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Study on External Protective System of Waterproofing Refuge Chamber in Guilaizhuang Gold Mine

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ABSTRACT
Refuge chamber, which have a positive impacts on facilitating escape for miners trapped underground by a fire, explosion, or rock collapse, need further perfection and research with respect to waterproofing function at present in China in case of mine floods. A waterproofing refuge chamber, designed for the survival of 50 miners for at least 96 hours, along with its waterproofing, airtight, and other essential requirements has been proposed in Guilaizhuang gold mine in Shandong province. Focusing on the external protective system of the water-proof refuge chamber, critical items (including the water-proof door, bulkhead, and lining) are systematically presented in this paper. Specifics like exhausting and draining under water, were also take into consideration in the research. Accordingly, a waterproofing evacuation unit, emergency evacuation unit, and emergency drainage unit were designed. Tests and simulation results indicated that the refuge chamber had good positive pressure maintenance, air-tight property, and water-proof performance.
KEYWORDS: water-proof protective refuge chamber; external protective system; protective performance; field test; simulation analysis

1. INTRODUCTION

Refuge chamber, constructed by concrete and flame retardant inflatable material, equipped with sufficient breathable air, adequate foods and water, reasonable carbon dioxide scrubbing and temperature control (MSHA, 2008), have a positive impact on facilitating escape for miners trapped underground by a fire, explosion, or rock collapse (Saleh, 2011). Current researches in the field has mainly discussed the protective characteristics in cases of gas outburst, fire, and explosion emergencies in underground mines (Gao, 2013;Meyr Jr, 2013). As investigated, a significant amount of non-coal mines, especially those located in north, south, and south-west of China, are under complex hydrological-geological condition. In addition, most mines are continuously digging into deeper mining, where the risk of water burst increases as the depth of the tunnel increases (Xing, 2010). Thus, current emergency refuge technology needs further perfection and research with respect to the water-proof function to improve its applicability and safety.

In this paper, a water-proof refuge chamber was proposed in Guilaizhuang gold mine in Shandong province according to the practical situation in the underground mine . It was designed for the survival of 50 miners for at least 96 hours. This paper focuses on its external protective system. Compared with current refuge chamber in China, the water-proof function and both anti-hydrodynamic pressure and anti-penetrability performance were taken into consideration in this case. Critical items (water-proof door, bulkhead, and lining were included), as well as some specifics items (like exhausting and drainage in flood scenario) were systematically studied and presented in the paper. Then, site tests and simulation through ABAQUS software were carried out to verify the protective performance.

2. ESSENTIAL REQUIREMENTS

Based on an overall consideration of geological conditions, major hazard and accident underground, production status and mining plan, as well as current escape and rescue plan, the refuge chamber was set adjacent to the main roadway at the absolute altitude of –150 m, and 200 m away from the eastern mining boundary. Essential requirements were as follows:

(1) Capacity & Size

When in water inrush or other emergency case, miners should preferentially escape from the harmful environment to above ground; refuge chamber are for those miners trapped underground (Brake, 1999). According to statistical data of underground workers, up to 46 miners can be counted as protective objects.

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Thus, the refuge chamber was designed for the survival of 50 miners for at least 96 hours, with a reserve factor of 1.2.

According to relevant regulations (State Administration of Work Safety, 2011), refuge chamber should contain two entrances, a living zone area of no less than 60 m^2, and a transition zone should be more than 3 m^2. Considering the width of devices and operability, dimensions of the living zone profile are 4500 mm × 3500 mm (net width × net height), with an available area of 81 m^2, while the transition zone area is 2700 mm × 2700 mm, and 27 m^2 respectively.

(2) Waterproofing

Guilaizhuang gold mine, once a open pit surface mine, has been transferred to underground mining. The nearest entrance is at the elevation of -30 m. According to the geologic investigation report, this mine is under medium-complicated hydrologic condition. Uncertain quantity of karst caves, existing at an elevation of approximately -30m and recharged by atmospheric precipitation, were the main sources of inflows into the mines. Table 1 tabulates mine inflow rate of each main roadway.

Table 1: Mine inflow rate of each main roadway.

Elevation of roadway (m)	Aquifer thickness (m)	Drawdown (m)	Inflow rate (m^3/d)
-50	42.77	180.13	9100
-100	52.77	230.13	12353
-150	56.07	280.13	14553

The vertical distance from the aquifer and nearest entrance to the refuge chamber is 120 m. Assuming an inundated case with reserve factor of 1.2, the refuge chamber is expected to resist 1.5 MPa hydrodynamic load. As there is electrical equipment, food, water and other components stored inside, the water-proofing protection grade of the refuge chamber should be at level two (no water penetration is acceptable, damp area should be less than 2‰ tolerable), according to Chinese National Standard GB 50108-2001 (MOHURD, 2008).

