 16, 19, 23–

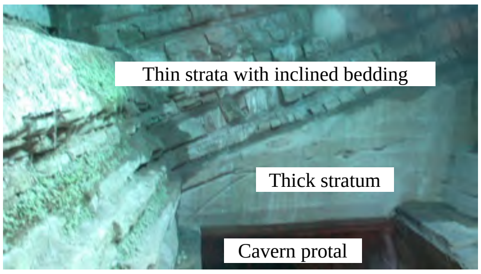


Fig.27 Thin and jointed strata above the cavern carved in thick and intact stratum of argillaceous siltstone.

25. Table 3 lists the pillar heights from 4.6 to 12.0 m and the cross-section areas from 1.3 to 5.0 m^2. As shown in Figs.16 and 20, the cross-sections have irregular pentagonal or triangular geometries. The wider side *AB* is always toward the cavern portal and along the cavern longitudinal direction. The point *C* is always toward to the end sidewall. In Table 3, the base width is the width of the wider side *AB* and the base length is the distance from the point *C* to the wider side *AB*, as shown in Figs.16 and 20.

Table 3 Dimensions and slenderness ratios of rock pillars in complete caverns No.1–5.

Pillar No. and dimensions						Slenderness ratio		
No.	Height, H (m)	Cross-section area, S (m^2)	Base width, w (m)	Equivalent diameter, $d = 2(S/\pi)^{1/2}$ (m)	Base length, t (m)	H/w (A)	H/d (D)	H/t (T)
P11	7.2	1.3	1.3	1.29	1.5	5.54	5.60	4.80
P21	11.0	2.4	1.4	1.75	2.6	7.86	6.29	4.23
P22	9.0	2.3	1.2	1.71	2.4	7.50	5.26	3.75
P23	8.2	2.6	1.4	1.82	2.7	5.86	4.51	3.04
P24	4.6	1.7	1.3	1.47	2.2	3.54	3.13	2.09
P31	8.8	5.0	1.9	2.52	2.8	4.63	3.49	3.14
P32	6.4	2.3	1.3	1.71	2.4	4.92	3.74	2.67
P33	6.0	1.2	1.0	1.24	1.6	6.00	4.85	3.75
P41	9.0	3.0	1.6	1.95	2.3	5.63	4.60	3.91
P42	12.0	2.7	1.8	1.85	2.0	6.67	6.47	6.00
P43	8.2	1.3	1.0	1.29	1.4	8.20	6.37	5.86
P44	7.4	1.3	1.0	1.29	1.8	7.40	5.75	4.11
P51	12.0	2.7	1.3	1.85	3.0	9.23	6.47	4.00
P52	9.4	2.5	1.4	1.78	2.2	6.71	5.27	4.27
P53	6.5	3.3	1.6	2.05	3.0	4.06	3.17	2.17

Three slenderness ratios, noted with A, D and T in Table 3, can be calculated for each pillar by dividing the pillar height with respect to the base width, the equivalent diameter and the base length, respectively. The calculated results in Table 3 demonstrate that rock pillars are slender pillar structures. Furthermore, each of the slenderness ratios associated with the base length is much smaller than its corresponding slenderness ratios associated with both the base width and the equivalent diameter. The average slenderness ratios of the fifteen pillars for the types A, D and T are equal to 6.25, 5.00 and 3.85, respectively.

The direction of the base length is along the cavern longitudinal direction and follows the dip direction of the inclined ceiling rock slope. The base width direction is perpendicular to the base length direction and follows the cavern transversal direction. Furthermore, the small slenderness ratios (T) strongly increase the pillar rigidity with respect to the loading of the inclined ceiling rocks and hence largely enhance the pillar capability to resist bending deformation caused by the inclined ceiling rocks.

In addition, as shown in Figs.4, 28 and 29, an arc connection was made of in-situ rock between the pillar and the ceiling so that the rock connection area was enlarged, which could reduce the stress concentration at the pillar and ceiling interface zone.

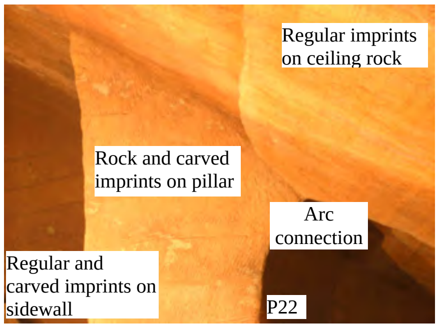


Fig.28 Arc connection for in-situ rock between pillar and ceiling and the regular carved imprints on ceiling, pillar and wall.

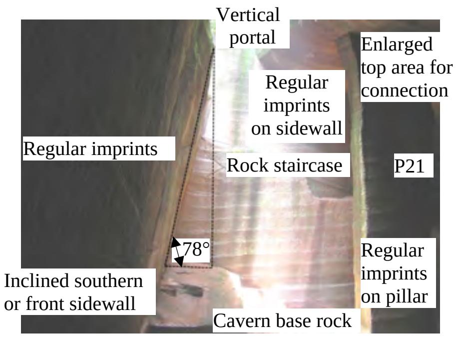


Fig.29 Inclined sidewall and other details for the complete rock cavern No.2.

Three-dimensional numerical analyses were carried out to assess the functions of the rock pillars to the stability and deformation of the rock caverns. The assessments include: (1) the function of the special horizontal cross-sections of the pillars shown in Figs.1 and 20; (2) the function of the arc connections between the pillars and the ceiling rocks shown in Fig.28; and (3) the function of the L-shaped pillar base, as shown by the pillar P21 in Fig.4. The numerical results indicate that: (1) the supports from the pillars are important for the stability and serviceability of the rock caverns; and (2) the special rock pillar designs are better for reducing the settlement of roof rock and formation of plastic zones in the surrounding rocks [14].

3.3.5 *Inclined sidewalls*

A majority of the sidewalls in the five unwatered complete caverns are inclined toward their interior spaces. An example is given in Fig.29 where the southern sidewall of the cavern No.2 is dipped 78° toward the cavern interior space. Table 4 lists the average dip angle of each sidewall of the five unwatered complete caverns.

Table 4 Dip angles of the inclined sidewalls in the unwatered complete caverns No.1–5.

Cavern No.	Dip angle of inclined sidewalls (°)			
	Eastern	Western	Southern	Northern
1	84	86	75	90
2	75	87	78	88
3	84	78	83	79
4	88	85	-	85
5	84	86	90	82

Rock mechanical analyses were carried out numerically to compare the effects of inclined and vertical sidewalls on rock cavern stability [14, 36]. The compared numerical results include tensile stresses, shear stresses, roof settlement, and wall bulge. The numerical results indicate that the rock cavern with inclined sidewalls is more stable than that with vertical sidewalls. This result can be explained with the presence of arch effect in the rock cavern with inclined sidewalls so that the stress concentration in the roof rock can be minimized.

3.3.6 *Regular and angular carved imprints*

When the water was pumped out, the carved angular imprints with regular patterns were observed on the rock surfaces of sidewalls, ceilings and pillars. As shown in Figs.30 and 31, the imprints have two types. One type is the regular long straight imprints. They are shown as the ones linking *A* to *A*′, *B* to *B*′, *C* to *C*′,

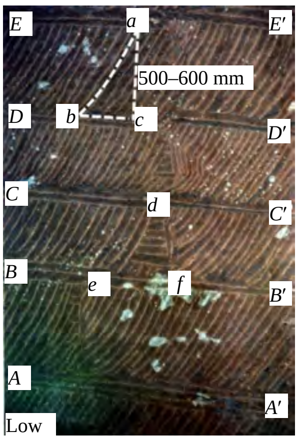


Fig.30 Regular and elegant long straight imprints and short curved imprints carved on sidewall rock surface in the complete cavern No.3.

