TOPOLOGY OPTIMIZATION OF STEEL-LINED ROCK CAVERNS FOR UNDERGROUND STORAGE OF CHEMICAL ENERGY

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Abstract The paper presents the topology optimization of lined rock caverns designed for underground storage of chemical energy. This type of storage can store a high amount of hydrogen, methane, natural gas, carbon dioxide or other substances. The caverns are made of concrete shells and lined with thin steel sheets to seal the content. Optimization is performed by the mixed-integer non-linear programming (MINLP) approach. The MINLP computer program GAMS/Dicopt is used. The model includes the cost objective function, which is subjected to geomechanical and design constraints. In this attempt, the topology calculation is included in the discrete optimization of the underground storage. A numerical example at the end of the paper shows the overall discrete MINLP optimization of an underground gas storage facility. The optimal discrete design with the optimal number of caverns of the storage is explicitly determined. Additional investment savings are achieved.

Keywords:
underground storage, topology optimization, cost optimization, mixed-integer non-linear programming, MINLP

University of Maribor Press

DOI https://doi.org/10.18690/um.fkkt.2.2022.5
ISBN 978-961-286-598-6

1 Introduction

This paper deals with the topology optimization of lined rock caverns (LRC) designed for underground storage of chemical energy. This type of storage can store a high amount of hydrogen, methane, natural gas, carbon dioxide or other substances. The LRC caverns consist of 2 meters or more thick, cylindrically shaped concrete walls and are lined with 12-15 mm thin steel sheets. They are up to 100 m high, are built with diameters of up to 30 m or more and are bored to a depth of 300 m. Because the LRCs contain the gas under high pressure (between 3 and 30 MPa), they have to be bored into a rock with high strength (limestone, dolomite, granite, gneiss). The concrete walls of the caverns transfer the internal pressure onto the rock mass, while the steel lining seal the gas content. The surrounding rock mass carry the gas pressure, see (Sofregaz US Inc., 1999), (Brandshaug *et al.*, 2001), (Chung *et al.*, 2003) and (Glamheden & Curtis, 2006).

In the near past, some investigations have been carried out in the field of optimization of underground gas storages. For example, the optimization of a single gas cavern with non-linear programming (NLP) was introduced by (Kravanja & Žlender, 2010), the optimization of any number of caverns in the UGS was later presented by (Žlender & Kravanja, 2011), while the optimization in different rock environments was reported by (Kravanja & Žlender, 2012) and (Jelušič *et al.*, 2019). The latter reference introduced a prediction of the minimal investment costs using an adaptive network based fuzzy inference system (ANFIS) for the UGSs with capacities from 10 to 100 million m^3 of natural gas. The optimization of the discrete dimensions of the caverns was performed by (Kravanja & Žula, 2018) using mixed-integer non-linear programming (MINLP).

Underground gas storage facilities (UGS) are usually constructed from one to four LRCs. The correct determination of the number of LRCs built is very important as it has a strong impact on the investment costs. Therefore, we perform the topology optimization of the UGS with the calculation of the optimal number of LRCs. The topology logical constraints are inserted into the optimization model. In this way, the optimal discrete design of the storage facility with the optimal number of caverns is explicitly determined.

2 MINLP problem formulation

The optimization problem of the lined rock cavern is non-linear, continuous and discrete. Mixed-integer non-linear programming (MINLP) is thus applied. The general MINLP optimization problem is formulated as follows:

$$\begin{gathered} \min \ z = f(\mathbf{x},\mathbf{y}) \\ \text{subjected to: } g_k(\mathbf{x},\mathbf{y}) \le 0 \quad k \in K \\ \mathbf{x} \in X = \{\mathbf{x} \in R^n\text{: } \mathbf{x}^{\mathrm{LO}} \le \mathbf{x} \le \mathbf{x}^{\mathrm{UP}}\} \\ \mathbf{y} \in Y = \{0,1\}^m \end{gathered}$$

where **x** is a vector of continuous variables and **y** is a vector of discrete (binary 0-1) variables. The function $f(\mathbf{x}, \mathbf{y})$ is the objective function, which is subjected to the (in)equality constraints $g_k(\mathbf{x},\mathbf{y})$. At least one function must be non-linear. All functions must be continuous and differentiable.

3 MINLP optimization model

According to the above MINLP formulation, the MINLP optimization model of the UGS is being developed. The model comprises the cost objective function of the system, which is subjected to geomechanical, design and logical constraints. The model input data (constants) and variables are also defined.

