

Underground Powerhouse Caverns of Jurong Pumped Storage Power Station Analysis of Safety Monitoring Results

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Abstract. The surrounding rock structure of the underground powerhouse of Jurong Pumped Storage Power Station is complex, with unfavorable geological conditions such as argillaceous dolomite bands, karst caves and corrosion fissures. This paper introduces the monitoring instruments and burial arrangements of the two caverns of the main and auxiliary power houses and the main transformer room. Combined with the monitoring results of the two caverns during the construction period, the deformation of surrounding rock and the magnitude of anchor load are analyzed. The results show that the arrangement of the columns between the caverns is reasonable. Compared with the monitoring results of other similar projects, the surrounding rock of the underground powerhouse of Jurong Pumped Storage Power Station is basically stable, with small deformation, and the deformation control measures are reasonable and effective.

Keywords: Pumped Storage Power Station; Underground Powerhouse; Safety Monitoring.

1. Project Overview

Jiangsu Jurong Pumped-storage hydroelectricity is located in Jurong City, Jiangsu Province, 65km away from Nanjing, 36km away from Zhenjiang, and 26km away from Jurong County. The main buildings of the power station hub project are composed of an upper reservoir, a water conveyance system, an underground powerhouse, a ground switch station, and a lower reservoir, with a total installed capacity of 1350MW. The underground powerhouse system is located in the northeast direction of Lunshan Mountain, consisting of two main tunnels (main and auxiliary powerhouse tunnels, main transformer tunnels), busbar tunnels, outlet shafts and adits, access tunnels, ventilation and safety tunnels, drainage corridors and other auxiliary tunnels. Excavation size of the main and auxiliary powerhouse tunnels $246.5\text{m} \times 25.8\text{m} \times 57.2\text{m}$ (length \times wide \times High), excavation size of main transformer chamber $242.35\text{m} \times 18\text{m} \times 22.15\sim 28.85\text{m}$ (length \times wide \times High), with an axis direction of $N62^\circ W$; The two main chambers are arranged in parallel, and the main power house and the main transformer chamber are connected through six bus tunnels. The spatial layout is shown in Figure. 1.

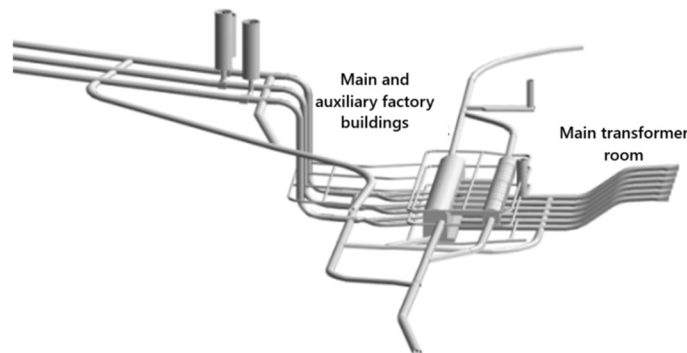


Fig 1. Three dimensional layout of diversion and power generation system of Jurong Pumped-storage hydroelectricity

The underground powerhouse and the main transformer room are characterized by developed faults, small scale, mainly Grade III structural plane, steep dip angle, including fault F45 N40~45 ° W, NE \angle 68 °, width of about 1.7~2.0m, strong alteration, full strong weathering, contact zone of strong weathering, width of 0.3m, Calcite vein densely developed in the zone, located at the upstream of the powerhouse, small intersection angle with the tunnel axis, upstream f32 ($\delta\mu$ 39) Occurrence N50 ° W, SW \angle 80 °, width about 0.5m, intrusion of diorite porphyrite vein, alteration in a silt like state, dissolution of contact surface, transverse cutting of busbar; F38 occurrence: N80~90 ° W, NE \angle 80 °, width: 0.5~1m, filled with red clay and Calcite vein, corrosion width: 5~15cm, passing through the upstream side of the right end wall of the power house; F36 occurrence: N70 ° E, SE \angle 80 °, width 0.2m, contact surface dissolution, red clay filling, inclined through the factory building, with an angle of about 60 ° with the side wall; F34 occurrence: EW, N \angle 80 °, width 0.05-0.3m, dissolution width 2-5cm, filled with red clay. $\delta\mu$ the occurrence of x4 rock veins is N35-45 ° W, NE \angle 70-80 °, with a width of 1-5m. At an elevation of 46.00, the width is 0.5-1.6m. The local stability of the surrounding rock of the underground powerhouse cavern is poor, classified as III1 to III2, and locally classified as IV-V. There are karst caves and hidden karst caves developed at the top arch and arch shoulder of the powerhouse. The length range of Class IV surrounding rock accounts for about 54%, as shown in Figure. 2.