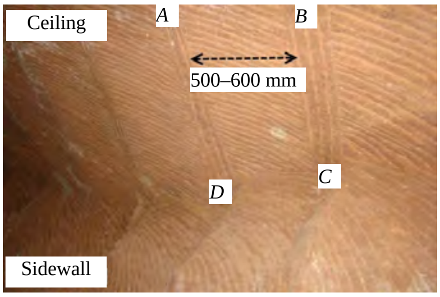


Fig.31 Regular and elegant long straight imprint and short curved imprint carved on sidewall and ceiling rock surfaces in the complete cavern No.4.

D to *D*′ and *E* to *E*′ in Fig.30 and the ones linking *A* to *D* and *B* to *C* in Fig.31. Each group of straight imprints has two to three long carved troughs. The spacing between any two sets of adjacent straight imprints is 500 to 600 mm, as shown in Figs.30 and 31. On the rock surfaces of sidewalls and pillars, the straight imprints are usually horizontally placed, as shown in Fig.30. On the ceiling rock surfaces, they are usually placed along the transversal direction of the cavern, as shown in Figs.19 and 31. Their surfaces are very smooth and fine.

The other type is the regular short curved imprints. Their lengths are usually limited between 540 and 750 mm. They are shown as the curved troughs between the straight imprints in Figs.30 and 31. A typical example is the curved trough linking *A* and *B* in Fig.30. The angle between a curved trough and its lower straight trough set (i.e. the angle ∠*abc* in Fig.30) is 60° to 75°. The trough depths are variable between 6 and 14 mm and its average depth is 10 mm. The distance between two adjacent troughs is 30–50 mm.

As shown in Fig.31, special effort and design were made to connect the straight imprints on the ceiling to those on the sidewall and to connect the curved imprints on the ceiling to those on the sidewall. Besides, the triangle with the points *d*, *e* and *f* in Fig.30 shows a special design for connecting the curved imprints between two adjacent sets of long straight imprints.

3.3.7 *Footpath staircases*

As shown in Fig.29, each complete cavern has a footpath staircase from the vertical portal to the cavern base. The staircases were carved in in-situ intact rock. Their horizontal widths are larger than the height of each staircase step.

3.3.8 *Drainage system*

Each complete cavern has a system of surface drainage to collect rainfall and seepage water. The system includes some drainage troughs, some drainage channels, and a water trap. The drainage troughs were carved in the sidewall rocks to guide seepage water to flow down the wall, as shown in Fig.32. The water traps were carved in the cavern base rock to collect water in the cavern, as shown in Fig.33.

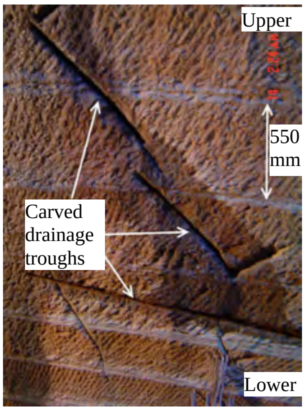


Fig.32 Drainage troughs carved in sidewall rock for guiding seepage flow.

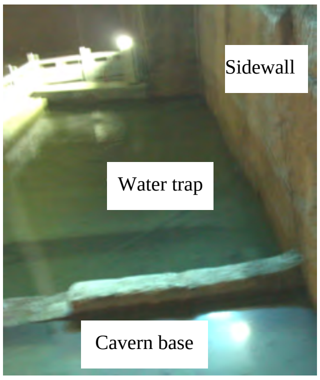


Fig.33 Water trap carved in the cavern base rock for collecting water.

4 The failed rock caverns

As shown in Fig.5, the other fourteen rock caverns in the small hill site partially or completely failed. Seven failed caverns are located in the northeastern quarter of the site. They are the caverns No.9–15. The other seven failed caverns No.18–24 are located in the southwestern quarter of the site. The elevations for these two areas are about 10 m higher than the central area where the ten complete rock caverns are located.

Table 5 summarizes the survey results for the conditions of the fourteen failed rock caverns. Various failures or damages in these caverns occurred historically. Their actual occurrence time was earlier than 1992. The causes of failure were due to both mechanical damage and weathering deterioration in the surrounding rocks.

Table 5 Results of condition survey for fourteen originally completely or partially failed rock caverns.

Cavern No.	Estimated cavern horizontal area (m × m)	Ceiling elevation (m)	Presence of water	Water elevation (m)	Modes of failures
9	8.7 × 2	49.2	None	—	Fall of rock blocks, development of cracks
10	15 × ?	47.6	Partially fill	45.7	Partial collapse at entrance
11	8.7 × 15	51.8	None	—	Delaminated slab fall of ceiling, collapse of right sidewall, shear failure of a rock pillar at entrance
12	20 × (15–20)	54.2	None	—	Delaminated slab fall of ceiling, chisel marks on the roof disappeared
13	10.3 × ?	47.1	Partially fill	44.4	Wedge failure at entrance, rock block falls, cracks well developed
15	8 × 6	57.5	None	—	Delaminated slab fall of ceiling, entrance collapse
18	11.4 × (9–10)	48.4	Partially fill	42.4	Delaminated slab fall of ceiling showing coarse sandstone, long cracks well developed in the sidewall
19	12 × (9–10)	49.4	Partially fill	42.4	Delaminated slab fall of ceiling showing coarse sandstone, long cracks well developed in the sidewall
20	4.85 × ?	49.2	Partially fill	45.3	Ceiling rock weathered, some block falls
21	(7–20) × (12–20)	52.2	None	—	Block collapse due to joints in ceiling, left sidewall collapse, jointed pillar
22	5 × 4	47.7	None	—	Small cavern, wedge collapse above the cavern entrance
23	30 × 415	47.2	Partially fill	44.5	Many ceiling rock collapsed, many sidewall collapsed, pillar P232 weathered, hole developed through ceiling rock
24	80 × 50	46.2	Partially fill	44.5	Delaminated slab collapses for several meters

Note: "?" presents that the data cannot be obtained due to immersion in water.

4.1 Modes of failures

At least five failure modes can be identified in the fourteen failed rock caverns. They are: (1) collapse of cavern portals, (2) delaminated slab fall of cavern ceiling/roof rocks, (3) block fall of sidewall rocks, (4) cracks in cavern rocks, and (5) weathered or smoothened carved imprints. Figures 34–39 show the situations of the collapsed rock caverns No.14 and 23. The five failure modes can be observed in the figures.

4.2 Grades of cavern failures

The failure extents of the fourteen caverns can be classified into five grades (I–V). The two rock

Fig.34 Site photograph showing the collapsed rock cavern No.14 and its water pool.

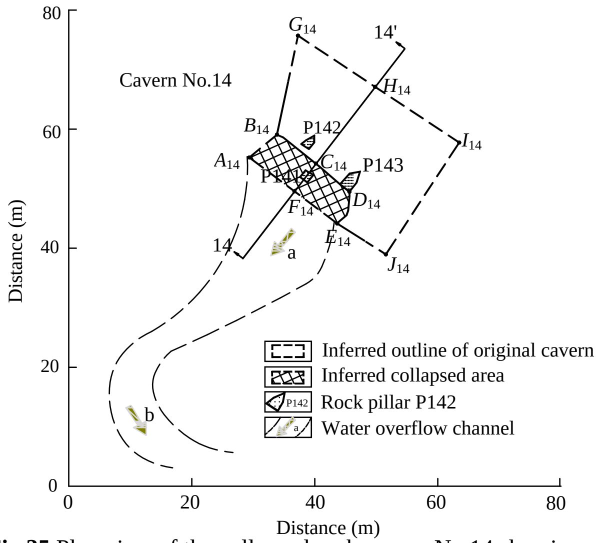


Fig.35 Plan view of the collapsed rock cavern No.14 showing collapsed portal area (water pool) and pillars.

