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Perspective

Energy storage salt cavern construction and evaluation technology

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Abstract:
With the demand for peak-shaving of renewable energy and the approach of carbon peaking and carbon neutrality goals, salt caverns are expected to play a more effective role in oil and gas storage, compressed air energy storage, large-scale hydrogen storage, and temporary carbon dioxide storage. In order to effectively utilize the underground space of salt mines on a sound scientific basis, the construction of salt caverns for energy storage should implement the maximum utilization of salt layers, improve the cavern construction efficiency, shorten the construction period, and ensure cavern safety. In this work, built upon design experience and on-site practice in salt cavern gas storage, the four pivotal construction stages – conceptual design, solution mining simulation, tightness assessment, and stability evaluation – have been thoroughly enhanced, strengthening the technical framework for salt cavern energy storage.

Salt rock is an extremely dense and widely distributed sedimentary rock in the Earth's crust. Salt caverns constructed by solution mining in the salt layer have good stability, airtightness and chemical inertness, and form an important place for large-scale energy storage (Wan et al., 2023). Salt caverns have been widely used for energy storage such as oil and natural gas, and have played an important role in the field of energy security. With the approaching demand of renewable energy peak shaving and carbon peak and neutrality goals, salt caverns are expected to play an increasingly important role in energy storage, including large-scale hydrogen storage, compressed air energy storage, and carbon dioxide storage. The construction of salt-cavern mainly focuses on conceptual design, solution mining, tightness assessment and stability evaluation. The key processes and main steps in the construction of energy storage salt-cavern are briefly shown in Fig. 1.

1. Mathematical model and solving method for solution mining

The solution mining process of salt rock can be regarded as the convection-diffusion process of solute (salt rock molecules) in solvent (water), caused by the concentration difference in the cavern. Relying on Brownian motion, the salt rock molecules gradually diffuse from the high-concentration area to the low-concentration area and finally reach saturation (equilibrium state). Even if there is no externally driven flow throughout the cavern, convection-diffusion still occurs.

1.1 Flow mass transfer and boundary movement

With the rise in solution temperature and dissolution dip angle, the dissolution rate of rock salt gradually increases.

