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The feasibility analysis of underground gas storage caverns

Bojan Žlender [a,*], Primož Jelušič [a], Djamalddine Boumezerane [b]

[a] University of Maribor, Faculty of Civil Engineering, Smetanova 17, 2000 Maribor, Slovenia
[b] University of Bejaïa, Civil Engineering Department, Route Targa Ouzemmour, 06000 Bejaïa, Algeria

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ABSTRACT

This paper presents the fuzzy concept for the feasibility analysis of Underground Gas Storage (UGS) designed from Lined Rock Caverns (LRC). For this purpose, it is necessary to carry out a number of steps. The first is the determination of the geological model of the UGS region. The next is transferring of the geological model into the geomechanical model, which could be achieved by applying the system of Hoek and Brown based on the geological strength index (GSI). The equivalent Mohr–Coulomb strength parameters should be determined. The geomechanical analysis for risk during construction and later during operation of UGS using Finite Element Method (FEM) is carried out. The series of FEM analyses should be calculated for the determination of changes in the response functions due to changes in the design variables. The results of FEM analyses are given in table form. The cost of UGS is calculated with developed equations. The construction costs comprise the investment and operational costs of the UGS system. The total construction costs per unit of gas include the sum of fixed costs and variable costs. Once the results of FEM and cost analysis are obtained, we use those solutions to develop ANFIS models. In this paper the ANFIS model for cost prediction is described in detail and the similar procedure is used to develop geomechanical constrain functions. These models are the basis for the feasibility analysis of underground gas storage caverns.

1. Introduction

The high pressure reservoirs of gas are generally designed in cylindrical form. Such structures of reservoirs are, due to high internal pressures, pretentious and expensive. Therefore, about 40 years ago the idea of underground high pressure gas storage appeared. There are two types of rock caverns used for this purpose; Unlined Rock Caverns and Lined Rock Caverns (LRC). 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 main idea of the LRC is to prevent the gas leakage from the cavern by a thin steel lining. The gas in LRC is at high pressure and the LRC wall is supported by the surrounding rock [4–7]. In normal conditions, the LRC is completely impermeable and no special hydraulic analysis for gas containment is necessary. Such UGS is performed by one or more of the LRC. The structure of LRC is simple. Its wall is forming a wall of concrete and steel lining. The concrete wall is mechanically not regarded as reinforced concrete structure this means that the steel-coating does not supply the load, but only sealing.

This paper presents the use of ANFIS for feasibility analysis of underground gas storage caverns. Adaptive Network-based Fuzzy Inference System (ANFIS) is a combined system of a fuzzy inference system (FIS) and a back propagation neural network algorithm based on some collection of input-output data. FIS is a process of mapping from a given input to output using fuzzy logic. Fuzzy sets were introduced by Zadeh [8], as a means of representing and manipulating data that are not precise. It was especially designed to mathematically represent uncertainty and vagueness and to provide formalized tools dealing with imprecision. There are two types of FIS systems: Mamdani-type [9] and Sugeno-type [10]. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant. ANFIS was developed by Jang [11] and supports only Sugeno-Type systems. ANFIS structure is presented in Section 4.

ANFIS model for cost prediction is described in detail. In order to show the use of ANFIS in condenses form we develop a model for COSTPERM3 for four caverns, one rock type and given volume of gas. In present study different number of lined rock caverns, volume of gas storage and rock masses are not considered.

2. Components of UGS with LRC

The Underground Gas Storage (UGS) contains one or more Lined Rock Caverns (LRC). The LRC is a pressure tank containing stored

* Corresponding author. Tel.: +386 2 22 94 328; fax: +386 2 25 24 179.
E-mail addresses: bojan.zlender@um.si (B. Žlender), primoz.jelusic@um.si (P. Jelušič), dboumezerane@gmail.com (D. Boumezerane).

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gas under high pressure. The gas pressure is transmitted through the cavern wall to the surrounding rock. The design, construction and safe operation of the LRC is influenced by many factors, like: LRC structure and geometry, geomechanical properties of the rock mass, loading (internal gas pressure, external rock pressure), drainage system, entrance tunnels, the construction process, risks and the impact on the environment.

The design of the LRC structure is similar to the already constructed UGS in Skellen [12]. The cavern wall, which transmits the gas pressure on the surrounding rock, is composed of several elements [13], see Fig. 1. The task of steel lining is sealing and bridging small cracks of the concrete. Sliding layer enables the corrosion protection for the steel and reduces the friction between steel and the concrete wall. The concrete wall uniformly transmits the internal pressure to the rock and consequently uniformly distributes the deformations. The reinforcement in concrete prevents tangential deformations. The task of the drainage system is to collect and to drainage the water. A layer of special low strength permeable shotcrete is placed closest to the rock surface. The purpose of the shotcrete is to protect the drainage system. Rock provides the LRC capacity.

