THE INFLUENCE OF SAFETY FACTORS ON THE OPTIMAL DESIGN OF UNDERGROUND LINED ROCK CAVERNS

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Abstract This paper presents the influence of safety factors on the optimal design of lined rock caverns (LRC), designed for underground gas storage (UGS). For this system, adequate safety precautions and sufficient strength of the surrounding rock must be ensured. Security steps must be provided for all risks which may occur. This is assured by the inclusion of two special constraints and safety factors into the UGS optimization model. In order to study the influence of safety factor on the system, a parametric mixed-integer non-linear programming (MINLP) optimization of the system is performed for different values of the safety factors. A cost optimization is carried out and GAMS/Dicopt is used. A numerical example at the end of the paper shows the influence of safety factors on the optimal production costs and design of an LRC.

Keywords: Lined rock cavern, Safety factor, Cost optimization, Mixed-integer non-linear programming, MINLP.

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1 Introduction

This paper examines the influence of safety factors on the optimal design of a lined rock cavern (LRC) designed for underground gas storage (UGS). The LRC contains gas under high pressure, and the UGS system is usually designed with one or more LRCs. The LRC is normally constructed inside a rock mass. It is comprised of a cylindrically shaped concrete wall which has a steel lining in order to ensure impermeability. The surrounding rock supports the gas pressure; see Stille and Sturk (1994), Sofregaz US Inc. (1999), Brandshaug *et al.* (2001), Chung *et al.* (2003) and Glamheden and Curtis (2006).

We present a continuation of earlier research in which non-linear programming (NLP) optimization of a single gas cavern was described by Kravanja and Žlender (2010) and later extended to optimization of an entire UGS with any number of caverns by Žlender and Kravanja (2011), and to the optimization in different rock environments by Kravanja and Žlender (2012) and Jelušič *et al.* (2019). The latter reference introduced a prediction of the minimal investment costs for the UGSs, with capacities from 10 to 100 million m^3 of natural gas, with the help of an adaptive network based fuzzy inference system (ANFIS). Analyses of the LRC/UGS with the ANFIS were reported by Žlender *et al.* (2012, 2013) and Jelušič and Žlender (2014).

For this study, an NLP optimization model of an UGS was developed in which the cost objective function of the system was subjected to geomechanical and design constraints. While the geomechanical constraints assure sufficient strength of the LRC´s surrounding rock, the design constraints define the relations between the LRC's dimensions, inner gas pressure and the rock. In Kravanja and Žula (2018), discrete alternatives for rounding the dimensions of the LRC were added to the optimization model and mixed-integer non-linear programming (MINLP) optimization was applied.

According to Žlender and Kravanja (2011) and Jelušič *et al.* (2019), four of the most important risks which may occur during the construction/operation of an LRC and UGS can be prevented by four geomechanical constraints: the strength of the rock mass is sufficient, uplift of the rock above the cavern is prevented, collapse of the rock between the caverns is prevented and deformations of the concrete wall and steel lining are limited (large deformations or destruction of the steel lining are prevented); see also Kravanja and Žula (2018). These constraints were derived from a series of the finite element method (FEM) analyses using the Hoek-Brown failure criterion; see Hoek *et al.* (2002).

Two of the risks mentioned, uplift of the rock above the cavern and collapse of the rock between caverns, are countered by the inclusion of safety factors into two geomechanical constraints. In order to study the influence of these safety factors on the system, a parametric mixed-integer non-linear programming (MINLP) optimization of the system was performed for different values of these safety factors.

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:

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

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

The optimization model of the LRC is developed according to the above MINLP formulation. The model is comprised of the cost objective function, geomechanical and design constraints, input data (constants) and variables. The design variables ($\mathbf{x}$), which are rounded on whole discrete values during the MINLP optimization process, are: 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.

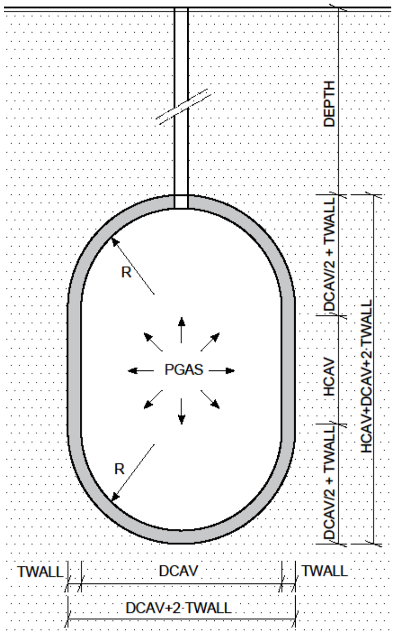

Figure 1: Vertical cross-section of lined rock cavern.