(3) Other requirements

Other requirements include: airtight, high temperature and fire resistant; functions of gas monitoring, warning alarm, telecommunication and signaling transmission; adequate power, energy, food, water and first aid tools; proper components for basic survival needs. (State Administration of Work Safety, 2011).

3. WATERPROOF CONSTRUCTION & AUXILIARY FACILITIES

3.1 Door & Bulkhead

Over-sized or over-weight doors may increase operation difficulty and even cause failure to open or close the door for the miners injured in the accident. Thus, a thin-shell water-proof door (ML type, Wuhan Mingqing Environmental Protection Engineering Technology Co., Ltd) with dimension of 1500mm *W* × 1800mm *H* was applied in this case. The doorframe, an I-shaped composite frame structure, and door leaf, stiffened thin-shell structure with square rubber strip mounted around, were wedged by a cuneiform slide block mechanism to achieve the expected sealing requirement. As tested underground, the average time to fully open then close the door with two miners was in the range of approximately 4 to 6 minutes. During the incident, trapped sediment with the water flow would lead to leakage through the gap between the doorframe and leaf. Thus, to reduce the likelihood of such sediment retention, the floor of the refuge chamber was designed to be 500 mm higher than the outer roadway floor, and a 200 mm high threshold was set.

Water-tight bulkhead, expecting to withstand 1.5 MPa water pressure, was designed as a wedge-shaped reinforced concrete structure, with a thickness of 1000 mm (determined by calculation on the basis of shear strength theory and compressive strength theory). Available experiences have suggested that seepage in poured concrete structures often occurred at cracks or pipe penetrations. Thus to maintain integrity of the wall, the embedded through-pipes, which were installed in-situ during the casting of the concrete, were all designed as U-shape, passing through under the wall. All the through-pipes were sealed carefully with expanding water bar and sealant. Rigid water-proofing casing was adopted for exhaust, compressed-air-supplying, water-supplying, drainage, and reserved pipes; while flexible water-proof casing was adopted for those power cable through-pipes. The distances from the pipe to wall angle and between adjacent through-pipes were designed under the requirements of technical code for waterproofing of underground works (MOHURD, 2008).

3.2 Supporting structure

The cross-section of the refuge chamber was a classic three-centered arch, and the composite shell lining, which consisted of a supporting layer and water-proofing layer, was applied. The supporting layer was designed to take ground load or other load, while the waterproofing layer was mainly for water-proofing and air-tight purpose.

(1) Supporting layer

Based on engineering analogies, the main parameters for the supporting layer were listed as follows: anchor, made of deformed steel bar with one direction of screw thread rotating leftward and without longitudinal bar (Φ 20 mm × 2400 mm) , was installed according to the distribution of 800 mm × 800 mm (row × column); primary sprayed concrete lining was constructed with 50 mm thick concrete (intensive grade of C25); secondary sprayed lining was of 100 mm thickness, with reinforcement of steel bars (Φ 10 mm) at a grid of 150 mm × 150 mm; third poured concrete lining was constructed by C30 concrete, with a thickness of 100 mm.

(2) Waterproofing layer

The waterproofing lining was constructed of water-tight concrete (strength grade: C40; impermeability grade: P8) and steel mesh (Φ 10 mm), with the main reinforcement of 300 mm × 300 mm grid, and connecting reinforcement of 600 mm × 600 mm grid. The thickness of lining was 350 mm (calculated by thick wall cylinder theory).

Self waterproofing components (wall and water-proofing layer) are the main part to resist potential harmful substance from outside, their actual performance can be influenced by several factors (Qi, 2007):

- Anthropic aspects like improper design or maintenance, construction quality dissatisfaction, etc.;
- Environmental aspects like high temperature fume, harmful gases, mineral water, impulsion pressure, and drilling-and-blasting operations nearby, etc.;
- Inherent defects of concrete, which would gradually grow with time and cause structural performance deterioration.

Among the mentioned factors, anthropic implications can be controlled by reasonable designation and management. However, being involved in complex disaster surrounding, concrete performance, especially permeability, may decrease afterwards, and further causing structural damage. Both watertightness and airtightness would be affected. This will be fully studied in the future.