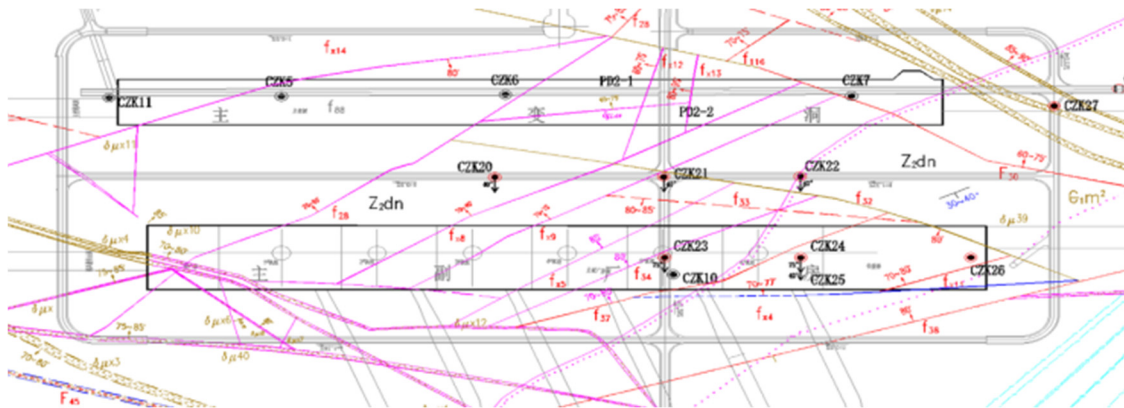


Fig 2. Spatial distribution of rock veins in the underground powerhouse area

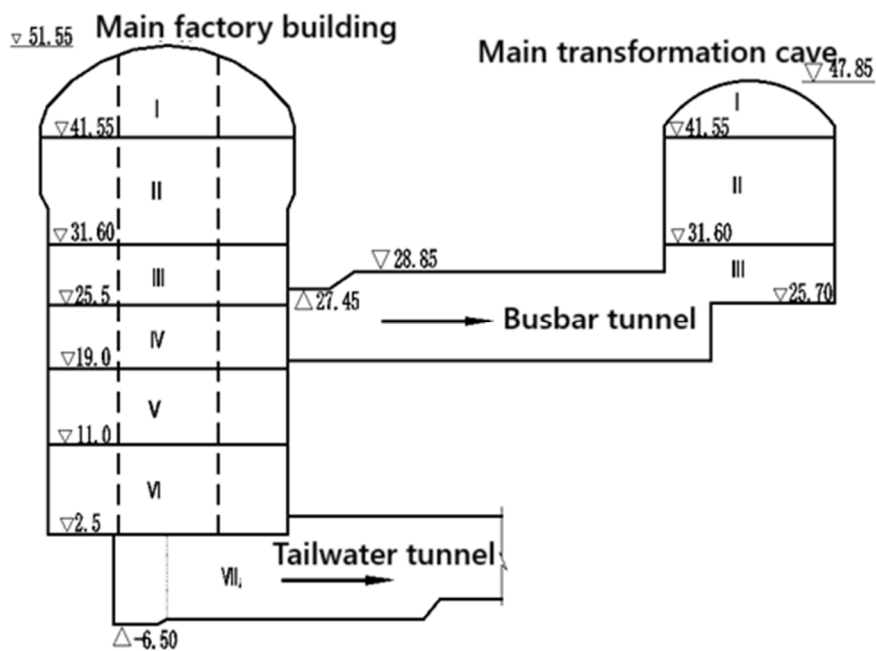


Fig 3. Schematic diagram of layered excavation of underground powerhouse

Layered excavation plan for the main and auxiliary power houses and main transformer rooms: The main and auxiliary power houses are excavated in 7 layers, and the main transformer room is excavated in 3 layers. The excavation depth of each layer is controlled at 6-9m, using the "tunnel (groove) first and then the wall" method. The excavation is divided into three steps, a total of six steps. The excavation sequence of the three steps is: (1) pre cracking of the middle groove, excavation of the middle groove, and (3) excavation of the protective layer and rock platform. The six steps are: 1) (pre cracking of the middle groove edge line) → 2) (slope descent excavation) → 3) (layered excavation of the middle groove) → 4) (excavation of protective layers and rock benches on both sides) → 5) (excavation of left and right end walls) → 6) (demolition of the slope), as shown in Figure 3 for the layered excavation.

2. Introduction to Safety Monitoring Design

Safety monitoring during the construction period of underground power plants, focusing on the relaxation and deformation of surrounding rock, and Support stress monitoring is the main focus, and the number and types of monitoring instruments designed for the two major cave groups are shown in Table 1.

Table 1. Statistics of the Number of Monitoring Instruments Designed for the Two Major Caverns (Unit: Units/Set)

Instrument Type	Multipoint Displacement Meter	Rock Bolt Load Cell	Cable Load Cell	Remarks
Main & Deputy Plant	60	44	37	The multi-point positioner is mainly of the four-point type
Bus Tunnel	1	6	0	The multi-point positioner is mainly of the four-point type
Main Transformer Room	18	17	4	The anchor cable dynamometer is of the rock column penetration type
Total	79	67		The multi-point positioner is mainly of the four-point type
Notes:	General four-point type burial depth is 2m, 7m, 15m, 25m	General two-point type rock bolt load cell burial depth is 2m, 6.0m	General cable length is 20~40m, locking load is 60% of 1500~2000KN	This table does not include rebar meters, rock bolt load cells, joint meters, etc. at the rock anchor beams