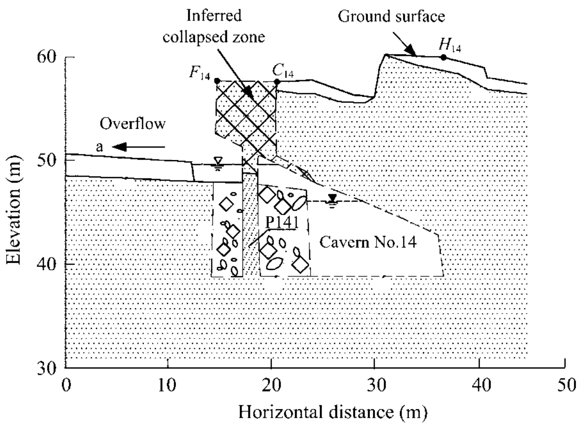


Fig.36 Geological cross-section 14-14′ in Fig.35 for the collapsed rock cavern No.14.

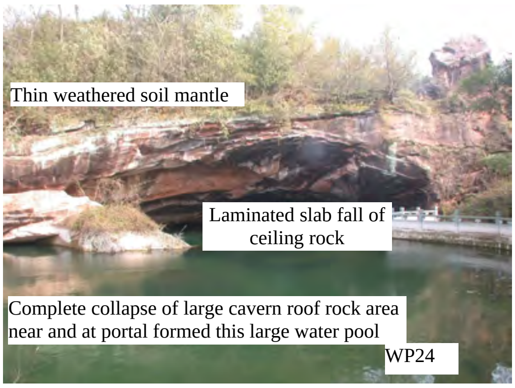


Fig.37 Site photograph showing part of the collapsed rock cavern No.23 and its water pool WP24.

Fig.38 Site photograph showing part of the collapsed rock cavern No.23 and its rock pillar P232.

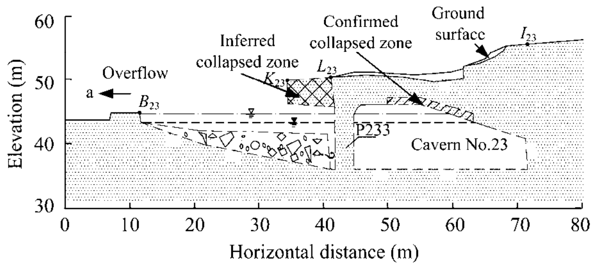


Fig.39 Geological cross-section for part of the collapsed rock cavern No.23.

caverns No.9 and 22 are in grade I and have intact surrounding rocks with carved imprints weathered and smoothened and a few local broken rocks. The three rock caverns No.18–20 are in grade II and have stable cavern structures with cracks in the surrounding rocks and carved imprints almost completely smoothened. The four rock caverns No.12, 15, 21 and 22 are in grade III and have many cracks, local rock block falls, delaminated falls or separations in ceiling rocks, pillar damage and carved imprints faded. The four rock caverns No.10, 11, 13 and 24 are in grade IV and have local collapses due to cracks in pillars and roof falls. The rock caverns No.14 and 23 are in grade V and have major cavern collapses and sinkholes.

4.3 Cavern structures and depths

A conceptual design sketch can be drawn in Fig.40 to show the essential structure of the failed rock

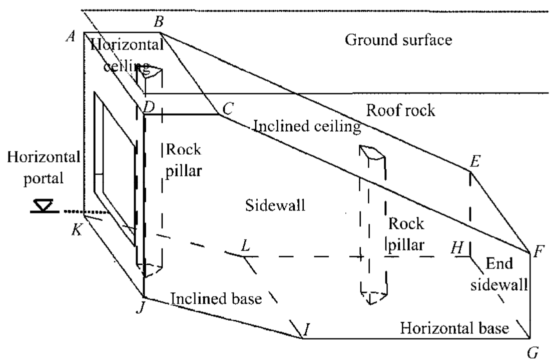


Fig.40 Conceptual design sketch for rock cavern structure with horizontal portal (H-type).

caverns. Comparing the conceptual design in Figs.26 and 40, it can be found that the essential differences in the failed and complete cavern structures are the differences in their portals. The failed caverns have the type of horizontal portal while the complete caverns have the type of vertical portal.

Table 6 gives the estimated values of the minimum depth and the transversal span for each of the fourteen failed rock caverns. The ratio of the minimum depth to the span is basically less than 1, which demonstrates that the ten failed caverns are also extremely shallow and were subjected to various failures.

Table 6 Ceiling depths and spans of the fourteen failed rock caverns

Cavern No.	Minimum ceiling depth to ground surface, *H* (m)	Span width, *B* (m)	*H*/*B*
9	3.5	≥8.7	≤0.4
10	2.73	≥15	≤0.18
11	4.3	8	0.54
12	3.1	≥20	≤0.16
13	9.7	≥10.3	≤0.94
14	9.6	≥12.4	≤0.77
15	0.75–1.7	≥8	≤(0.09–0.21)
18	3.2	11.4	0.28
19	3	15	0.2
20	4.4	≥4.5	≤0.98
21	5.8	≥7	≤0.83
22	5	5	1
23	4–10	≥10.5	≤(0.4–0.95)
24	9.6	≥49.1	≤0.2

4.4 Rock properties and behaviors

The above descriptions of the ten complete and fourteen failed rock caverns have demonstrated that they were manually carved in argillaceous siltstone. The large amount of manual carving in argillaceous siltstones and the evident failures of the surrounding rocks for the fourteen rock caverns at the small hill site clearly demonstrate that the rocks are neither hard and strong nor soft and poor. Many field and laboratory tests have been conducted to quantify the physical, chemical and mechanical properties of the surrounding argillaceous siltstone [14, 16, 18]. Some results are briefly given below.

The intact rock is composed of 70% particle minerals and 30% argillaceous cements. The particle minerals include quartz more than 65% and feldspar and zircon less than 5%. The argillaceous cements have the minerals of quartz, plagioclase feldspar, calcite, chlorite, illite and montmorillonite, and their percentages are 44%, 20%, 12%, 5%, 6% and 17%, respectively. The rock cementation coefficient is 3.79, which indicates a medium cemented rock. The presence of clay minerals and calcite indicates that the in-situ rock can suffer a high degree of physico-chemical weathering, which is evidenced by the smoothened imprints in the failed rock caverns [14–18].

In dry condition, the values of the unit weight, modulus, Poisson's ratio, uniaxial compression strength, tensile strength and P-wave velocity of the intact rock are equal to 21.8 kN/m^3, 4.5 GPa, 0.27, 31.6 MPa, 1.6 MPa and 2.0 km/s, respectively. In wet condition, the values of the unit weight, modulus, Poisson's ratio, uniaxial compression strength, cohesion and internal friction angle are equal to 23 kN/m^3, 3.0 GPa, 0.27, 18.1 MPa, 5.6 MPa and 26°, respectively. The uniaxial compression strength was reduced from 28.5 to 13.0 MPa for increasing water contents from 0.72% to 8.28%. Inside a 100 kPa vacumm vessel, the rock had a fully saturated unit weight of 23.5 kN/m^3. Three point bending tests show that the bending modulus is about 1 GPa and is variable with the loading rate for rock samples with a natural moisture content of 1.1%, a natural unit weight of 22.1 kN/m^3 and a void ratio of 20.9% [18]. These data further show that the surrounding rock is soft-medium rocks with low-medium strength and low-medium stiffness. Its stiffness and strength can be reduced significantly as its water content increases.

Core samples of borehole investigation indicate that the rock mass thickness is more than 100 m. Field mapping indicates that the rock masses are relatively intact, and they has blocky and integral structures, as shown in Fig.41. The rock strata experienced a very

Fig.41 Rock mass profile exposed due to collapse of a carved rock cavern on Qujiang River about 3.5 km west to the small hill site.

limited regional tectonic movement (i.e. overall inclination). The *RQD* value can be 100. It has three sets of joints. The *Q* value is 9 and the rock mass can be rated in the good category [16].