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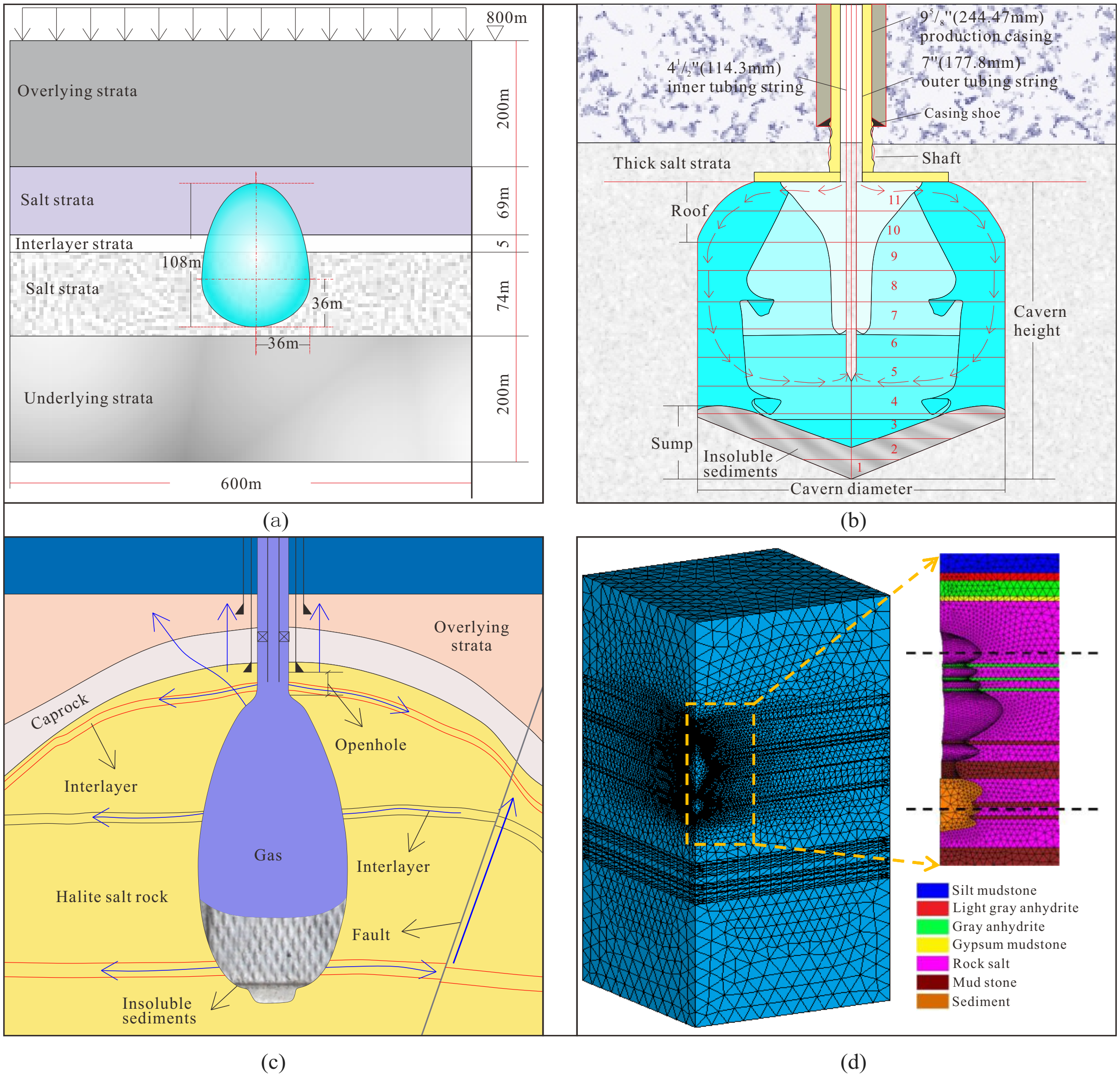

Fig. 1. Construction flowchart of salt cavern for energy storage. (a) Conceptual Design, (b) leaching simulation (Yuan et al., 2021) (c) tightness assessment (Chen et al., 2019) and (d) stability evaluation (Liu et al., 2020).

Therefore, the following law exists in the solution mining process: upper dissolution rate > side dissolution rate > bottom dissolution rate; this can provide theoretical guidance for on-site cavern construction. Considering the needs of actual engineering, Wan et al. (2019, 2021) made necessary simplifications to the problem of solution mining, then revised and improved the basic assumptions of previous numerical simulation of solution mining, bringing the numerical solution closer to the real working conditions. Based on the classic Navier-Stokes method, a three-dimensional (3D) leaching mathematical model is established. This includes the flow and mass transfer in the cavern and the boundary movement of the cavern. In addition, the definite solution conditions of the mathematical model are determined.

According to the semi-staggered grid settings, the finite volume method is used to discretize the basic control equations of incompressible flow. The semi-implicit method for pressure-linked equations algorithm is utilized to solve the velocity field and concentration field, and the virtual large viscosity method and volume of fluid algorithm are implemented to solve the boundary movement of the cavern wall and then further solve the expansion of the cavern geometry.

By utilizing established mathematical models and numerical solutions, the program design and development are executed. The computing kernel is written in Visual C++ language, leveraging its advantages of suitability for numerical calculations, high speed, and capacity for complex structured program development. The graphical interface is developed in Python language, which plays a role of “glue language” and facilitates calling other languages. Additionally, third-party graphical user interface function libraries can be used for 3D visualization (Wan et al., 2019). The developed 3D solution mining program for solution mining cavern includes five modules: formation information input, technical parameter input, concentration field flow field calculation, cavern geometry expansion calculation, and insoluble settlement.