3 Safety factors

Adequate safety factors of the LRC/UGS and the strength of the surrounding rock must be calculated/checked. Security steps should be provided for all risks which may be occur. Two risks, uplift of the rock above the cavern and collapse of the rock between caverns, are prevented by the inclusion of two safety factors SF_{up} and SF_{horiz} into two geomechanical constraints in the model; see Eqs. (1) - (4). The safety factor against rock uplift above the cavern SF_{up} must be, according to Žlender and Kravanja (2011) and Jelušič *et al.* (2019), greater than a defined minimal value $SF_{up,min}$, see Eq. (1). SF_{up} is defined by Eq. (2). The same holds with the safety factor against rock collapse between two caverns SF_{horiz}, which must be greater than a defined minimal value $SF_{horiz,min}$; see Eq. (3). SF_{horiz} is determined by Eq. (4). It should be noted that these two safety factors, Eqs. (2) and (4), were derived as approximation functions from a series of the finite element method (FEM) analyses for different values of inner gases *PGAS*, depths of the cavern *DEPTH* and diameters of the cavern *DCAV*. Coefficients $c_1 - c_3$, $f_1 - f_3$, $g_1 - g_3$, $i_1 - i_3$ and the initial values of safety factors $SF_{up,0}$ and $SF_{horiz,0}$ depend on the type of rock in which is the LRC constructed; see these values in Jelušič *et al.* (2019). The initial values of the variables are: $PGAS_0 = 20$ MPa, $DEPTH_0 = 150$ m and $DCAV_0 = 25$ m.

$$SF_{up} \geq SF_{up,min} \tag{1}$$

$$SF_{up} = SF_{up,0} \cdot c_1 \cdot \left(\frac{PGAS}{PGAS_0}\right)^{f_1} \cdot c_2 \cdot \left(\frac{DEPTH}{DEPTH_0}\right)^{f_2} \cdot c_3 \cdot \left(\frac{DCAV}{DCAV_0}\right)^{f_3} \tag{2}$$

$$SF_{horiz} \geq SF_{horiz,min} \tag{3}$$

$$SF_{horiz} = SF_{horiz,0} \cdot g_1 \cdot \left(\frac{PGAS}{PGAS_0}\right)^{i_1} \cdot g_2 \cdot \left(\frac{DEPTH}{DEPTH_0}\right)^{i_2} \cdot g_3 \cdot \left(\frac{DCAV}{DCAV_0}\right)^{i_3} \tag{4}$$

The minimal values of safety factors $SF_{up,min}$ and $SF_{horiz,min}$ should be taken to be at least 2. In cases where the LRC/UGS is located in a rural/mountain area, $SF_{up,min}$ and $SF_{horiz,min}$ are usually defined to be 2.5. Here, two questions arise: if we define higher values of safety factors, how much will the investment costs of the LRC increase and what are changes in the LRC's design. The latter is necessary in cases when the LRC/UGS is planned to be constructed close to an urban area. In order to study the influence of safety factors on the system, parametric mixed-integer non-linear programming (MINLP) optimization of the system is performed for different values of safety factors.

4 Numerical example

A parametric MINLP optimization of the investment costs of a lined rock cavern designed for underground gas storage in Senovo, Slovenia is presented. The parametric optimization was performed seven times for different values of safety factors SF ($SF_{up,min}$ and $SF_{horiz,min}$): from 1 to 6. The UGS in Senovo is planned to be constructed with four LRCs of 5.56 million m^3 of natural gas capacity each; see Žlender and Kravanja (2011).

The MINLP optimization model includes similar constraints as in Kravanja and Žlender (2010) and in Kravanja and Žula (2018). Cost items and prices defined in the cost objective function are the same as those used in the project and our previous optimizations; see Table 1. The model is written in GAMS, the General Algebraic Modelling System by Brooke *et al.* (1988). The combinatorics of the MINLP problem is relatively high: altogether 4735 binary variables of alternatives give $1.508 \cdot 10^{12}$ different LRC structure alternatives. One of them is optimal. This simple parametric cost and rounded dimension optimization is carried out with the GAMS/DICOPT program developed by Grossmann and Viswanathan (2002). Note that comprehensive MINLP problems were usually optimized with MipSyn by Kravanja (2010).

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

Table 2: Optimal results for different safety factors SF.