5 Relevant studies and findings

The five unwatered complete rock caverns No.1–5 were particular and fantastic. The unearthing of the five complete rock caverns in 1992 immediately attracted numerous media attentions in China because of their values in cultural relics and archaeology, and their numerous unknowns and confusing phenomena. Few historical records and cultural relics about the cavern history were found in the caverns and in the region.

Even with the great effort made by archaeologists and historians in China, there are still many questions to be answered and unknowns to be revealed. Some of the questions and unknowns are: (1) who carved them? (2) why did they carve them? and (3) when did they carve them? In the ensuing content, some relevant studies by others are briefly reviewed so that the rock caverns and their history can be much appreciated.

5.1 Construction purpose

The county of Longyou is a city with more than 3 000 years history in Chinese civilization [37]. The area was named as Gumie in about 1046 B.C. and experienced many changes and wars. The county was established in 223 B.C. by the Qin Government. Therefore, based on some indirectly related information in the region, archaeologists and others gave many different construction purposes for the rock caverns. They include stone quarrying, mausoleum (tombs), underground storage space, Taoist home, secret military camp, a place for offering sacrifices to gods or ancestors, and a palace. Each purpose can have many reasonable arguments to support but also encounter many other questions and suspects. So far, there is no consensus about the construction purpose of the large rock caverns.

It is also noted that soon after they were discovered, the large rock cavern relics were named as Longyou Grottos. This name has been continuously used in the literatures. However, the use of grottos is inadequate for large rock cavern relics.

5.2 Construction time

Few historical records and culture relics were found in the caverns and in the region. Undisturbed soil samples or wood samples in the caverns were not obtained for using the ^{14}C age dating method. Therefore, the cavern construction time cannot be determined and confirmed. So far, only one written record was found about the caverns. It was a Chinese poem written by Mr Yu Xun between 1626 and 1676. It can be used for confirmation of the construction time before 1626. Furthermore, other two Chinese poems possibly on the rock caverns were also found. They were separately written by two ancient men in the Song Dynasty from 960 to 1279. They can be used for confirmation of the construction time before 960.

Thirdly, on October 19, 2001, when cleaning the silt soils in the complete cavern No.2, the workers accidentally found some pieces of glazed clay china. Archaeologists and historians on site put them together and recovered two incomplete glazed clay pots, as shown in Fig.42, and confirmed they were typical clay pots in the Western Han Dynasty of China from 206 B.C. to 23 A.D.. Based on the assumption that they were put into the cavern No.2 two thousand years ago, the rock cavern No.2 would be constructed earlier.

Fig.42 Two incomplete glazed clay pots unearthed from silt mud in cavern No.2 (courtesy of the Cultural and Tourism Bureau of Longyou County Government).

Furthermore, Fig.43 shows the photograph illustrating a relief sculpture of a horse, a bird and a fish carved on the northern sidewall of the rock cavern No.1. Some archaeologists and historians reasoned and judged that the relief sculpture was carved between 206 B.C. and 589 A.D..

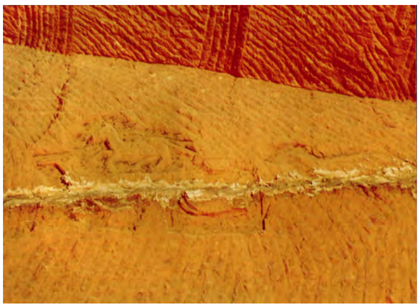


Fig.43 A relief sculpture of horse, bird and fish carved on the sidewall of the rock cavern No.1.

The authors believe that these issues and questions will be continuously asked until new and sound evidences are revealed. Most possibly, further evidences may be found in the remained mud sediments on the cavern bases and in association with the ^{14}C age dating. For an ease of communication, the authors adopted that the cavern construction time was 2 000 years ago.

5.3 Studies in rock mechanics and engineering

The community of rock mechanics and engineering in China and abroad probably did not pay any attention to the discovery of the large rock cavern relics until December 1998. Since then, many researchers in rock mechanics and engineering have conducted various investigations on the large rock cavern relics. Part of the investigations is briefly introduced below.

Sun et al. [38–40] inspected the relics in 2000, further examined the rock structures and rock pillars of the rock cavern relics in terms of engineering science, and considered that the general spatial arrangement of the caverns was consistent with modern rock engineering and the underground positioning of the individual caverns was of high surveying accuracy. Wang [41] also visited the relics and described them as a man-made natural wonder to highlight the achievement of our ancestors in underground construction. He assessed the surrounding rocks and considered them “soft rocks, good integrity but medium to low strength”.

In his speech at the closing ceremony of the Symposium of China’s Longyou Ancient Underground Construction Group on December 13, 2000, Qian [42] evaluated the rock cavern relics. In particular, he highly appraised and appreciated the underground surveying results of the rock caverns and considered that the rock cavern project was a wonder of underground space development with national and international standards. Yang [43] indicated that the rock cavern group “in overall, has a high scientific value to the evidence based research of ancient culture, art and construction techniques in China”.

From the viewpoint of geosciences, Mei [44] discussed the scientific values of the rock cavern relics and pointed out the adequacy and suitability of site and material selections. From the rock cavern stability, he also suggested that “Longyou Grottos have very good characteristics in hydrogeology and engineering geology”. Furthermore, Li et al. [45–47] examined the site geological and hydrogeological conditions and the mineral and chemical properties of the argillaceous sandstone and the in-situ water. Ding et al. [48] and Lu et al. [49] carried out experimental studies on the chemical reinforcement of resisting weathering of the argillaceous siltstone (or red sandstone).

6 Reconstruction of ancient design and construction methods

The descriptions and data on the cavern relics in Sections 3–5 demonstrate that the ancient people have a set of design and construction methods and they have used them to complete the rock caverns successfully. Therefore, questions can be asked on the design and construction methods. Some questions are: (1) how did the ancient people think in the selections of cavern site and buried-depth? (2) how did the ancient people undertake the site investigation? (3) how did the ancient people resolve the problem of lighting during construction? (4) how did the ancient people carve the large rock caverns in gently dipping rock strata? (5) how did the ancient people carve the regularly patterned imprints? and (6) how did the people survey and position during the construction? These questions are addressed below.

6.1 Selection of site and strata

As discussed above, the small hill site is very good in terms of engineering geological conditions. The rock selection should be in accordance with the ancient construction tools. Furthermore, the rock strata in Quzhou—Jinhua Basin are complicated. The ancient people should have good experiences in carving rocks in Longyou area. They might use the analogical method to select the small hill site as the place for constructing the 24 rock caverns.

Furthermore, the rock strata comprising the small hill include coarse, medium and fine sandstones, thick argillaceous siltstone, thin siltstone and mudstone. They are located at different locations and depths. The thin siltstone and mudstone are very poor and definitely not suitable for caverns. Therefore, the ancient people might use trial-by-error method to select the actual location for each cavern. While constructing the portal, they might evaluate the rock quality. If the rock quality was not suitable, they might abandon the site and try a new site. This trial pit method was supported by two abandoned pit sites, where mudstone seams (soft rock) were found at the base of the excavation. Therefore, they chose the thick argillaceous siltstone as the cavern roof rock for stability and carvability. In addition, they tried to select an adequate site for each cavern portal so that the portal slope did not collapse.

6.2 Caving lighting

When entering the large rock caverns, we cannot help thinking how the ancient people carved the regularly patterned imprints in the dark underground space. They had to light the cavern so that they could carve. Otherwise, they also could not see clearly to carve.

Of course, they could use sunlight, as shown in Fig.4. However, for the large caverns, the sunlight from their vertical portals is not adequate. This question may be answered by the observation of many small holes in the rock pillars and sidewalls. An example of such small holes is given in Fig.44. It is suspected that each small hole was used for inserting a firebrand on the rock surface. Therefore, firebrands might be used for lighting during the construction.