1.2 Solution mining optimization based on artificial neural network

The construction design and geometry control of salt cavern are the keys to ensure its storage capacity and operational safety. However, the current design method based on physical/numerical forward simulation can only obtain the corresponding cavern formation for a certain set of cavern constructing parameters and cannot directly give the optimized design suggestions. Therefore, the optimization of cavern construction design still relies on the cycle of simulation-artificial adjustment-simulation. It is extremely difficult to obtain the best optimized solution due to the numerous possibilities of multi-stage combinations of cavern constructing parameters, such as depth of injection, depth of brine discharge, injection flow rate, concentration of injection, and duration of water injection. To solve this problem, a method of machine learning is proposed to assists with the prediction of cavern construction and design optimization.

1.2.1 Volume prediction and leaching optimization

Herein, a data generation rule is proposed to generate the cavern constructing parameters. A dataset was formed using 1,253 sets of randomly generated parameters for cavern construction as inputs, while the outputs included the effective volume and maximum radius obtained from the self-developed single-well salt cavern leaching simulation (SSCLS). Then, this dataset was used to train a back-propagation artificial neural network (BPANN) model for salt cavern construction prediction to estimate the effective volume and maximum radius of the salt cavern. Through cross-validation, the proposed model achieved an average mean absolute percentage error of 1.838% for the prediction of effective volume and 3.144% for the prediction of maximum radius, indicating that the prediction accuracy of the model meets the engineering design requirements. Moreover, the prediction efficiency of this model was approximately 6×10^7 times higher than that of traditional software (Li et al., 2022).

Based on our back-propagation neural network model, a design parameter optimization method is put forward. The workflow of this method includes randomly generating design parameters, predicting the corresponding effective volume and maximum radius of cavern, and screening the cavern design parameters according to the predicted effective volume and maximum radius. By employing this method, three sets of optimized parameters were selected from one million sets of randomly generated design parameters. The optimized salt cavern shape exhibited an average volume ratio of 3.83% larger than the average of the three chambers at the Jintan salt cavern gas storage site, which verifies the reliability of the proposed BPANN-based salt cavern optimization design method.

1.2.2 Storage morphology prediction and cavern construction design

By utilizing the dataset from Section 1.2.1, an additional 1,207 sets of simulation data for salt cavern construction were collected. These data utilized randomly generated design parameters for cavern construction as inputs, while the salt cavern geometries (radius data at different depths) were acquired as outputs through the SSCLS numerical program. Then, a gated recurrent unit model for salt cavern geometry prediction was selected and trained from 600 artificial neural networks with different structures and hyperparameters. This model achieved an error of 1.28 m on the test set and a predicted mean absolute error of 2.83 m when applied to the geometry of salt cavern JT52 in Jintan, thus it was considered to meet the site design requirements (Li et al., 2019).

Building upon the gated recurrent unit model, a target-oriented optimization design approach was introduced. The workflow of the method encompasses the random generation of design parameters, forecasting the salt cavern morphology, assessing the variance between the predicted and desired morphologies, and performing iteration until the variance aligns with the set criteria. In practice, regarding the standard ellipsoid shape as the target morphology, an ideal elliptical salt cavern was successfully designed after approximately 660,000 iterations, which took about 51 minutes (with an error of 4.1% compared to the standard ellipsoid and a volume ratio of 3.8%).

The above two methods of cavern morphology prediction and design parameter optimization based on artificial neural networks demonstrate that, following physical modeling and numerical modeling, data inversion relying on machine learning has the potential to become a third-generation design method and is expected to play a significant role in the design of salt cavern gas storage construction.

2. Rheological damage coupling and stability evaluation

Under the condition of multi-field coupling, due to the existence of interface (or joint surface) and interlayer, the distribution range, geometric shape, time-varying evolution law, and failure mode of surrounding rock damage zone are considerably different from those of homogeneous rock mass, and the creep propagation law of cracks will be strongly disturbed by the mismatch (or "constraint" effect) between the bimaterial rock mass and interface.