3.3 Auxiliary facilities

(1) Water-proof evacuation unit

Overpressure relief valve, of which the outlet installed at a height of 0.5 m above the floor of the refuge chamber, was used for regulating pressure inside the refuge chamber. It is possible that water outside could flow inside through the valve in the event of water inrush. Thus, a particular designed evacuation unit, composed of a controlling component (consisted of hydrostatic release unit, guide sleeve, piston, cylinder barrel, etc.), brake valve (installed out of the refuge chamber), and pressure release valve (installed inside the refuge chamber), was mounted at the outlet of the overpressure relief valve. In a normal state, the brake valve remains open so that the overpressure relief valve can work regularly to keep a safe air pressure inside the refuge chamber. When the outer water pressure rises to 5 kPa (critical pressure of the hydrostatic release unit), the outer brake valve would close automatically by controlling component to prevent the water inflow and keep refugees safe. In this case, to avoid over-pressure inside the refuge chamber, compressed air lines or borehole should be cut off; and habitable circumstances will be sustained by a compressed oxygen/air cylinder or chemical oxygen generator, with the assistance of air scrubbing and conditioning methods.

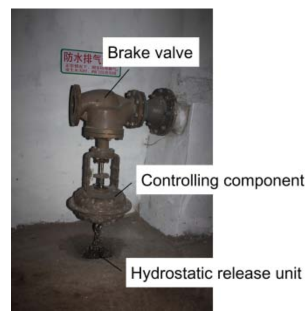

Figure 1: Water-proof evacuation unit.

(2) Emergency evacuation unit

The refuge chamber may be completely isolated from the external environment once the evacuation unit described in Section 3.1 closed down in water inrush emergency. Based on our previous study, within a totally sealed space (internal volume of 24.5 m^3) with 10 subjects living in it, the barometer readings varied from -400 Pa to 1200 Pa in the duration of nearly 9 hours, and it was predicted that the maximum pressure would be up to 8718 Pa in 96 hours (Li et al., 2015). In addition, if air supplied by compressed air lines running throughout the mine was not cut off in time due to wrong operation or other reasons after the evacuation unit closed, the pressure inside the refuge chamber would rapidly rise to a hazardous level. Thus for the sake of safety, an emergency evacuation unit with capacity of 100 m^3/h was installed in the refuge chamber. The outlet of the evacuation line was placed in the -110 m level roadway, and proper protection measures were taken.

(3) Emergency drainage unit

Wastewater in the refuge chamber can be drained via floor drains when the water level in the main roadway is lower than 600 mm. Otherwise, an emergency drainage unit with the capacity of 20 m^3/h and discharge head of 50 m would be used.

4. TESTS & SIMULATION ON PROTECTIVE PERFORMANCE

4.1 Hydrostatic test of water-proof door

The hydrostatic test of the water-proof door was carried out in Structure Mechanics Laboratory of China Ship Scientific Research Center in Jiangsu Province. The door was mounted in a flat position as required (SAC, 1991); then pressurize hydrostatic pressure to 2.0 MPa by a pressure gradient of 0.5 MPa, and maintain for 30 minutes. A total number of 20 measuring points were monitored in the experiment. Figure 2 shows the distribution and the strain changing curve of five representative points. No deformation or leakage was observed on the door frame after the experiment. The door showed a perfect water-resistant performance.

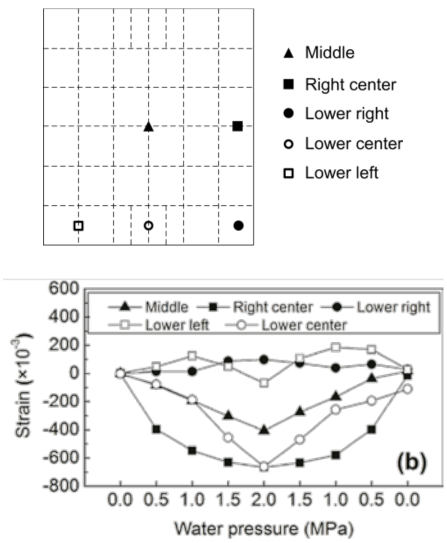

Figure 2: Hydrostatic test of water-proof door: (a) five typical measuring points distribution; and (b) strain curve at each point.

4.2 Positive pressure maintenance test

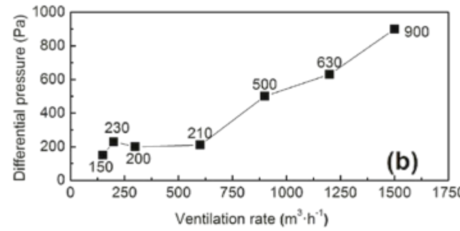

Figure 3: Positive pressure maintenance: (a) experimental site; and (b) change curve of differential pressure between inside and outside of refuge chamber.