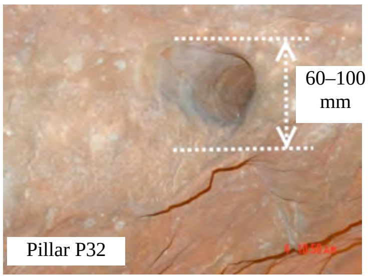


Fig.44 Small hole of 60–100 mm in diameter and 80–150 mm in depth and upward angle 40°–60° in rock surface of pillar P32.

However, no smoking stains were found at all on the rock surfaces, which might suggest that the imprints were formed after the formation of cavern space to a certain depth (2 to 3 m). As a result, the final rock surfaces were smoking stains free, which might be a requirement of the cavern design.

6.3 Construction methods

6.3.1 *Construction steps*

The first step was to construct the vertical or horizontal portal. Then, the cavern was carved with a top to down and layer by layer sequence. According to the design, the rock pillar, the inclined ceiling and the sidewalls were also formed layer by layer from top to bottom. Each layer might have the thickness of the two adjacent horizontal toughs, as shown in Fig.30. This process was repeated until the cavern base. As discussed above, the imprints were carved after the formation of the cavern to a suitable depth.

6.3.2 *Carving tools*

Based on the site investigation, it is highly possible that the cavern was formed by carving rock stones from top to bottom and layer by layer. The tools might be short chisels with different sizes. Figure 45 shows four short chisels unearthed in the rock caverns No.1 and 5. They are made of steel. It is also guessed that the hammers were made of hard woods.

(a) Chisel of 80 mm long with wide sharp toe.

(b) Chisel of 220 mm long with two point sharp ends.

(c) Chisel of 80 mm long with wide sharp end.

(d) Chisel of 125 mm long with one point sharp end.

Fig.45 Relics of four short steel chisels unearthed in rock caverns No.1 and 5.

6.3.3 *Carving method for rock blocks*

A relic of uncompleted carving for rock blocks was found in a small cavern adjacent to the collapsed rock cavern in Fig.46. Based on this relic and other facts, the method for carving a rock block is reconstructed as follows: (1) carving four deep troughs to separate the rectangular rock block from this surrounding rocks; (2) drilling a number of equally and horizontally spaced holes near the base along one length side; (3) then pumping the chisels inserted in the holes gently and one by one splitting the rectangular rock block with its base rock; and (4) finally removing the rock block.

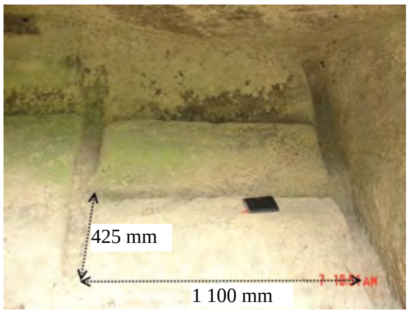


Fig.46 Relic of uncompleted carving for rock blocks in a small rock cavern.

6.3.4 *Carving method for imprints*

So far, no additional relic was found about the construction of the carved imprints. The rock can substantially decrease its strength and stiffness once it is saturated with water. This rock behavior might be used by the ancient people. They might wet the surface rock along the horizontal lines and the near-vertical curves. They might then use the steel chisels to carve the imprints along the wet lines. Each man might use his left hand to hold a steel chisel and his right hand to hold a wood hammer to blow the chisel into the rock. So, the trough-shaped imprints were formed.

6.3.5 *Water trap functions*

The water trap associated with each cavern can have at least three functions: (1) to collect water so that the construction could be carried out in dry condition; (2) to collect water after the completion of construction; and (3) to collect water for people to use. The ancient people might construct a water trap at each excavation depth so that the construction could be conducted in dry condition.

6.4 Construction surveying

As shown in Figs.9 and 11, the rock wall separating the complete caverns No.1 and 2 has a thickness of 0.55–1.3 m. It is 16.5 m long and 5 m high. Furthermore, the 24 rock caverns were constructed within a small volume of underground rock occupying a horizontal plane area of 350 m × 280 m (long × wide). However, the caverns were well positioned and did not have any interference. These facts can show that the ancient survey capability was high [42, 44]. Therefore, it is suspected that the ancient people used a compass-like tool for the underground surveying during the cavern construction.

7 Long-term stability and integrity

It is evident now that the relics of the complete rock caverns are man-made natural wonders and invaluable in both culture and underground rock engineering. They deserve to be preserved forever. Therefore, the following questions are asked and addressed.

(1) Question A: why can the ten caverns have been stable and integral for more than 2 000 years?

(2) Question B: why were the rock surfaces of the ceiling, sidewalls and pillars of the ten complete rock caverns free of cracks when their water were pumped out?

(3) Question C: did the ancient people have plans to design and construct the rock caverns so that they have remained stable and integral for at least 2 000 years?

(4) Question D: can the ten complete caverns be stable and integrity for next 2 000 years? If yes, how can they be preserved?

Analyses and answers to these four questions will be briefly given below. More details can be found in Refs.[14, 17, 18].

7.1 Analysis and answer to Question A

Evidently, the failures and damages associated with the fourteen failed rock caverns are expected results and can be anticipated using the modern theories of rock mechanics. This statement is based on the facts that (1) the large rock caverns are extremely shallow-buried and (2) the surrounding argillaceous siltstone rocks have low modulus, and shear, tensile and compressive strengths.

However, the ten complete rock caverns are still stable and keep the original integrity. The fourteen failed rock caverns and the ten complete rock caverns are located closely and adjacently. They have the same surrounding rocks and the similar history. Furthermore, they should have experienced the same loads from far distance such as earthquake. So, the complete caverns are unexpected results! Question A has to be addressed.

Further examinations indicate that the failed and the complete caverns have only one difference, as shown in Figs.26 and 40. The complete caverns have the V-type structure with a vertical portal. The failed caverns have the H-type structure with a horizontal portal. Due to the fact that water can flow out of the horizontal portal, the failed caverns could not be fully filled with water, as shown in Figs.34–39. On the other hand, due to the fact that water cannot flow out of the vertical portal, the complete caverns could be fully filled with water, as shown in Figs.3, 10, 11, 21 and 22. The water in the complete caverns can fully immerse their surrounding rocks including the inclined rock roofs, while the water in the failed caverns can only partially immerse their inclined rock roofs, which is the main difference between the complete and failed caverns.

Consequently, it can be concluded that the full water occupation of the complete caverns is the key natural factor that has made them stable and kept them integrity for more than 2 000 years. The full water in the complete caverns can function as a completely flexible support material to the surrounding rocks. Results of the numerical analysis in Fig.47 have shown that the full water support can reduce the stress level and deformation of the surrounding rocks [14]. Furthermore, it can offer a sealed and static environment against physico-chemical weathering to the surrounding rocks. Consequently, the rock caverns were stable and complete, and their carved imprints could also keep sharp and vivid, as if they were recently made (Figs.28–32, 43 and 48).

7.2 Analysis and answer to Question B

When water was pumped out of the five complete caverns No.1–5 in 1992 and the three complete rock caverns No.6–8 later, almost no cracks were observed with naked eyes on the rock surfaces of their sidewalls, ceilings and rock pillars. In other words, the interior rock surfaces were free of old cracks.

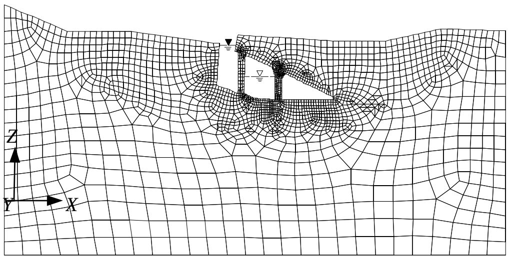


Fig.47 Numerical modeling of water effects on stress and deformation fields in surrounding rocks of the complete rock cavern No.2.

