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Cost optimization of the underground gas storage

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ABSTRACT

The paper presents the cost optimization of an underground gas storage (UGS), designed from lined rock caverns (LRC). The optimization is performed by the non-linear programming (NLP) approach. For this purpose, the NLP optimization model OPTUGS was developed. The model comprises the cost objective function, which is subjected to geomechanical and design constraints. The geotechnical problem is proposed to be solved simultaneously. Geomechanical rock mass parameters are determined from geological conditions of a selected suitable UGS location and a special FE model is generated. The rock mass strength stability and safety of the system are then analyzed for various combinations between different design parameters like inner gas pressures, cavern depths, cavern diameters and cavern wall thickness. As a result, geomechanical constraints are approximated and put into the optimization model OPTUGS. This way, the optimization enables not only the obtaining of an optimal solution but also that the rock mass achieves sufficient strength stability and safety. The optimization is proposed to be performed for the phase of preliminary design. The numerical example at the end of the paper demonstrates the efficiency of the introduced optimization approach.

1. Introduction

High pressure gas reservoirs are typically designed in a cylindrical form from steel, pre-stressed concrete or composite walls. The construction of these type of structures is relatively difficult and expensive due to high internal pressures. Special care has to be paid to systems' safety. For this reason, an idea to design underground gas storages was raised forty years ago. In the beginning, engineers/researches designed gas or oil storage in deep aquifers or leaved wells. Since such solutions proved to be ineffective, the concept of high pressure underground gas storage (UGS), carried out by the technology of rock caverns, was promptly created and applied in praxis.

There are two types of rock caverns used for this purpose: unlined rock caverns and lined rock caverns (LRC). The main request in the designing and construction of rock caverns is the prevention of gas leaking from the storage. In the unlined rock cavern, gas is kept from escaping by ensuring that groundwater pressure in the surrounding rock exceeds the gas pressure in the storage [1]. The required gas pressure can be achieved by locating a cavern at a sufficient depth or by installing a ''water curtain'' around the cavern [2,3]. The latter requires performing a comprehensive hydraulic analysis for gas containment of the storage terminal. By contrast to the unlined rock cavern, the concept of the lined rock cavern, LRC, is an UGS of gas at high pressure, supported by the surrounding rock [4–7]. The main idea of the LRC is to prevent the gas leakage from the cavern by a thin steel lining. In normal conditions, the LRC is completely impermeable and no extra hydraulic analysis for gas containment is needed.

The UGS, considered in this paper, is planned to be constructed with one or more LRCs. The structure of the LRC is simple: its reservoir wall is designed from a concrete wall and a steel lining. Although the concrete wall is reinforced, it just transports the gas pressure from the cavern onto the surrounding rock. The same holds for the steel lining, which only enables impermeability (sealing). The LRC load capacity is thus provided by the surrounding rock only.

To improve the economic effectiveness of the UGS designed with LRCs, this paper introduces a cost optimization of the UGS structure. Since a recent attempt [8] was based on the optimization of a single gas cavern only, this research handles the optimization of the entire UGS with any selected number of caverns. The optimization is performed by the non-linear programming (NLP) approach. For this purpose, the NLP optimization model is developed. Since the optimization is proposed to be performed for the phase of the preliminary design, only some basic conditions are defined in the optimization model in order to assure sufficient strength safety of the rock mass and impermeability of the cavern wall and steel lining. The latter is achieved by the limitation of the steel lining and concrete wall stains. The primary objectives of the proposed optimization are:

- Minimization of the investment costs of the UGS system,
- Storing the highest possible quantity of gas under high pressure,

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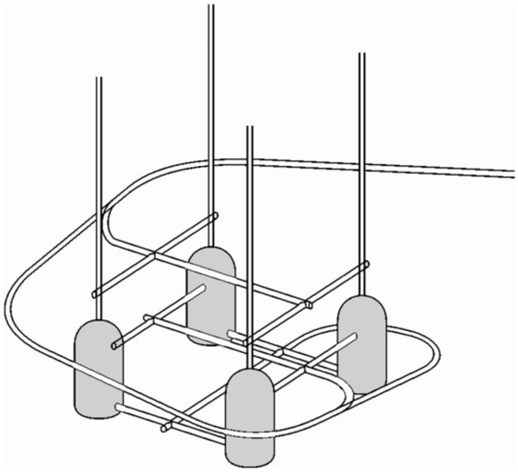

Fig. 1. Underground gas storage (UGS) with four caverns.

- Ensuring the safety of the UGS at the time of construction and service,
- Calculation of the inner gas pressure, the cavern depth, the cavern inner diameter, thickness of the cavern concrete wall and the height of the cavern tube in the optimization.

