Design of Test Platform for Coupling Field of Rock Stress and Seepage in Underground Storage Cavern

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Abstract. Although domestic experimental devices can ascertain the basic rock mass parameters needed in the design process of a cavern to meet the needs of the underground storage project. It is hard to analyze and test the complex fluid-solid coupling state in the full-life-cycle process of a cavern. In this paper, a three-dimensional physical model is designed to apply the stress field and seepage field, simulating the whole life cycle from excavation to operation. The experimental model obtains parameters of rock deformation and stress, water inflow, and seepage pressure. All these experimental models are expected to refine calculation methods or theories for different construction and operation conditions.

KEYWORDS
Experimental model, Underground cavern, Full-life-cycle, Underground stress, Seepage field

1. INTRODUCTION
China has performed considerable theoretical research and numerical analysis on the construction and operation of underground cavern reservoirs and has gained considerable engineering experience in this respect. However, relevant theories, technologies, and process parameters need to be further studied, especially in physical model research and technical verification, absent at this stage. Establishing an underground storage laboratory can realize multi-angle and multi-period mutual validation of the geological model, excavation support, stability analysis, water seal design, and give full technical advantages of engineering integration research [1–2].

2. DESIGN CONCEPT
The test platform was designed to innovatively simulate the original conditions of the water-sealed cavern and actualize the whole process simulation method of excavation, support, water-sealed, process operation, and monitoring. First, according to engineering principles, the initial three-dimensional physical condition is established. Then stress field and seepage field are loaded step by step to simulate the entire life cycle changes from excavation to operation. Expected test level and accuracy of the platform [3–5]:

A) The geological body model has the function of simulating joints and excavation in caverns.
B) The load and seepage control device has the functions of applying in-situ stress, seepage force, and grouting, with a controlled accuracy rate of more than 95%.
C) The monitoring device with its platform has the functions of tracking deformations, stresses, permeabilities, and temperatures, at an accuracy level of more than 95%.
D) The set-up can simulate the micro-permeation process of oil and water in the rock mass.
E) Its prediction of stability and seal-effect of underground reservoirs in caves is over 80%.

3. COMPOSITION OF EQUIPMENT

![Components of Water Seal Simulation Test System](image)

Figure 1. Components of Water Seal Simulation Test System

The test platform is designed to simulate the coupled effects of stress and seepage in a surrounding rock, composed of seven parts: reaction sealing device, stress loading system, oil-injection-control system, water-injection-control system (water curtain, natural water level), a tunnel excavation system, grouting system, and data collection and analysis system.

4. EQUIPMENT TECHNICAL ROUTE

Test Platform for Coupling Rock Field Stress and Seepage is proposed by the scale of 1:100, divided into several parts by the technical route.

4.1. Reaction Sealing Device

The reaction sealing device adopts a modular-combined self-reaction structure, which adapts to variations in geological boundary conditions, with the function of actual triaxial strain loading in 3D water-sealed caverns. The design is loaded on four sides, i.e., the model’s top, rear, left, and right, with the front and bottom operating as reaction sides. The loading device has a loading guide frame and excavation perspective window. The tunnel shape can be adjusted, and the perspective window can be sealed after excavation.

4.2. Stress Loading System

The stress loading system comprises a hydraulic pump station, automatic hydraulic control system, embedded hydraulic cylinder of a front flange, and an oil pipeline. The hydraulic pump
station and the fully automated hydraulic control system are combined and installed in the same cabinet. The automated hydraulic control system uses an industrial control computer and programmable logic controller (PLC) to administrate the complete set of equipment.

4.3. Oil-injection-control System
This system includes an oil injection pump, protective liquid barrel, oil pipe, oil cushion height probe, and control system. The oil injection pump is composed of a micro motor, reducer, and oil cylinder. The power of the micromotor lifts the piston of the oil cylinder through a reducer to realize oil injection or oil recovery into the tunnel.

4.4. Water-injection-control system
Water-injection control system mainly includes hardware and software control systems. The hardware system comprises a high-pressure water pump, pressure stabilization system, air pressure pump, gas storage tank, connection pipeline and joint, valve block, etc. It can simulate the water pressure from surrounding rock and apply constant water pressure to any part of the model. Moreover, the water pressure can be adjusted rapidly with a maximum value 0.5MPa.

4.5. Tunnel Excavation System
The tunnel excavation system includes a forward drive and a rotary drive supported by a frame. The rotary movement facilitates automatic excavation aided by the control system and is monitored in real-time. The forward dive employs a head cutter for tunnel excavation; the head cutter can be used for automatic excavation of arbitrary shapes.

4.6. Grouting System
The grouting system reinforces rock-mass joints, cracks, and other fractured zones. The small grouting pump operates under constant pressure. The grouting pressure is 0-0.5 MPa, and the grout flow is 1 L/min. This grouting system is composed of a bracket, a servo motor, screw, grouting cylinder, grouting fluid preparation, pipeline, grouting head, drilling rig, and control system. The control system controls the servo motor’s rotation driving the grouting cylinder; the cylinder sucks in the grouting fluid and reverses the grouting.

4.7. Data Test and Analysis System
The data test and analysis System can monitor the dynamic strain, pressure, displacement, seepage pressure, flow rate (water injection and inflow), velocity (internal rock-mass), temperature, and other physical quantities of the surrounding rock. The data test and analysis system can be equipped with other multi-physical quantity acquisition systems, as the fiber Bragg grating testing system, resistance strain testing system, and acoustic emission system. The analysis system needs to be completed using professional computing software or programs.

5. EXPECTED FUNCTIONALITY
By establishing the physical models of geology conditions, construction, and operation processes, which includes simulating geological bodies of different rock-mass structures, faults, and dikes, the experimental test attempts to assess the feasibility of the Cavern Design Scheme. The test platform is designed to change the laying-out, cavern size, ground stress, and rock parameters to mimic actual projects. The water seal effect and the water-curtain system are the key engineering indicators, which can be simulated by changing water-curtain-setting, grouting conditions, seepage pressure, and boundary. The test data includes water inflow, seepage distribution, and pressure [6–7].
The construction phase test program encompasses the following:

1) Rock samples are collected and processed using an auxiliary system to ascertain elastic modulus, strength, permeability, and other physical characteristics. Next, using the engineering similarity principle, analogous material mechanical properties are evaluated, and a similarity scale and model size are determined [8].

2) Model reaction sealing device is assembled, and the loading system is connected to the reaction sealing device through the oil pipeline.

3) Sensors embedded in modal and data lines are drawn out and connected to the testing and analysis system.

4) Water is pumped through the water-injection control system, as the tunnel excavation and testing system and testing and analysis system are ready for excavation test.

5) The excavation test, employing a mini-header, starts with the designed excavation speed.

6) The strain/stress, displacement, seepage, and acoustic emission of surrounding rock are collected during the test.

7) For easy leakage parts such as rock cracks and fissures, grouting reinforcement can be used to ensure that the cavern is compact and stable until the test is completed [9].

8) Comparison and analysis of experimental results with numerical simulation and field monitoring is carried out.
6. CONCLUSION
The test platform design for coupling field of rock stress and seepage in underground storage cavern was based on the multi-disciplinary integrated sharing model, capable of simultaneously validating the geological model, excavation support, stability analysis, water seal design, and numerical analysis [10]. Thus the platform can make up for the lack of experimental research and help promote the integration of underground water-sealed cavern engineering studies.

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