2.1 Evolution law of salt rock-interlayer

Under the condition of the multi-field coupling experiment, a series of macro/meso-experimental studies were carried out. At the meso-scale, the interlayers treated in different multi-field coupling environments were quantitatively and qualitatively characterized at multiple scales. The evolution trend of porosity, pore size distribution and fractal dimension of interlayers under multi-field coupling environment were revealed, and the spatial distribution characteristics and spatio-temporal evolution law of interlayer pore fissure clusters/interlayer rock matrix under multi-field coupling conditions were displayed at multiple scales. As a result, the meso-pore fissure parameters (pore size distribution characteristics, porosity, pore throat ratio, specific surface area, and pore number) of interlayers under 3D full stress field were obtained.

Next, the uniaxial/triaxial mixed I ± II type static/creep fracture characteristics experiment of interlayer under multi-field coupling environment was carried out at the macro-scale. The evolution law of interlayer permeability under multi-field coupling environment was revealed, and the nonlinear seepage characteristics and seepage mechanism of interlayer under multi-field coupling environment were determined (Meng et al., 2020). By introducing the fracture process zone value at the crack tip, a fracture criterion considering the fracture process zone size and bedding angle was proposed. The creep fracture process of the interlayer under different peak loads was presented, the three processes of creep fracture (i.e., crack initiation stage, steady-state crack propagation stage and accelerated crack propagation stage) were clarified, and the crack propagation rates at different stages were measured in real time.

2.2 Triaxial creep characteristics of fractured salt rock-anhydrite composite

True triaxial creep fracture experiments were carried out on salt-gypsum composites with single cracks under different heterogeneity terms, and then the inhibition/promotion mechanism of crack propagation was clarified by comparison with the true triaxial creep fracture characteristics of single-crack homogeneous salt rock and anhydrite.

Under different heterogeneous conditions, true triaxial creep fracture experiments of salt-gypsum composite with double cracks were carried out. Then, by comparison with the true triaxial creep fracture characteristics of double cracks in homogeneous salt rock and anhydrite, the competitive mechanism of double crack interference effect and double rock mass constraint effect were elucidated. Based on the configuration force theory and J-integral theory, the effective/additional crack propagation driving forces and interface parameters under different heterogeneous conditions were obtained by numerical simulation, and the corresponding variation laws with time and crack length were summarized. Then, through the correlation and regression analysis of the experimental results, the evolution equations of the composite factors of inhibiting fracture, promoting fracture and competing fracture were obtained (Meng et al., 2022).

3. Permeability and tightness assessment

Based on the geological characteristics of bedded salt rocks in China, the tightness assessment of energy storage salt caverns should be carried out from three aspects: regional tightness, bedded salt rock permeability, and tightness of cavern wall rock. The focus should be on constructing a tightness assessment system for the cap-rock and interlayers, revealing the permeability properties of the surrounding rock and establishing corresponding models, as well as forming tightness assessment methods for cavern wall rocks, thus providing scientific reference for storage site and lithological section selection, storage media selection, and the setting of the top protection salt layer.

3.1 Evaluation of tightness performance of cap-rock and interlayers

Mudstone cap-rock, interlayers and interfaces usually have higher permeability and porosity than salt rock, and under the cyclic injection-withdrawal operations of the storage cavern, there is a risk of shear slip failure at the interface between the salt rock and interlayers. In the site selection stage, emphasis should be placed on the performance of regional traps, the lithology of overlying strata, and their porosity and permeability characteristics, to construct a comprehensive evaluation system for the tightness capacity of cap-rock and interlayers.

3.1.1 Regional tightness characteristics

The salt rock energy storage cavern (or cavern group) requires the entire salt layers and adjacent rock layers to have good structural trapping capacity at the macro-level. That is, for the horizontal direction, the cap-rock has good continuous distribution performance, and the surrounding control structural faults are not active and far from the proposed storage caverns. As for the vertical direction, the distribution of the strata is stable, the thickness of the cap-rock is immense, and its tightness is superior to the overlying aquifer strata (Liu et al., 2016a).