The LRC concept involves large caverns with a diameter of 20–50 m and the high from 50 to 100 m, with cylindrical wall and sphere upper and lower part. They are located at depths from 100 to 300 m and are surrounded by 2 m or more thick concrete wall and coating with a thin steel sheet (15 mm).

The external pressure acts on the wall of the cavern (during the construction and operation). The high of the external pressure (2–5 MPa) depends on the depth of the cavern. It is expected that the pressure 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 minimum lifetime of the LRC is limited to be higher than 500 cycles.

The cavern is constructed at a depth of 100–300 m, which means that the hydrostatic pressure reaches 1–3 MPa. The drainage system is installed on the outer side of the cavern wall. It drainages the water and enables the monitoring, collection and removing of gas in the case of gas leakage.

The system of tunnels is designed to transport material and to allow the access for machinery during the construction of the underground chambers. The tunnels also provide a cost-effective mining of caverns. The cross-section of tunnels amounts about 25 m^2 in the flat areas and 40 m^2 in curved areas.

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. Models

We propose a methodology for the cost and geomechanical constrain functions prediction (Fig. 2). In solving the geotechnical problems it is necessary to determine geology and geotechnical properties. For this purpose we use the Hoek–Brown failure criterion [14]. The series of FEM analyses should be calculated for the determination of changes in response functions due to changes in the design variables. The results of FEM analyses are given in table form. Similarly the cost of UGS is calculated via developed equations. Once the results of FEM and cost analysis are obtained, we use those solutions to develop the ANFIS model. With the ANFIS model we can predict cost and geomechanical constrain functions for various design values.

3.1. Geomechanical model

3.1.1. Determination of the rock mass parameters

In order to determine the rock mass parameters it is necessary to carry out the geological mapping of surface, structural drilling, geotechnical field measurements and laboratory testing. Rock mass parameters are determined on the basis of the generalized Hoek–Brown failure criterion [14]. The computer program *RocLab* was used. The program provides a simple and intuitive implementation of the Hoek–Brown failure criterion, allowing the user to obtain easily reliable estimates of rock mass properties and to visualize the effects of changing rock mass parameters on the failure envelopes [15]. By using the generalized Hoek–Brown failure criterion, all necessary parameters were obtained by geological measure-

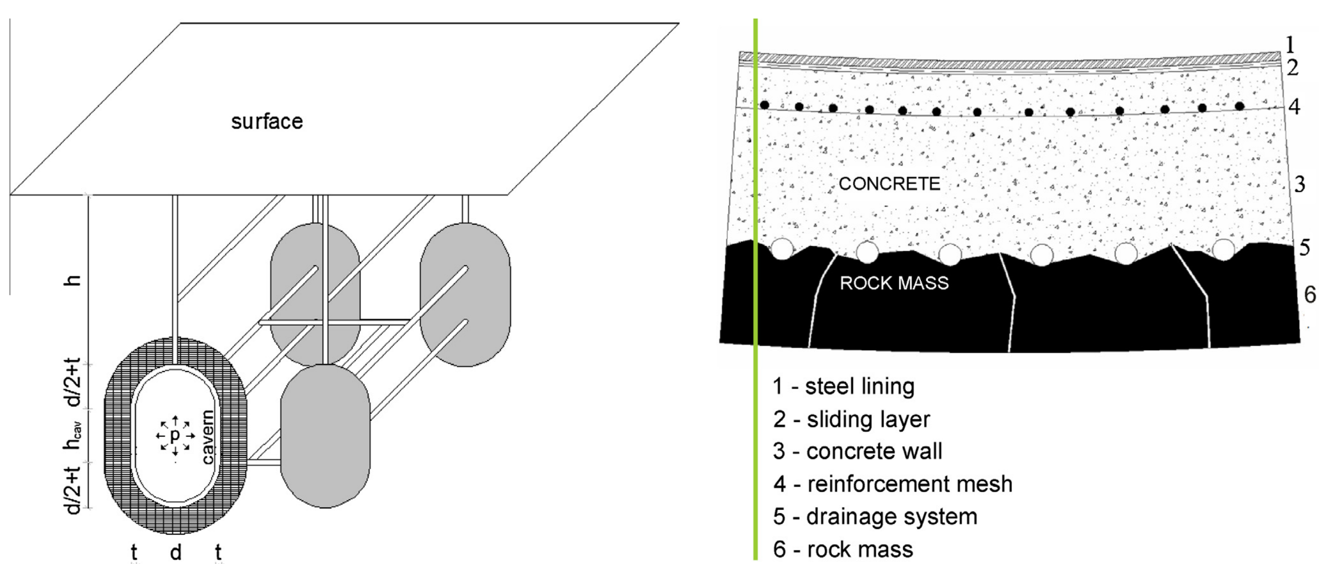

Fig. 1. UGS with four caverns (left) and the cross-section through the cavern wall (right).