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# Fuzzy Sets concept for optimization underground gas storage

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ABSTRACT: The paper deals with the underground gas storage (UGS), designed from one or more lined rock caverns (LRC). The LRC is a pressure tank containing stored gas under a 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: 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 influence on the environment. This paper presents the Fuzzy Sets concept to improve performance of UGS with LRC's. For this purpose, it is necessary to carry out a number of steps. First is the determination of the geological model of UGS region. 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: number of caverns, distance between them, inner gas pressures, cavern depths, cavern diameters and cavern wall thickness. A Fuzzy Inference System (FIS) optimizing cavern is carried out. The approach is illustrated in the case of UGS Senovo, which is in the planning stage. The FIS allows optimizing, regarding to risk conditions, the most suitable solution depending on the site and on the financial possibilities available. Several rules were built and fired for all the intervening parameters and the final result is obtained after defuzzification.

*Keywords: Underground gas storage (UGS), Lined rock cavern (LRC), Fuzzy Sets, Fuzzy Inference System (FIS)*

## 1 INTRODUCTION

The underground gas storage (UGS) contains one or more lined rock caverns (LRC). The LRC is a pressure tank containing stored gas under a 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 influence on the environment.

In order to achieve the optimal design of UGS with LRC the geomechanical model, the cost optimization model and Fuzzy inference system are involved.

Fuzzy Inference System (FIS) is carried out to improve performance of UGS with LRC's. FIS is one of the tools used to model a multi-input, multi-output system.

Primary objectives to improve performance of UGS with LRC's are:
- Minimization of the total construction and operational costs per unit of gas,
- Safety on all risks which may occurs during the construction and operation,
- 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 through the optimization.

## 2 UGS WITH LRC

The design of the LRC structure is similar to the already constructed UGS in Skellen [1]. Cavern wall, which transmits the gas pressure on the surrounding rock, is composed of several elements [2]. 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 concrete wall. 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 drainage system is collect and drainage the water. 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 35 to 40 m and high from 60 to 100 m, with cylindrical wall and sphere upper and lower part. They are located at depths from 100 to 250 m and are surrounded by 2 m or more thick concrete wall and coating with a thin steel sheet (15 mm).

The evaluation of rock mass properties is a partly subjective process because there always exist a different interpretation of the investigated results (deviation). Many methods were developed in the past for the determination/interpretation the rock mass properties. In this work the generalized Hoek-Brown failure criterion [3] is proposed to be applied and the Mohr-Coulomb strength parameters are determined.

The external pressure acts on the wall of the cavern (during the construction and operation). The high of the pressure (2 MPa to 5 MPa) depends on the depth of the cavern. The internal pressure is beginning to occur in service. 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.

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

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

The LRC is linked with the ground surface by the vertical shaft. The shaft is made from a steel pipe for filling and emptying the gas storage [4]. The construction of the LRC starts with the erection of access tunnels. The mining of caverns is then performed downwards from the top. 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 excavated cavern surface and steel lining with concrete. When self compacted concrete is used, no concrete vibration is needed.

The LRC concept of UGS should provide a safe and environmentally friendly mode for gas storage. Since the gas should never been in contact with the surrounding rock mass, the gas storage is designed as a closed system.

## 3 GEOMECHANICAL ANALYSIS

### 3.1 *Geomechanical model*

The geomechanical model is done based on geological data, UGS design data, geomechanical parameters and FEM analyses results.

### 3.2 *Determination of the rock mass parameters*

The research included a geological mapping of surface, structural drilling of five deep boreholes, geotechnical field measurements and laboratory testing of samples from boreholes in order to determine their geomechanical parameters. Rock mass parameters were determined on the basis of the generalized Hoek-Brown failure criterion [5]. By using the generalized Hoek-Brown failure criterion, all needed parameters were obtained by geological measurements in the field, laboratory testing and calculations, see Table 1. In the beginning determined were strength parameters like the unconfined compressive strength of intact rock $\sigma_{ci}$ [MPa], the geological strength index GSI [-], the intact rock parameter mi [-] and the disturbance factor D [-] as well as the intact rock deformation modulus $E_i$ [MPa].