The top arch, upstream side wall, and downstream side wall of the main and auxiliary power houses are equipped with 5 monitoring sections at stake positions 0+000.00m, 0+088.00m, 0+140.00m, 0+118.00m, and 0+200.00m, respectively. They are mainly arranged along the direction of limestone, dolomite, fault zones, altered rock veins, and dissolution fractures, and are oblique or orthogonal to the longitudinal axis of the tunnel. The main transformer room is combined into three circular monitoring sections at the 0+000.00m, 0+088.00m, and 0+140.00m stake positions. The top arch, upstream and downstream arch shoulders, and the upstream side walls of the main and auxiliary power houses are all drilled with a displacement meter of ∇ 31.00m from the drainage gallery and pre embedded in place before excavation.

3. Monitoring Results During Tunnel Construction Period

3.1 Surrounding Rock Deformation

The surrounding rock of the main and auxiliary power houses is deformed. Five comprehensive cross-sections were counted with multi-point displacement meters, and 56 sets of orifice displacements were less than 15 mm, accounting for 93.3%. Two orifice displacements were between 15 and 20 mm, with maximum monitoring displacements of 19.61 mm and 20.50 mm, respectively. They occurred at 0+088.00m to the right of the upstream side wall factory, with elevations of ∇ 24.4 m and ∇ 16.5 m. The larger displacement of this section is closely related to the comprehensive influence of adjacent fx5 rock veins, faults, and complex geological structures. The deformation influence depth of the surrounding rock area from III1 to III2 in the main and auxiliary power houses is basically within 7m; In areas with distribution of rock veins, the relaxation deformation of Class IV surrounding rock extends to the middle and deep areas between 7m and 15m in some areas.

The surrounding rock of the main transformer chamber is deformed. 18 sets of multi-point displacement meters were counted for three comprehensive sections, with all hole displacements less than 15mm and a maximum displacement of 8.61mm. The depth of influence of surrounding rock deformation is mainly within 15m.

The busbar hole converges and deforms. Three sections and one set of 4-point displacement meters are set up in the busbar tunnel, with all hole openings displacement less than 5mm.