While the geomechanical constraints assure sufficient strength of the surrounding rock, they also prevent the uplift of the rock above the cavern, they prevent rock collapse between caverns and they limit the large deformations of the concrete wall and steel lining. The design constraints define the relationships between the dimensions of the LRC, internal gas pressure and the rock. They also represent the upper and lower bounds of the variables. The logical constraints define the relationships between discrete (binary 0-1) variables and determine the system topology (number of caverns) and the discrete dimensions of the structure. Since the model is simple and contains only some main constraints, it is suitable for use in the preliminary design phase.

The design variables (**x**) represent the number of caverns *NOCAV*, the inner diameter of the cavern *DCAV* [m], the depth of the cavern *DEPTH* [m], the height of the cavern tube *HCAV* [m], the thickness of the concrete cavern wall *TWALL* [m] and the gas pressure *PGAS* [MPa], see Fig. 1. These variables are explicitly rounded on whole discrete values during the optimization process.

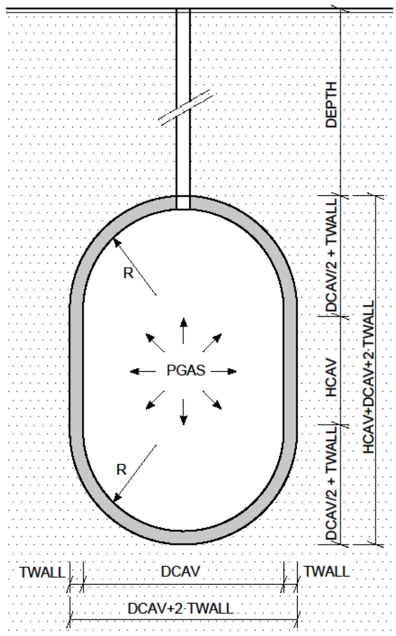

Figure 1: Vertical cross-section of lined rock cavern.
Sourece: own.

The objective function includes the investment costs of the UGS system *COSTS* [€]. It is defined by Eq. (1).

$$COSTS = FIX + f(\mathbf{x})\cdot NOCAV \tag{1}$$

The equation defines the fixed costs *FIX* and the dimension-dependent costs *f*(**x**) of a cavern, multiplied by the number of caverns *NOCAV*. While the fixed costs include the upper-ground and underground works, the dimension-dependent costs represent the excavation and protection of the cavern and its tunnel, as well as the costs for the drainage system, concrete, reinforcement and steel lining of the cavern.

Topology logical constraints define the objective variable $NOCAV$ - the number of caverns built in a UGS facility, see Eqs. (2)-(4). The variable $NOCAV$ is calculated as the sum of the binary variables y_{NOCAVi}, $i \in I$, see Eq. (3). Eq. (4) defines only one possible vector of binary variables, which is assigned for each topology (number of caverns). For example, the minimal topology with a single cavern is defined in this way by the vector of binary variables $\boldsymbol{y}_{NOCAV} = \{1,0,0,0,0,\ldots,0\}$ and not by $\boldsymbol{y}_{NOCAV} = \{0,1,0,0,0,\ldots,0\}$ or others.

$$NOCAV^{LO} \leq NOCAV \leq NOCAV^{UP} \tag{2}$$
$$NOCAV = \sum_i y_{NOCAVi} \tag{3}$$
$$y_{NOCAVi-1} \geq y_{NOCAVi} \tag{4}$$

Discrete dimensions are determined by Eqs. (5)-(7). For example, the height of the cavern tube $HCAV$ is calculated as a scalar product between a vector of the discrete value alternatives $\boldsymbol{q}_{HCAV}$ and a vector of the binary variables $\boldsymbol{y}_{HCAV}$, see Eq. (6). Only one discrete value is then selected for the variable, since the sum of j, $j \in J$, binary variables is equal one, see Eq. (7). All design variables are determined in this way.

$$HCAV^{LO} \leq HCAV \leq HCAV^{UP} \tag{5}$$
$$HCAV = \sum_i q_{HCAVj} \cdot y_{HCAVj} \tag{6}$$
$$\sum_i q_{HCAVj} = 1 \tag{7}$$

4 Numerical example

The simultaneous topology, discrete dimension and cost optimization of the underground gas storage in Senovo, Slovenia, is presented. The UGS in Senovo is planned to store 22.24 million m^3 of natural gas.

Note that the primary project comprised four lined rock caverns, which were to be included in the UGS - to store 5.56 million m^3 of natural gas each. This design (with the specified number of four caverns) was optimized with MINLP by (Kravanja and Žula, 2018) and achieved the optimal result of 72.88 million EUR., see Fig. 2, which represented 47.7 % of the savings compared to the design obtained with the classical method (FEM).