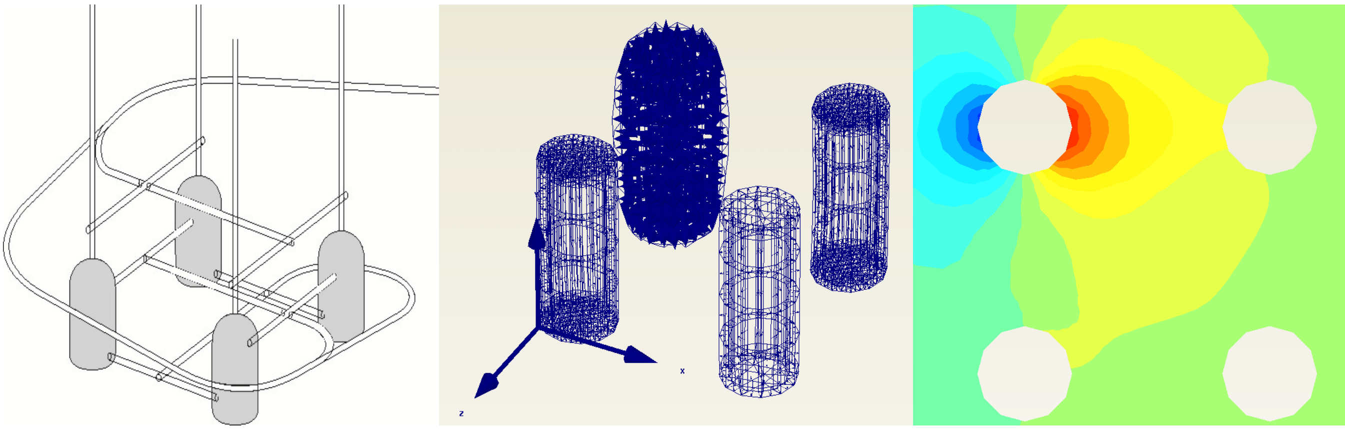

Figure 1. 3D UGS model in Plaxis FEM program

### 3.3 *Risk conditions*

The risk during construction and in the operation of the system should be analyzed. Geological conditions, hydro geological conditions and geomechanical rock mass properties around LRC significantly impact on all of the risks. The risks which occur during the construction are similar to ones at the construction of tunnels: large scale failure of the rock cover, large deformations of the cavern wall, irruption of the water and impact on water resources in the surrounding area. For the designing and optimization the risks during the operation are decisive. Hence the following risks have to be considered:

- Risk 1: Failure of the rock mass (rock strength is exceeded),
- Risk 2: Uplift of the rock cover,
- Risk 3: Failure of the rock between two caverns,
- Risk 4: Large deformation or destruction of the steel lining,
- Risk 5: Unequally deformation of the LRC structure because of the rock heterogeneity,
- Risk 6: Drainage system does not work.

Using FEM calculation it is insure that rock strength is not exceeded (Risk 1). The last two risks (Risks 5 and 6) are prevented with the correct construction of the LRC in a homogeneous rock mass and with the properly construction and operation of the drainage. Three conditions have to be defined in a form of three geomechanical inequality constraints for the (Risks 2-4):

- Condition 1: Uplift of the rock cover is prevented (Risk 2),
- Condition 2: Failure of the rock between two caverns is prevented (Risk 3),
- Condition 3: Strains of the steel lining need to be limited under the acceptable value (Risk 4).

Condition 1 is satisfied when the calculated safety factor against the rock cover uplift $SF_{up}$ is greater than a defined minimal value $SF_{up,min}$, see Eq. (1).

$$SF_{up} \geq SF_{up,\min} \quad (1)$$

The calculated safety factor against the rock failure between two caverns $SF_{hor}$ must be greater than a defined minimal value $SF_{hor,min}$, see Eq. (2).

$$SF_{hor} \geq SF_{hor,\min} \quad (2)$$

Strains of steel lining $\varepsilon$ are limited to be smaller than a defined maximal strain $\varepsilon_{max}$, see Eq. (3).

$$\varepsilon \leq \varepsilon_{\max} \quad (3)$$

The risks increase with the increasing of the gas pressure in the caverns and diameter of the cavern and decrease with the increasing the depth of the LRC and the thickness of the concrete wall. The gas pressure is cyclically increases and decreases, which affects on the fatigue of materials.