3.2 Anchor Rod Stress

According to the force statistics of 134 anchor rod measurement points in the main and auxiliary power houses, main transformer rooms, and busbar tunnels, the proportion of 125 measurement points less than 200Mpa is 93.2%; The proportion of 5 measuring points at 200-300MPa is 3.7%; The proportion of 4 measuring points greater than 300Mpa is 2.9%, among which 1 measuring point is subjected to a tensile load exceeding 400MPa (exceeding the design load).

The overall stress of the anchor bolts in the tunnel group is at a moderate level, with the busbar tunnel being relatively low, with measuring points less than 200Mpa accounting for nearly 93.2%. This indicates that the relaxation and disturbance of the shallow rock mass are not severe, and also indicates that the comprehensive control level of blasting excavation is good.

3.3 Changes in Anchor Cable Load

According to the statistics on the load changes of 41 sets of anchor cables in the two major caverns, 58% of them maintain the locked value or below, and 19% of them increase the load by less than 10%. The total proportion of the two is 77%; Four sets of anchor cables have a load growth rate of 15% to 20%. Only one set of anchor cable has a load growth rate of 20.34%, located at 0+200 on the right side of the upstream arch shoulder of the factory building. It indicates that the deep unloading adjustment of the rock mass is not severe.

Statistical analysis was conducted on 9 sets of anchor cables in the main and auxiliary power houses and 2 sets in the main transformer room. Among them, 6 sets had a load loss of less than 7%, 4 sets had a load increase of 7-9%, and 1 set had a load increase of 14.21%. The monitoring data for the anchor cables was generally stable, indicating that the rock column area, as the core area for rock mass stress adjustment in the tunnel group, is generally stable.

3.4 Comprehensive Analysis of Monitoring Results

Evaluation of the deformation of surrounding rock and the magnitude of anchoring load. According to the above statistical results, 93.3% of the measurement points have deformation of less than 15mm in the surrounding rock of the two major caverns, 93.2% of the measurement points have a force of less than 200Mpa on the anchor rod, and 77% of the measurement points have a change rate of anchor cable load within \pm 10%; The overall deformation of the surrounding rock is not high,

and the vast majority of anchor rod forces and anchor cable loads are within the normal design load; Only local rock veins have significant deformation in the affected area.

Characteristics of deformation trend of surrounding rock. The accumulated deformation of the multi-point displacement meter cf-0+088-7 at EL.16.0m on the right side of the main and auxiliary power houses is 20.50 mm, as shown in Figure 4 for the process line. The Force meter of the anchor cable at this position is Dpcf-0+088-3, and the anchor force accumulatively increases by 11.16%. See Figure 5 for the process line. The anchor stress gauge Rcf-0+088-4 at this location has a cumulative stress value of 226.07Mpa at a measuring point 6m from the orifice, as shown in Figure 6 for the process line.