Fig.48 Severely weathered rock surface with blocky cracks exposed above water.

However, since 1992, more and more new cracks have been quickly initiated and developed in the rock surfaces of the sidewalls, pillars and ceilings associated with the five unwatered complete rock caverns No.1–5, as the cracks shown in Figs.49–51. A summary of the new cracks and failure conditions in the five unwatered complete rock caverns No.1–5 is given in Table 7.

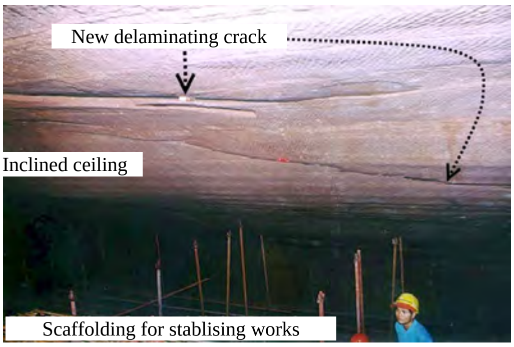
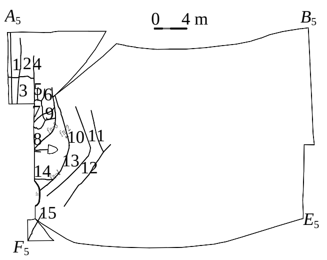


Fig.49 Newly developed cracks delaminating inclined ceiling rocks in complete rock cavern No.3.



No.	Attitude (°)	(°)	Characteristics
1	15	75	L = 7.5 m
2	15	75	L = 7.0 m
3	50	60	L = 3.3 m, bending flexure
4	20	75	L = 4.8 m
5			L = 1.4 m
6	210	22	L = 3.5 m, bending flexure
7	235	51	L = 3.0 m, bending flexure
8	40	16	L = 3.3 m, shaped
9	220–260	43–55	L = 12.3 m, shaped
10	10	8	L = 4.7 m
11	275	72	L = 8.7 m
12			L = 2.3 m
13	26	50	L = 3.4 m
fn-1	40	16	L = 8 m, b = 30–40 m
fn-2	45	14	L = 12 m, b = 1–6 m
fn-3			L = 6.3 m, shaped b = 20–40 m

Fig.50 New cracks initiated and developed on the rock surface of the inclined ceiling near the vertical portal A_5 to F_5 of the complete rock cavern No.5 (after Li et al. [16]).

Fig.51 Seepage and new calcareous sinter from new cracks on rock wall of the complete cavern No.2.

Table 7 New cracks and failures in surrounding rocks of the complete rock caverns No.1–5.

Cavern No.	Descriptions of new cracks, failures and deformation initiated and developed since 1992
1	Fractures and seepage developed in sidewalls and ceiling. The northern sidewall, the rock pillar P11 and the ceiling above P11 initiated and developed fractures seriously
2	Severe deformations occurred in southern sidewall. Fractures developed in ceiling near the southern sidewall. Long and wide fractures developed in northern ceiling
3	Severe deformation developed in southeastern ceiling. Severe deformation occurred in pillars P31 and P32. Two pillars were reinforced. Many fractures developed in ceiling between two pillars
4	Fractures with dislocation movements developed in western sidewall. The western sidewall and rock pillar P41 were reinforced
5	Severe weathering developed in cavern portal. Shear fractures developed in upper portion of rock pillar P51. Small rock block falls occurred at intersection zones of western sidewall, rock pillar P52 and ceiling

Furthermore, it can be sure that the construction took a long time. During the construction, the empty caverns would initiate and develop cracks because the argillaceous siltstone has low tensile and shear strengths [50]. They might also experience droughts. The water drawdown could cause the roof rocks to be exposed in air and unsupported by water when cracks could develop in the ceilings.

Hence, Question B needs to be addressed.

A hypothesis has been proposed to answer the question and explain the phenomena. It is about self-healing of cracks in argillaceous siltstone immersed in static or no-flow water with weak acidity. The argillaceous siltstone immersed in weak acid water has the ability of self-healing of its hairline cracks within a short period of time. Therefore, the old cracks developed on the cavern surface rocks were self-healed over the years when the caverns were fully filled with rain water. As a result, the cavern rocks were free of old cracks at the time when their water was pumped out in 1992 or later.

This hypothesis is consistent with the field observations of many calcareous sinters developed in new cracks in association with seepage in the interior rocks of the five unwatered complete caverns (Fig.51).

The new quickly developed calcareous sinters can be considered as an indicator for crack self-healing. Moreover, the water in Qujiang River and the seepage water in the complete caverns No.1, 3, 6 and 24 were tested to have pH values of 5.0–6.3, showing that the water had a weak acidity. After the rock specimens were put into distilled water, the water's pH values became 8.50–9.30 [45–47]. Similarly, after the rock specimens were put into weak acidity water with a pH value of 6.6, the water's pH value was increased to 7.9 [18].

These test results demonstrate that the argillaceous siltstone is of weak alkalinity. Therefore, when it is immersed in weak acid water for some time (few months to a few years), the argillaceous siltstone would be able to make chemical reactions generate new minerals such as calcite. Since rainfall and seepage water can continuously fill into the caverns, such chemical reactions would not stop. The generation of more and more new minerals would be able to infill the cracks and then heal the cracks with time. Further investigation is needed to valid this hypothesis.

7.3 Analysis and answer to Question C

The eight facts and/or arguments are summarized below for addressing Question C. (1) As discussed above, the rock cavern site is a stable site in terms of engineering geology. (2) The seismic activity in Quzhou—Jinhua Basin is inactive. From 1513 to now, three earthquakes of magnitudes less than 6 were recorded. (3) Under a subtropic trade wind climate, the site has abundant precipitations with an annual rainfall of 1 542–1 763 mm. Consequently, the rock caverns can be always fully filled with water and the groundwater table in the small hill is high. (4) The argillaceous siltstone is thick and develops very limited discontinuities. So, it has a very low permeability. Hence, water can be maintained in the rock caverns for very long time. (5) The saturated rock can have much low values of elastic modulus and much high ductility against brittle fractures. Naturally, as discussed above, the full water occupation protected the surrounding rocks of the complete rock caverns from brittle fracture failures. The brittle fracture failures were initiated and developed more and more in the surrounding rocks after the complete rock caverns were empty in 1992. (6) As discussed in Section 6, the caverns were carefully designed and constructed with manual carving method, which induced little excavation disturbed zone [51]. (7) The complete caverns with the V-type structure were constructed in the small hill site with the ground level generally 10 m lower than the ground level where the fourteen failed rock caverns with the H-type structure were located (Figs.5, 28, 40). Hence, the full water occupation could happen in the ten complete rock caverns. (8) The rainfall is of weak acidity while the rock is of weak alkalinity, which can cause the chemical reaction for generation of new minerals to self-heal cracks in the rocks.

These eight facts or arguments seem to give a positive answer to Question C. However, the following evidences and analyses do not support this positive answer.

As discussed above and shown in Figs.29, 32 and 33, water traps, drainage channels and staircases are present in the complete rock caverns No.1–5. The traps, channels and staircases were constructed in the in-situ argillaceous siltstone and were intrinsic parts of the caverns. Therefore, they were originally constructed. Hence, the rock water traps and drainage channels can be the evidence to show that the ancient people tried to dry the caverns or use the caverns in dry conditions. The rock staircases can be the evidence to show that the ancient people tried to foot in the caverns. So, the caverns had to be free of water.

Consequently, the answer to Question C is that the ancient people did not have plans to design and construct the caverns for their stability and integrity over 2 000 years. The relics of the complete rock caverns are a consequence of coincidental combinations of human effort and natural factors. Therefore, the relics are invaluable to science.