In the experiment, all the openings were sealed and the door was closed, but to keep the evacuation unit operating at a normal state, and regulate the ventilation airflow rate at 150, 200, 300, 600, 900, 1200, and 1500 m^3/h respectively. It can be seen that, the differential pressure in and out of the refuge chamber, as shown in Figure 3, increased with ventilation rate. The maximum differential pressure was up to 900 Pa, but not harmful to health. The results indicated that the refuge chamber is able to maintain and regulate inner pressure as required.

4.3 Air impermeability performance test

The refuge chamber was kept in a completely confined state during the test. All doors and openings are closed as well as the evacuation unit. Pressurize the inner space with compressed air until the differential pressure rises above 1000 Pa. The changing curve of differential pressure afterwards was shown in Figure 4. It can be seen that the pressure decreased rapidly from nearly 1300 Pa to below 250 Pa in the first 200 seconds, then stabilized at around 50 Pa in 10 minutes. The airtight requirement is fulfilled.

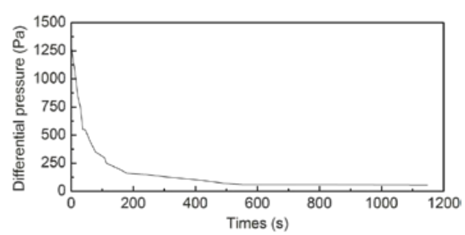

Figure 4: Air permeability performance.

4.4 Test & Simulation on water-proof lining

(1) Property of waterproofing concrete sample

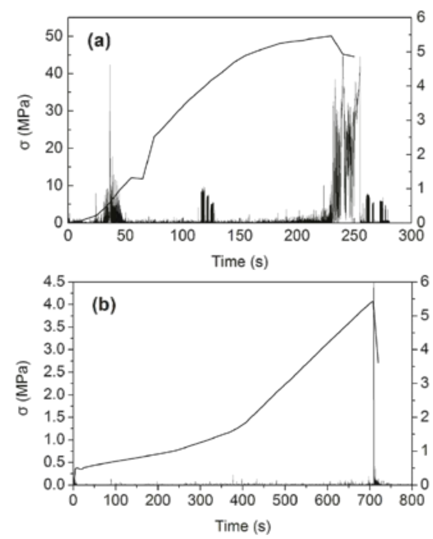

Figure 5: Experimental results of water-proof concrete sample: (a) uniaxial compressive behaviour; and (b) splitting tensile behaviour.

The uniaxial compressive behaviour, splitting-tensile behaviour, and anti-penetrability performance of concrete sample were tested according to Chinese National Standards (MOHURD, 2002; MOHURD, 2009). Acoustic emission (AE) was adopted to reveal the damage evolution of each sample. The following experimental equipment was used: WEP-600 hydraulic universal tester (Changchun Chaoyang Test Instrument Co., Ltd), DH3821 static strain testing analyzer (Jiangsu Donghua Testing Technology Co., Ltd; resolution: 1με; system indication error: ≤0.2%±3με); SZ120 resistance wire strain gauge (Xingtai Kehua Resistance Strain Gauge Plant; sensitivity: 2.06±0.1%); PCI-2 6 channel AE system (Physical Acoustics Co., Ltd); BY-HS16B concrete impermeability instrument (China Academy of Building Research; nominal pressure: 1.6 MPa; pressure maintenance error: ±0.05 MPa). All the tested samples were kept in standard conditions for 28 days.

The tested concrete samples presented an average ultimate compressive strength of 50.27 MPa, splitting tensile strength of 4.24 MPa, and impermeability coefficient of 1.53×10^{-11} m/s. Figure 5 shows the stress and AE counts changing curve of one of the samples under centric axial compression and splitting tension states respectively. With the increasing magnitude of stress, especially near the critical point, internal cracks formed and propagated, leading to final damage. Due to significantly lower tensile strength, stresses produced byloads, temperature changes, shrinkage, settlement, etc. would induce active or dormant cracks on the concrete structure. Thus, in the following simulation analysis, a concrete damage plasticity model was employed to identify the possible crack information zones within the waterproof lining.