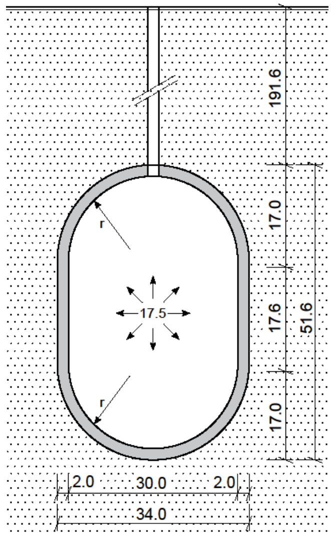

Figure 2: Optimized lined rock caverns of the UGS (Nocav = 4).
Sourece: own.

The topology, discrete dimension and cost optimization of the Senovo UGS is performed using a new MINLP optimization model, which includes topology logical constraints and some other modifications. The cost items and prices defined in the cost objective function are the same as those used in the project and in our previous optimizations, see Table 1. The model is written in GAMS, the General Algebraic Modelling System by (Brooke *et al.*, 1988). Four different topologies have been defined that determine 1, 2, 3 or 4 caverns. The LRC superstructure also includes 200 different rounded dimension alternatives for the inner diameter of the cavern, 2000 alternatives for the depth of the cavern, 2000 alternatives for the height of the cavern tube, 30 alternatives for the thickness of the concrete cavern wall and 200 discrete alternatives for the internal gas pressure. The overall combinatorics of the discrete problem is high: a total 4434 binary variables of the alternatives yield $1.92 \cdot 10^{13}$ different LRC structural alternatives. One of them is optimal.

This discrete MINLP optimization is performed with the program GAMS/DICOPT, which was developed by (Grossmann & Viswanathan, 2002). Note that comprehensive MINLP problems we usually optimize with the computer synthesizer MipSyn by (Kravanja, 2010). The optimal result represents the minimal total investment costs of the UGS of 57.62 million EUR. The optimal topology with

2 caverns is obtained. Fig. 3 shows the vertical cross-section of the optimized lined rock caverns. The figure shows the calculated "optimal" discrete variables (dimensions and the internal gas pressure). Note that this optimal result shows an additional 21 % of the net savings compared to the previous optimized design with fixed topology.

Table 1: Cost items and prices.

Cost item	Price	
Upper ground works	2 982 500	EUR
Underground works	2 798 025	EUR
Price of the tunnel excavation	2 440	EUR/m[1]
Price of the tunnel protection	1 340	EUR/m[1]
Price of the cavern excavation	100	EUR/m^3
Price of the cavern protection	90	EUR/m^2
Price of the cavern drainage	60	EUR/m^2
Price of the cavern wall concrete	190	EUR/m^3
Price of the wall reinforcement	2 000	EUR/t
Price of the steel lining	920	EUR/m^2

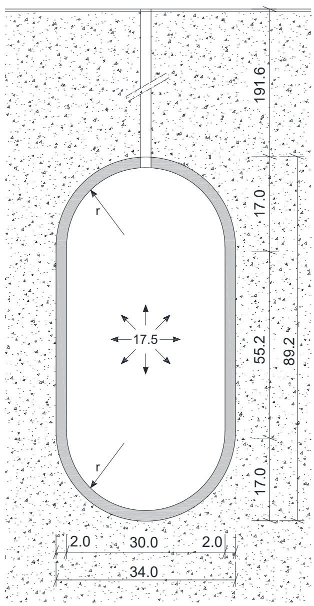

Figure 3: Optimized lined rock caverns of the UGS (Nocav = 2).

Sourece: own.

5 Conclusions

The paper discusses the simultaneous topology, discrete dimension and cost optimization of the lined rock caverns of underground storage of chemical energy. The optimization is performed by the mixed-integer non-linear programming, MINLP. The MINLP optimization model is developed into which the topology logical constraints are inserted. The numerical example at the end of the paper shows the advantages of the presented simultaneous optimization approach, tested on the case of the underground gas storage Senovo, Slovenia. A new optimal topology of two caverns is found. Significant additional investment savings are achieved. The result achieved represents the trade-off between the storage capacity and the investment costs of construction. In a future study, the operating costs of the underground storage facility, including filling and emptying of the storage, will be investigated. The proposed approach is also attractive for the optimization of underground storage facilities for hydrogen or methane.

Acknowledgments

The authors are grateful for the support of funds from the Slovenian Research Agency (research programes P2-0129, P2-0268 and P2-0032).

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