7.4 Analysis and answer to Question D

Since 2001, emergent protection measures such as anchoring, sprayed concreting, buttress walls, dewatering, and surface drainage provision have been used to protect the unwatered complete rock caverns No.1–5 [1, 4, 6, 8, 11, 13, 14, 16, 52, 53]. An example is shown in Fig.52. However, such protection measures cannot stop the crack development in the surrounding rocks.

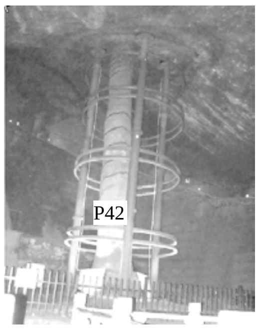


Fig.52 Steel structure supporting measure for rock pillar P42 in the complete rock cavern No.4.

As shown in Fig.53, the originally partially failed rock cavern No.24 collapsed entirely and formed a sinkhole in the ground in the afternoon of September 30, 2010. The collapsed roof rock volume was about 250 m^3. The rock mass fell into the water pool and surged up a heavy wave. Prior to the roof collapse, small size delaminating collapses in the ceiling occurred for ten times.

Fig.53 New roof rock collapse with a plane area of 75 m^2 of the originally partially failed rock cavern No.24.

Hence, the safety for people touring the complete caverns No.1–5 is an issue pending adequate solutions. The long-term stability and integrity of the unwatered complete rock cavern relics are also concerned to many people. We would be extremely sad and sorry if the whole roof collapse in Fig.53 could soon happen to the complete rock caverns No.1–5. We do not want to see such disasters to occur although partial failures have occurred to them. Therefore, we must address Question D.

The answer is clear now. The answer to the five un-watered complete caverns No.1–5 is no. They would completely collapse if they are not effectively protected and preserved soon. The answer to the other five complete rock caverns No.6–8, 16 and 17 is yes, since they are still fully filled with water. They would be stable and maintain their integrity for next 2 000 years if they are not disturbed by human beings and strong earthquakes.

Many protection and preventive measures have been applied to the complete rock caverns No.1–5. However, their long-term stability and integrity are still an urgent issue. It is necessary to investigate the effective and efficient methods to protect and preserve the five unwatered complete rock caverns No.1–5. Refilling water into them can be one of the methods.

8 Concluding remarks

In the above, a comprehensive summary of the data, analyses and findings has been presented on the mechanics of the relics of large Longyou rock caverns. These information, analyses and findings have demonstrated that the relics are invaluable to culture, engineering and science. They have extended and enriched our experience and knowledge on long-term (over thousand years) stability and integrity of man-made underground rock cavern engineering projects. Long-term protection and preservation of the large rock cavern relics are of national and international interests and importance.

However, the relics of the five unwatered complete, large and elegant rock caverns No.1–5 are in danger of entire collapse in the near future. It would be a tragedy if such entire collapse happens to one of the five relics. We urge herewith to investigate effective measures to preserve the relics from cracking and collapsing.

Furthermore, Needham [54] studied and investigated the science and technology in ancient China. It seems that the projects of large underground rock engineering in ancient China are not documented in his treatises [54]. The present work can be useful for the treatises (new edition) to include large ancient rock caverns in China such as the Longyou cavern relics.

Acknowledgements

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References

[1] Yang Zhifa, Wang Sijing, Xu Bing, et al. Analysis of the engineering geological conditions of Longyou stone caverns and primary study on the protection strategies. Chinese Journal of Engineering Geology, 2000, 8 (3): 292–295 (in Chinese).

[2] Yang Zhifa, Li Lihui, Pan Wei, et al. Discussions about large-scale ancient underground engineering. Science Technology and Engineering, 2003, 3 (5): 464–466 (in Chinese).

[3] Yang Zhifa, Li Lihui, Zhang Luqing, et al. On the back analysis of long-term shear strength of No.4-2 rock pillar in the No.4 cavern of Longyou caverns. Journal of Engineering Geology, 2005, 13 (1): 62–67 (in Chinese).

[4] Li Lihui, Mu Huichong, Yang Zhifa, et al. Engineering geological conditions and diseases of Longyou large ancient underground caverns. Journal of Hunan University of Science and Technology (Natural Science), 2004, 19 (3): 18–22 (in Chinese).

[5] Li Lihui, Yang Zhifa, Zhang Luqing, et al. A discussion on the inclined roof design of Longyou caverns for engineering sciences. Chinese Journal of Rock Mechanics and Engineering, 2005, 24 (2): 336–343 (in Chinese).

[6] Li Lihui, Yang Zhifa, Yue Z Q, et al. Deformation and failure modes and reinforcement methods of ancient cavern group in Longyou

County. Chinese Journal of Rock Mechanics and Engineering, 2005, 24 (12): 2 018–2 028 (in Chinese).

[7] Li Lihui, Mu Huichong, Yang Zhifa, et al. Engineering geological and hydrogeological conditions of caverns No.1–5 shallow in Longyou. Journal of Engineering Geology, 2005, 13 (2): 206–211 (in Chinese).

[8] Wang Zhiyin, Yang Zhifa, Li Yunpeng,et al. Numerical simulation and back analysis of rheologic fracture process of Longyou grotto roof. Chinese Journal of Rock Mechanics and Engineering, 2006, 25 (1): 9–14 (in Chinese).

[9] Guo Gaimei, Yang Zhifa, Tao Bo. Back analysis of the long-term tensile strength of a rock pillar in Niuchang ancient underground caverns in Longyou County. Journal of Engineering Geology, 2006, 14 (4): 449–453 (in Chinese).

[10] Guo Gaimei, Yang Zhifa, Tao Bo, et al. Estimation of Long-term tensile strength of roof in cave No.1 of Niuchang ancient underground caverns, Longyou, Zhejiang Province. Journal of Jilin University (Earth Science), 2007, 37 (4): 783–788 (in Chinese).

[11] Gao Qian, Wang Jing, Yang Zhifa, et al. Stability analysis of the large ancient underground rock caverns in Longyou and the selection of maximum-security routes in the caverns. Rock and Soil Mechanics, 2009, 30 (9): 2 713–2 721 (in Chinese).

[12] Zhu Jiewang, Bai Song, Liu Encong, et al. Mechanics idea about Longyou grottoes structure. Rock and Soil Mechanics, 2008, 29 (9): 2 427–2 432 (in Chinese).

[13] Zhu Jiewang, Chang Zhonghua, Liu Encong, et al. Failure causes and reinforcement countermeasures for grotto No.1 of Longyou grottoes. Journal of Engineering Geology, 2009, 17 (1): 126–132 (in Chinese).

[14] Yang Zhifa, Yue Z Q, Li Lihui. Scientific and technological problems of large ancient underground cavern groups of Longyou grottos. Beijing: Science Press, 2010 (in Chinese).

[15] Guo Gaimei, Li Lihui, Yang Zhifa, et al. Weathering mechanism of the Cretaceous argillaceous siltstone caverns, Longyou, China. Bulletin of Engineering Geology and the Environment, 2005, 64 (4): 397–407.

[16] Li Lihui, Yang Zhifa, Yue Z Q, et al. Engineering geological characteristics, failure modes and protective measures of Longyou caverns of 2 000 years old. Tunnelling and Underground Space Technology, 2009, 24 (2): 190–207.

[17] Yue Z Q, Li Lihui, Yang Zhifa, et al. An investigation on long-term stability and integrity of surrounding rocks in Longyou caverns caved 2 000 years ago. In: Proceedings of the 11th Congress of the international Society for Rock Mechanics (ISRM 2007). Lisbon, Portugal: Taylor & Francis, 2007: 19–22.

[18] Yue Z Q, Fan Shaopeng, Yang Zhifa,et al. A hypothesis for crack free interior surfaces of Longyou caverns caved in argillaceous siltstone 2000 years ago. Frontiers of Architecture and Civil Engineering in China, 2010, 4 (2): 165–177.