In order to achieve the above mentioned objectives, the geotechnical problem is proposed to be solved simultaneously. Hence, geomechanical rock mass properties are determined from investigations in the field and in the laboratory. Many methods were in the past developed for determining of rock mass properties. In this work the generalized Hoek–Brown failure criterion [9] is proposed to be applied and the Mohr–Coulomb strength parameters (the cohesion and the friction angle) are determined. In addition, the rock mass tensile strength, the uniaxial rock mass compressive strength, the global rock mass compressive strength and the rock mass deformation modulus are calculated.

After the geomechanical rock mass parameters are determined for a selected UGS location, a special FE model is proposed to be generated. The strength stability of the rock mass and the safety of the system are then calculated/analyzed for various design parameters like inner gas pressures, cavern depth, cavern diameters and different cavern wall thickness. As a result, geomechanical constraints including the allowable safety/stability factors and strains of the system structure are in dependence of the mentioned design parameters proposed to be defined and put into the optimization model.

2. Underground gas storage (UGS)

The paper deals with the underground gas storage (UGS) designed from one or more lined rock caverns (LRC), see Fig. 1. The LRC is a pressure tank containing gas stored under high pressure. The gas pressure is transmitted through the cavern wall to the surrounding rock. The rock provides the LRC capacity. The system of tunnels is designed in order to transport materials and allow access for machinery during the construction of the underground chambers. The LRCs are linked with the ground surface by vertical shafts. The shaft steel pipes are made for filling and emptying the gas storage.

The design of the considered LRC structure is typical. It consists of the cylindrical wall and the upper and lower spheres, see Fig. 2. The caverns are typically 50 to 100 m high and are located at depths from 100 to 300 m. Their concept involves relatively large diameters: between 10 and 50 m. The concrete wall is 2 or more meters thick, the thickness of the steel lining amounts from 12 to 15 mm. The concrete wall uniformly transmits the internal pressure to the rock and consequently uniformly distributes the deformations. The reinforcement in the concrete prevents tangential deformations. The task of the steel lining is to seal and to bridge small cracks of the concrete. The drainage system is installed on the outer side of the cavern wall. It drains the water and enables the monitoring, collection and removal of the gas in case of gas leakage.

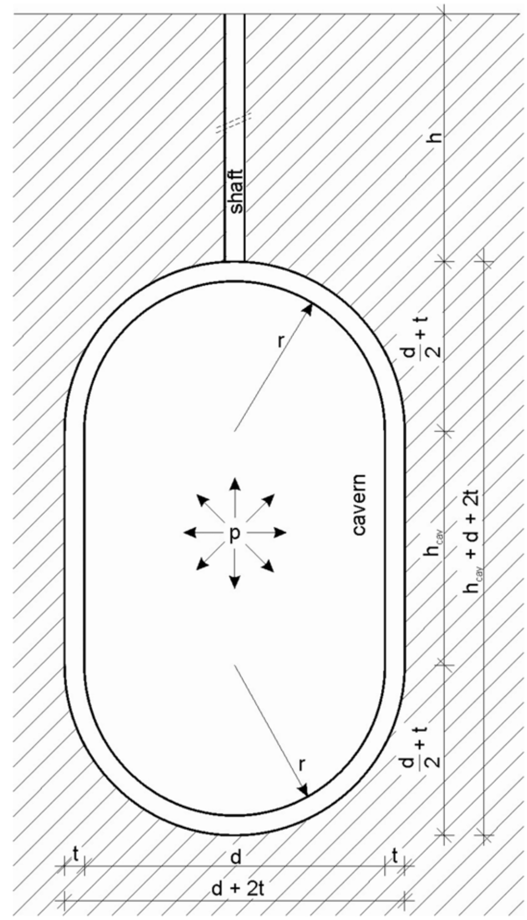

Fig. 2. Vertical cross-section of the lined rock cavern (LRC).

The external pressure of the rock mass (between 1 to 3 MPa) acts on the cavern wall during construction and operation. It depends on the depth of the cavern (between 100 and 300 m). The internal pressure of the gas cyclically increases and decreases during periods of gas supply and discharge between the minimal (3 MPa) and maximal (calculated) value. The internal pressure therefore causes static and cyclic loads. The lifetime of the LRC is typically designed to be higher than 500 cycles.

The construction of the LRC starts with the excavation of access tunnels. The mining of caverns is then performed from the top down. A drainage system is put on the cavern surface and a free-standing steel lining is assembled. The last phase presents the construction of the cavern wall by filling the space between the excavated cavern surface and the steel lining with concrete. The LRC concept should provide a safe and environmentally friendly mode for gas storage. Since the gas should never be in contact with the environment, the underground gas storage must be designed as a closed impermeable system.

3. Optimization model OPTUGS

In order to achieve the most rational investment costs of the UGS system, cost optimization is proposed to be performed for