(2) Simulation on water-proof lining

A two-dimensional model of waterproof lining for calculating its seepage and stress fields in water inrush emergency was established by ABAQUS software. The finite element mesh extended to 40 m × 40 m, seven times the excavation size. The tunnelling process, consisting of excavation and support installation steps (six steps in total), was simulated in the analysis by adding and removing corresponding elements. After the step-by-step tunnelling process, a pore pressure of 1.3 MPa was loaded on the boundary of the top surface, 1.7 MPa at the bottom, while at the vertical boundary the pore pressure linearly increased with depth. Mohr-Coulomb plasticity model, elastic-plastic model, and concrete damaged plasticity models were adopted in the calculation to identify the behaviour of corresponding material. As concrete is strong in compression but weak in tension, only the tension damage behaviour was considered in the simulation. Tensile damage was specified as a function of cracking displacement, calculated on the basis of the stress-strain curve obtained in Section 3.4.1 and relevant references (Jankowiak, 2005; Guo, 1997). Model details are shown in Table 2.

Table 2: Parameter setting of calculation model.

No.	Part	Material model	Element	Material properties
1	Surrounding rock	Classic Mohr-Coulomb plasticity model	CPE4RP	Young's modulus: 10.0Gpa; poisson's ratio: 0.26; cohesion: 2.0MPa; internal friction angle: 35°; dilation angle: 0°; and void ratio: 0.639.
2	Anchor	Elastic-plastic model	T2D2	Density: 7800kg/m^3; Young's modulus: 214GPa; poisson's ratio: 0.27; and sectional area per anchor: 3.14×10^{-4}m^2.
3	Rebar	Elastic-plastic model	T2D2	Density: 7800kg/m^3; young's modulus: 190GPa; poisson's ratio: 0.3; and sectional area per rebar: 7.85×10^{-5}m^2.
4	Concrete	Concrete plasticity damage model	CPE4RP	Poisson's ratio: 0.2; dilation angle: 30°; Flow potential angle: 0.1; biaxial and uniaxial tensile ultimate strength ratio: 1.16: constant stress ratio: 0.667; viscous coefficient: 0.0005; compression recovery: default; stress and strain data of C25 concrete: research results taken from Guo (Guo, 1997); parameters of C40 concrete (young's modulus, stress, strain, permeability

				coefficient, and damage factor): test values.

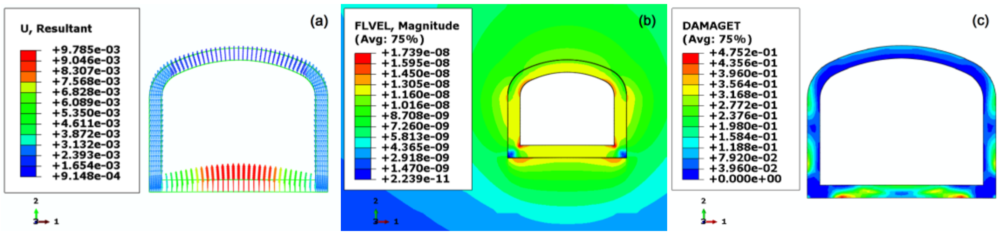

Figure 6: Simulation results of water-proof lining under 150m water pressure: (a) physical displacement components; (b) current magnitude and components of the pore fluid effective velocity vector; and (c) tensile damage variable.

Figure 6 illustrates the simulation results of the waterproofing lining under 1.5 MPa hydrodynamic pressure. It can be seen that maximum distortion appears at the arch bottom and magnitude of seepage velocity extends to the 10^{-8} order as compared to no-water state. In general, the supporting structure fulfills the expected requirements. The distribution of tensile damage variable of the waterproofing lining, which further identifies the possible crack formation zones and suggests ways to avoid their development, revealed that when under 1.5 MPa hydrodynamic pressure, the tensile damage at the arch bottom and side wall were relatively higher, ranging from 0.2 to 0.5. Thus these areas should be intensively monitored during regular maintenance and repaired in time.

5. CONCLUSION

Based on an overall consideration of practical conditions, a waterproofing refuge chamber with a capacity of 50 miners for at least 96 hours has been proposed in Guilaizhuang gold mine in Shandong province. Its external protective system, mainly composed of a thin-shell water-proof door, water-tight bulkhead, and composite shell lining, was designed to withstand 150 m hydrodynamic pressure with a water-proofing protection grade of level two, and also to fullfill the requirements of airtightness, fire resistance, etc.. A waterproofing evacuation unit, emergency evacuation unit, and emergency drainage unit were designed to solve the problem of exhausting and draining under water. The protective performance of the refuge chamber has been verified by hydrostatic tests of the water-proof door, a positive pressure maintenance test, and air permeability performance test. Meanwhile, a two-dimensional simulation on the waterproofing lining through ABAQUS software suggested that the tensile damage at the arch bottom and side wall were relatively higher when under 1.5 MPa hydrodynamic pressure, which provides a scientific basis for regular maintenance. Further research on protective performance evolution after typical disasters will be carried out in the future.

6. ACKNOWLEDGEMENT

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