[19] Hudson J A Comprehensive rock engineering: principles, practice, and projects. Oxford: Pergamon Press. 1993.

[20] Goodman R E. Introduction to rock mechanics. 2nd ed. New York: John Wiley and Sons, Inc., 1989.

[21] Wang Sijing, Yang Zhifa, Fu Bingjun. China rock mechanics and rock engineering: century achievements. Nanjing: Hohai University Press, 2004: 966.

[22] Nguyen T S, Selvadurai A P S. Coupled thermal-mechanical-hydrological behavior of fractured rock—implications for nuclear-fuel waste-disposal. International Journal of Rock Mechanics and Mining Sciences, 1995, 32 (5): 465–479.

[23] Hudson J A. Rock mechanics studies for disposal of radioactive waste in the UK: 1979–1999. In: Proceedings of the International Workshop on the Rock Mechanics of Nuclear Waste Repositories. Colorado, USA: [s.n.], 1999: 229–258.

[24] Wang Ju. High-level radioactive waste disposal in China: update 2010. Journal of Rock Mechanics and Geotechnical Engineering, 2010, 2 (1): 1–11.

[25] Gens A, Guimarães L do N, Olivella S, et al. Modelling thermo-hydro-mechano-chemical interactions for nuclear waste disposal. Journal of Rock Mechanics and Geotechnical Engineering, 2010, 2 (2): 97–102.

[26] Yang C H, Li Y P, Qian Q H, et al. Usability evaluation of the existing solution-mined caverns for gas storage. In: Mechanical Behavior of Salt–Understanding of THMC Processes in Salt. [S.l.]: [s.n.], 2007: 399–400.

[27] Li Zhongkui, Wang Kezhong, Wang Anmin, et al. Experimental study of water curtain performance for gas storage in an underground cavern. Journal of Rock Mechanics and Geotechnical Engineering, 2009, 1 (1): 89–96.

[28] Lu Ming. Rock engineering problems related to underground hydrocarbon storage. Journal of Rock Mechanics and Geotechnical Engineering, 2010, 2 (4): 289–297.

[29] Talesnick M L, Hatzor Y H, Tsesarsky M. The elastic deformability and strength of a high porosity, anisotropic chalk. International Journal of Rock Mechanics and Mining Sciences, 2001, 38 (4): 543–555.

[30] Hatzor Y H, Talesnick M, Tsesarsky M. Continuous and discontinuous stability of the bell-shaped caverns at Bet Gurvrin, Israel. International Journal of Rock Mechanics and Mining Sciences, 2002, 39(7): 867–886.

[31] Yang Zhifa, Zhang Luqing, Yue Z Q, et al. Waterproof of rock joint with lead strip for splitting tuff sheet in ancient China quarrying caverns. Science in China (E), 2011 (submitted).

[32] Wieliczka Salt Mine from World Heritage Convention at http://whc.unesco.org/en/list/32, 2011.

[33] Zuber A, Grabczak J, Garlicki A. Catastrophic and dangerous inflows to salt mines in Poland as related to the origin of water determined by isotope methods. Environmental Geology, 2000, 39 (3/4): 299–311.

[34] Basilica Cistern, from Wikipedia the free encyclopedia at http://en.wikipedia.org/wiki/Basilica_Cistern, 2011.

[35] Hatzor Y H, Benary R. The stability of a laminated voussoir beam: back analysis of a historic roof collapse using DDA. International Journal of Rock Mechanics and Mining Sciences, 1998, 35 (2): 165–181.

[36] Li Lihui, Yang Zhifa, Mu Huichong, et al. Engineering scientific highlights of grotto No.3 of Beixiangtang Temple grottoes in Handan. Rock and Soil Mechanics, 2004, 25 (9): 1 460–1 464.

[37] Xia Lingen. Introduction to Longyou history. Lu Min ed. In: Proceedings of Research on Longyou Grottos of the World Ninth Wonder. [S.l.]: [s.n.], 1999: 1–6 (in Chinese).

[38] Sun Jun. Examining the Longyou Grottoes from the view point of engineering science. News Journal of China Society for Rock Mechanics and Engineering, 2001, 53: 3–7 (in Chinese).

[39] Sun J, Ling J M, Jia G, et al. China's Longyou grottoes, Zhejiang Province. News Journal of the International Society for Rock Mechanics, 2001, 6 (3): 44–46.

[40] Sun Jun, Ling Jianming, Jia Gang, et al. Examining the Longyou Grottoes in the western land of Zhejiang Province from the view point of engineering science. Chinese Journal of Rock Mechanics and Engineering, 2001, 20 (1): 131–133 (in Chinese).

[41] Wang Sijing. Longyou grottoes—a man-made natural wonder. News Journal of China Society for Rock Mechanics and Engineering, 2001, 53: 8–9 (in Chinese).

[42] Qian Qihu. A summary of speech at the closing ceremony of the Symposium of China's Longyou Underground Ancient Construction Group. News Journal of China Society for Rock Mechanics and Engineering, 2001, 53: 10–12 (in Chinese).

[43] Yang Linde. Discussions on value of Longyou cavern group and preservation research. Yang L D, Yang Z F, Lu M ed. In: Proceedings of the International Symposium on Protection of Longyou Grottoes in China. Beijing: Cultural Relics Publishing House, 2006: 383–387 (in Chinese).

[44] Mei Anxin. Discussions on geosciences values of Longyou grottos. Lu Min ed. In: Proceedings of Longyou Grottos Research. Longyou: [s.n.], 2001: 52–56.

[45] Li Li, Chikaosa T. Research on the argillaceous cement of sandstone at Longyou Grottoes. Journal of Engineering Geology, 2005, 13 (2): 189–194. (in Chinese)

[46] Li Li, Chikosa To. Study of the water-stabilization of the sandstone of the Lonyou grottoes. Sciences of Conservation and Archaeology, 2005, 17(4): 28–33 (in Chinese).

[47] Li Li, Wang S J, Chikaosa T. Study of weathering characteristics of sandstone at Longyou grottoes. Chinese Journal of Rock Mechanics and Engineering, 2008, 27 (6): 1 217–1 222 (in Chinese).

[48] Ding W X, Feng X T, Chen C B. Experimental study on chemical reinforcement of resisting weathering of red sandstone. Chinese Journal of Rock Mechanics and Engineering, 2005, 24 (21): 3 841–3 846 (in Chinese).

[49] Lu Zude, Ding Wuxiu, Feng Xiating, et al. Experimental study on mechano-hydrochemical coupling process in cracked rocks. Chinese Journal of Rock Mechanics and Engineering, 2008, 27 (4): 796–804 (in Chinese).

[50] Qi S W, Yue Z Q, Wu F Q, et al. Deep weathering of a group of thick argillaceous limestone rocks near Three Gorges reservoir, Central China. International Journal of Rock Mechanics and Mining Sciences, 2009, 46 (5): 929–939.

[51] Sheng Q, Yue Z Q, Lee C F, et al. Estimating the excavation disturbed zone in the permanent shiplock slopes of the Three Gorges Project, China. International Journal of Rock Mechanics and Mining Sciences, 2002, 39 (2): 165–184.

[52] Zhang Wangmin, Xiao Chengzhong. Application of anchoring and sprayed concreting techniques to emergent stabilization of Longyou caverns No.4 and 5. China Science and Technology Information, 2006, 17(2): 36–37 (in Chinese).

[53] Zhao Lixin, Xiao Chengzhong. Stability analysis and reinforcement measures for roof rocks at eastern part of Longyou cavern No.3. China Science and Technology Information, 2007, 18 (September): 73–74 (in Chinese).

[54] Joseph Needham. Science and civilization in China Series. Cambridge: Cambridge University Press, 1954: 1 900–1 995.