### 3.4 *Geomechanical analyses*

A series of FEM analyses was carried out to satisfy conditions (1), (2) and (3). The FE mesh, consisted from triangle prismatic finite elements, was defined for the rock mass area of 280x280x300 m3 (x-y-z, with z the axis in depth). The FEM computer program Plaxis Version 3D [6] was used.

### 3.5 *Results*

Analysis with different combinations of parameters can be carried out. In the event that we have six different parameters and three values of each parameter then we have 729 different combinations. Each combination has its own effect on the strain, safety factors against the rock cover uplift $SF_{up}$ and the rock failure between two caverns $SF_{hor}$. Safety factors $SF_{up}$, $SF_{hor}$ and strains ε are obtained from a series of FEM analyses for all the mentioned combinations of parameters.

## 4 COST ANALYSIS

The cost model consist cost data, design data, dimension dependence quantities, and construction cost [7].

### 4.1 *Cost data*

The geomechanical input data are presented in 3.1.1. Economic data for the optimization include fixed costs per cavern: upper ground works $C_{up}$ and underground works $C_{under}$ and prices per unit like the price of the tunnel excavation $PR_{exc,tun}$ [€/m$^3$], the price of the tunnel protection $PR_{prot,tun}$ [€/m$^3$], the price of the cavern excavation $PR_{exc,cav}$ [€/m$^3$], the price of the cavern protection $PR_{prot,cav}$ [€/m$^2$], the price of the cavern drainage $PR_{drain}$ [€/m$^2$], the price of the cavern wall concrete $PR_{wall}$ [€/m$^3$], the price for the wall reinforcement $PR_{reinf}$ [€/t] and the price of the steel lining $PR_{steel}$ [€/m$^2$].

### 4.2 *Design data*

The value $L^{sf}_{exc,tun}$ [m] is the length of tunnel excavation. The length $L_0$ varies from the case to case and is dependent on the number of LRC's inside the UGS and the cavern depth. $V^{sf}_{exc,cav}$ [m$^3$] is the cavern excavation volume. $A^{sf}_{exc,cav}$ [m$^2$] is the cavern excavation area. Term $\left(V^{sf}_{exc,cav} - V^{sf}_{cav}\right)$ denotes the volume of used concrete and $V^{sf}_{cav}$ stands for the inner volume of the cavern. $A^{sf}_{cav}$ is the spread area of the steel lining (inner cavern area). The volume of concrete and the weight of reinforcement are estimated.

### 4.3 *Construction cost*

The construction cost comprises the investment and operational costs of the UGS system. The total construction cost per cavern [€/$_{cav}$] and total construction cost per unit of gas [€/m$^3$gas] include sum of fixed costs and variable (depending) costs (4): Fixed costs are sum of upper ground works $C_{up}$ and underground works $C_{under}$. Variable costs are sum of cost for the tunnel excavation $C_{exc,tun}$, the tunnel protection $C_{prot,tun}$, the cavern excavation $C_{exc,cav}$, the cavern protection $C_{prot,cav}$, the cavern drainage $C_{drain}$, the cavern wall $C_{wall}$ and the cost of the steel lining $C_{steel}$. Total construction and operational cost per unit depends of number of cycles ($No_{cycles}$ [-]) of gas supply and discharge (6).