Variable		SF=1	SF=2	SF=2.5	SF=3	SF=4	SF=5	SF=6
PGAS	[MPa]	17.5	17.5	17.5	17.5	17.5	17.5	17.5
DEPTH	[m]	191.6	191.6	191.6	225.8	314.2	405.8	496.7
DCAV	[m]	30.0	30.0	30.0	30.0	30.0	30.0	30.0
TWALL	[m]	2.0	2.0	2.0	2.0	2.0	2.0	2.0
HCAV	[m]	17.6	17.6	17.6	17.6	17.6	17.6	17.6
$COST_{LRC}$	[M€]	18.22	18.22	18.22	18.33	18.61	18.89	19.19
$COST_{UGS}$	[M€]	72.88	72.88	72.88	73.31	74.42	75.57	76.76

The optimal results for the defined safety factors from SF=1 to SF=6 represent the obtained minimal investment costs from 18.22 to 19.19 million EUR per lined rock cavern (*COST*$_{LRC}$) and from 72.88 to 76.76 million EUR per underground gas storage facility (*COST*$_{UGS}$); see Table 2. All these results exhibit savings of more than 45 % when compared to designs obtained by the classical method (FEM). All dimensions of the caverns and the inner gas pressure are also calculated. Figure 2 presents a diagram of the obtained optimal costs and depths for the UGS Senovo depending on different defined safety factors SF ($SF_{up,min}$ and $SF_{horiz,min}$).

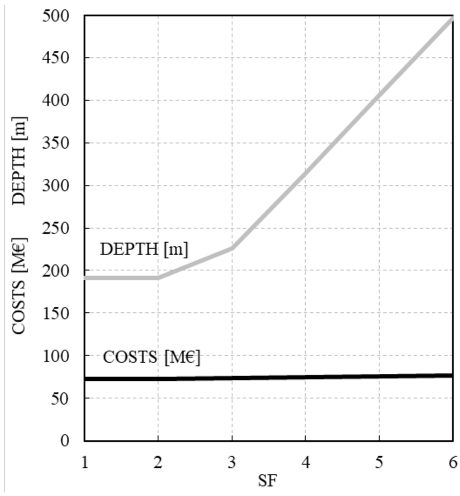

Figure 2: Diagram of the optimal costs and depths of the UGS Senovo.

It is somewhat surprising that all variables, except the depth of the cavern, remain the same for all different safety factors. While the optimal costs of the system rise slightly and monotonically, the optimal depths increase significantly for higher safety factors (SF). The results show that if we increase the safety factor from 2.5 to 5.0, the optimal investment costs rise by only 3.7 % although the cavern depth increases 2.1 times (from 191.6 m to 405.8m).

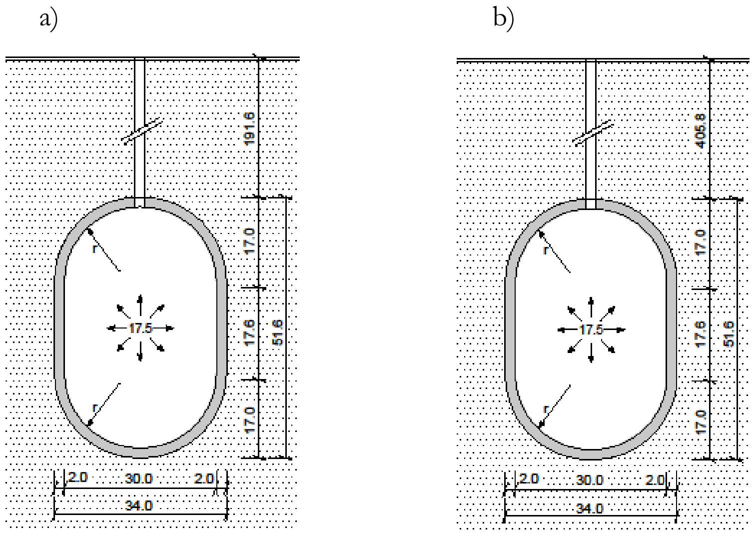

Figure 3: The optimized lined rock cavern, a) SF=2.5, b) SF=5.

5 Conclusions

We examined the influence of safety factors on the optimal design of a lined rock cavern (LRC) designed for underground gas storage (UGS). For this system, adequate safety precautions and sufficient strength of the surrounding rock must be provided. This is assured by the inclusion of two special constraints and safety factors into the UGS optimization model. In cases where the LRC/UGS is located in a rural/mountain area, the safety factor is usually defined as 2.5. However, when the LRC/UGS is planned to be constructed close to an urban area, we have to use higher safety factors. In order to study the influence of safety factors on the system, a parametric mixed-integer non-linear programming (MINLP) of the system is performed for different values of safety factors. Cost optimization is carried out using GAMS/Dicopt. A numerical example at the end of the paper shows that even with doubled safety factors, when the safety factor increases from 2.5 to 5.0, the optimal investment costs rise by only 3.7 %. The design of the cavern shell remains the same, but the cavern depth becomes twice as deep.

Acknowledgments

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