3.1.2 Lithological tightness of the interlayers

Cap-rock, such as mudstone, gypsum rock, gypsum-salt rock, etc., has good tightness capacity and plasticity. In addition, the cap-rock has a large thickness and good stability, which can produce good lithological tightness for the proposed cavern group. According to the tightness capacity of lithologies, gypsum-salt rock is the best cap-rock, followed by gypsum rock and mudstone, while for silty mudstone, special cautions should be taken. The stronger the plastic deformation of the cap-rock and interlayers, the more favorable it is for them to resist cyclic loads and promote local crack closure and damage repair.

The micro-tightness characteristics of the cap-rock and interlayers refer to the tightness performance of the micropores to the fluid, with the breakthrough pressure and pore size distribution as two key indicators. It is suggested that the tightness performance of cap-rock and interlayers should be evaluated by referring to the breakthrough pressure evaluation grade in petroleum geology. The cap-rock and interlayers, mainly composed of nano- and micropores, usually have excellent tightness performance, while those with medium to large pores often have poorer tightness capacity.

3.1.3 Porosity and permeability characteristics of the cap-rock and interlayers

The porosity of gypsum-salt rock, gypsum rock and mudstone is sequentially higher, while all three are cover layers with smaller porosity, generally between 1%-5%. It is generally believed that when the permeability of the cap-rock and interlayers is 0.01 md or lower, they have sufficient tightness capacity to meet the gas storage requirements. When selecting a storage site, it is still advisable to choose the blocks or lithosections that have fewer interlayers or lower permeability for storage cavern construction.

3.2 Permeability of bedded salt rock

The lithology of interlayers in China mainly includes mudstone, glauberite mudstone, gypsum interlayer, silty mudstone, calcareous mudstone, etc. These all have low permeability and the vast majority of them can meet the tightness requirements of gas storage. It should be noted that the focus should be on the interlayer with the highest or higher permeability.

The interface is the main channel of permeability, which is between 0.01 and 0.001 mD, much higher than that of salt rock and equivalent to or slightly higher than the interlayer. Most interfaces have high bonding strength. Relatively speaking, the permeability of the interface is still relatively low and it mostly meets the tightness requirements of gas storage.

The function of compression-dilatancy boundary, which reflects the onset of increasing permeability, has been established for bedded salt rock. In the plane, the envelope of compression-dilatancy boundary of bedded salt rocks is located above that of pure salt rocks, indicating that in bedded salt rock formations, there is low risk that salt rock will induce rapidly increasing permeability and in turn lead to gas leakage. Therefore, for gas storage in bedded salt rocks, special attention should be paid to the leakage risk of interlayers and interfaces.

3.3 Tightness assessment of bedded salt rock storage

Due to the much higher viscosity of gas than petroleum, it is prone to leakage under high pressure. Moreover, gas storage usually has much higher frequency of injection and production than oil storage. Therefore, the tightness assessment of storage caverns is mostly carried out for gas storage (Liu et al., 2016b).

The tightness assessment of bedded salt rock gas storage often adopts two main indicators: 1) during one injection-production cycle or within one year, the gas leakage should not exceed 1% of the working gas volume. 2) The pore pressure in the middle of the pillar of two adjacent caverns should not exceed the minimum operating pressure in the cavern. In addition, there are some special requirements; for instance, for gas storage near faults, it is a prerequisite that the gas seepage range is not connected to the fault.

The interlayer is the main channel for gas seepage in the cavern wall rock, which is responsible for over 98% of gas leakage and is the key formation determining the tightness of gas storage. The interlayer with the highest permeability is often at the location with the greatest leakage and largest seepage range. Therefore, it is recommended to avoid high-permeability interlayers and store high-viscosity media such as crude oil in salt caverns.

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Conflict of interest

The authors declare no competing interest.

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