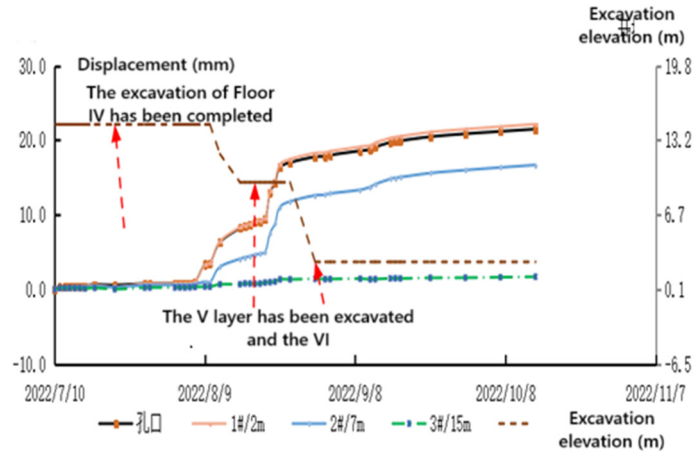


Fig 4. Displacement hydrograph of multi-point displacement meter Mcf-0+088-7

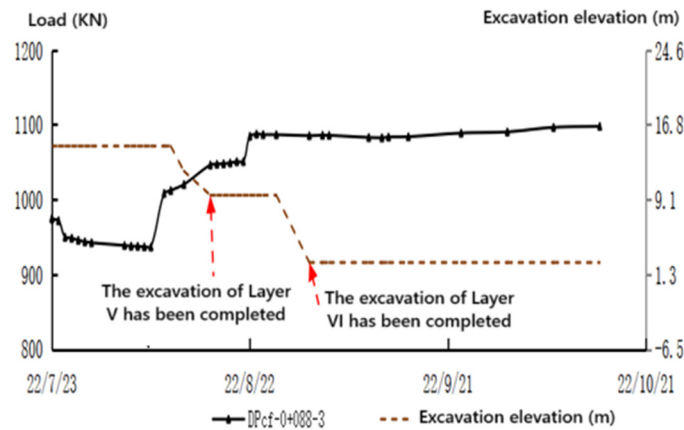


Fig 5. Process Line of Anchor Cable Force meter Dpcf-0+088-3

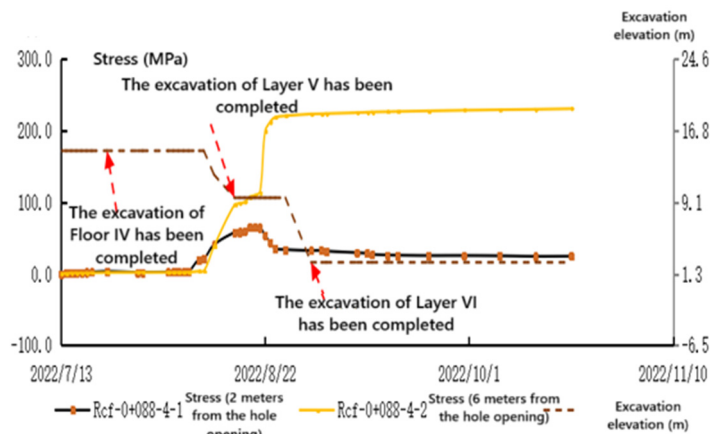


Fig 6. Stress Change Process Line of Anchor Rod Stress Meter Rcf-0+088-4

The deformation of the surrounding rock of the engineering cavern is mainly caused by the "excavation space effect". From the process lines in Figures 5 and 6, it can be seen that with the layered blasting excavation of the tunnel, most of the surrounding rock deformation shows a "stepped shape", and the excavation impact near the monitoring section is relatively significant.

The deformation of the surrounding rock shows a certain degree of timeliness in the areas affected by the rock vein structure, that is, the tunnel is in a standstill period of excavation, and there are still small incremental changes in the multi-point displacement meter. From the comparison of Figure 4, Figure 5, and Figure 6, it can be seen that as the factory building is excavated layer by layer, the deformation of the surrounding rock is synchronized with the increase of anchor cable load (such as on August 21-22, 2022, the cumulative amount of multi-point displacement meter increased from 9.44mm to 13.02mm, with a daily variation of 3.58mm, and the tensile stress of anchor cable measurement at the same location increased from 1050kN to 1084kN, with a daily variation of 34kN); Explain the effectiveness and necessity of anchor cable reinforcement measures.

The impact of geological conditions. The spatialization of the deformation results of the surrounding rock of the 15 comprehensive monitoring sections of the two major caverns shows that the areas with large displacements are closely related to the identified rock veins and structural distribution.

The comprehensive monitoring section of the main power house is 0+088.00m, with local falling blocks and significant deformation (14.81-18.45mm) of the upstream side wall ∇ 31.0m, which is related to faults and corrosion cracks in this area; The area has been reinforced with support The comprehensive monitoring section of the main power house is 0+088.00m, and the upstream side wall has a large relaxation deformation of ∇ 16.5m (16.67~20.50mm). The displacement of the measuring points is mainly manifested as deep movement, which is directly related to the fx5 rock veins, faults, and dissolution fractures distributed in the area. 3) The comprehensive monitoring section of the main power house is 0+200.00m, and the upstream arch shoulder is ∇ 48.33m with significant relaxation deformation. The anchor cable load is under tension, and the stress growth rate reaches 20.34%, which is related to the influence of wider fault zones and altered rock veins. 4) The comprehensive monitoring sections of the main transformer room at 0+088.00m and 0+140.00m are affected by dolomite, fault zones, and altered rock veins, resulting in slightly larger displacement of the arch shoulder and upstream side walls (8-8.61mm). 5) From a comprehensive perspective of upstream and downstream, the connection of dolomite and altered rock veins has affected the three monitoring sections of the main power house and main transformer chamber; The deformation of large surrounding rocks is closely related to geological structures.

4. Comparison and Analysis with Similar Projects

4.1 Maximum deformation of surrounding rock

From the basic data of the underground power houses of four similar power plants and the statistical table 2 of the maximum surrounding rock deformation, it can be seen that the displacement of the main and auxiliary power houses in Jurong is 20.50 mm, and the displacement of the main transformer room is 8.61 mm. The overall deformation is relatively small.

4.2 Deformation Characteristics of Surrounding Rock

The deformation of the surrounding rock of the Jurong Power Station shows a significant "step like" shape, indicating that the spatial excavation effect is dominant, and the "time effect" is not obvious. After excavation stops, it quickly tends to converge; With such deformation characteristics, it is necessary to strictly control the scale and degree of layered blasting excavation, otherwise it is easy to cause sudden large displacement of the rock mass.

Table 2. Maximum deformation of surrounding rock in the caverns of two power stations

Project Location	Power Station Name	Max Deformation (mm)	Monitoring Point Location
Main Plant	Jiangsu Yixing Tongangu Mountain	23.19	Top middle of the left bank upstream side wall at 0+005 of the plant
	Anhui Xiangshui River	20.68	Lower middle of the right bank downstream side wall at 0+064 of the plant
	Jiangsu Jurong	20.50	Lower middle of the left bank upstream side wall at 0+088 of the plant
	Anhui Jinzhai	16.23	Middle of the right bank wall
Main Transformer Room	Jiangsu Yixing Tongguan Mountain	8.85	Middle of the right bank downstream side wall at 0+048 of the plant
	Anhui Xiangshui River	28.01	Middle of the left bank upstream side wall at 0+064 of the plant
	Jiangsu Jurong	8.61	Middle of the left bank upstream side wall at 0+088 of the plant
	Anhui Jinzhai	6.66	Lower middle of the right bank downstream side wall at 0+42 of the plant

4.3 Stress Deformation of Rock Column Area

The rock column between the two major caverns is the core area for adjusting the stress of the surrounding rock, and the spatial distribution of the deformation of the surrounding rock shows that the deformation of the middle and lower parts of the side walls of the main power house and main transformer chamber is significantly larger.

The deformation of the surrounding rock column of the Jurong Power Station cavern group is within 15mm, and the influence and extension depth of the surrounding rock deformation do not overlap. The load variation of 11 sets of anchor cables is within $\pm 8\%$, and the overall stability of the cavern is achieved. The large deformation of the surrounding rock is mainly caused by the opening/dislocation/relaxation of the geological structural plane, and the deformation of the surrounding rock is mainly caused by the continuous compression failure of the rock mass.

For the "key blocks" formed by the main geological structural planes/rock veins, the design geological department should predict in advance, strengthen inspections by all parties during construction, and take corresponding reinforcement measures in a timely manner. This project has implemented special reinforcement measures for arch shoulders, side walls, etc. in areas with unfavorable structural planes such as muddy rock veins, faults, karst caves, and corrosion cracks.

5. Conclusion

Through statistical analysis of the monitoring data of the Jurong underground powerhouse, it was found that the deformation of surrounding rock, anchor stress, and anchor load changes showed overall consistency in terms of quantity, trend, and statistical law. This indicates that the monitoring results truly reflect the deformation of surrounding rock and anchor stress status of the tunnel group during the construction period. At present, the excavation of the main underground powerhouse of Jurong Power Station has been basically completed, and the deformation of the main surrounding rock is gradually stabilizing.

Compared with other similar underground engineering excavation monitoring results, the overall deformation level of the surrounding rock of the tunnel group in this project is relatively low, indicating that the deformation of the surrounding rock during the excavation process has been well controlled; At the same time, it also indicates that the layout of underground powerhouse tunnels is relatively reasonable and the depth of layered excavation is more suitable. The blasting excavation, progress control, and reinforcement measures are relatively reasonable.

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