$$COST/cav = \left(C_{up} + C_{under}\right)/N_{0,cav} + C_{exc,tun} + C_{prot,tun} + C_{exc,cav} + C_{prot,cav} + C_{drain} + C_{wall} + C_{reinf} + C_{steel} \tag{4}$$

$$\begin{aligned} COST/cav = {} & FC_{up} + FC_{under} + PR_{exc,tun} \cdot L_{exc,tun} + PR_{prot,tun} \cdot L_{exc,tun} + PR_{exc,cav} \cdot V_{exc,cav} + PR_{prot,cav} \cdot A_{exc,cav} \\ & + PR_{drain} \cdot A_{exc,cav} + PR_{wall} \cdot \left(V_{exc,cav} - V_{cav}\right) + PR_{reinf} \cdot \left(V_{exc,cav} - V_{cav}\right) \cdot \rho \cdot r_{perc} + PR_{steel} \cdot A_{cav} \end{aligned} \tag{5}$$

$$COST/m^3 gas = \frac{COST/cav}{V_{gas} \cdot N_{0,cycles}} \tag{6}$$

## 5 FUZZY INFERENCE SYSTEMS

The article aims to investigate the influence of various parameters on safety factors $SF_{up}$, $SF_{hor}$ and strain. Because of the enormous number of possible combinations of parameters it is necessary to carry out a lot of geotechnical analysis, which is demanding work. It is also difficult to determine geomechanical parameters from geological data. The main purpose is to obtain optimal parameter values. Nonlinear programming is a powerful tool by which we get the optimal parameters, but requires complex analytical equations to determine the interdependence of parameters.

Fuzzy logic is an effective paradigm to handle imprecision, which significantly reduces a number of geotechnical analyses. It can be used to take fuzzy or imprecise observations for inputs and yet arrive at crisp and precise values for outputs. Also, the Fuzzy Inference System (FIS) is a simple and commonsensical way to build systems without using complex analytical equations. Fuzzy sets [8] are widely used in engineering and especially in geological and geotechnical fields. A fuzzy set is defined as constituted by elements belonging with a degree of membership μ (x) to the set. The membership function varies between 0 and 1. Fig. 2a) shows the concept of FIS.

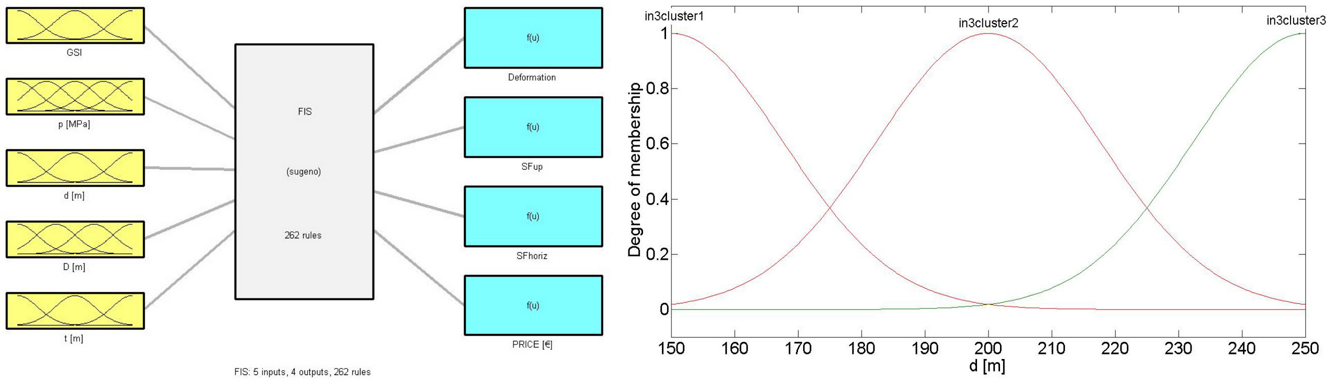

Figure 2. a) Concept of fuzzy inference system; b) Example of fuzzy sets INPUT parameter

### 5.1 *Fuzzy Inference System*

The fuzzy inference system for UGS is based on, INPUT Parameter, OUTPUT Parameters, Fuzzy rules and Defuzzification of the result (decision).

#### 5.1.1 *Input and Output parameters*

The number of rows represents the number of combinations calculated with geomechanical and cost model. A row constitutes a set of observed values of the 7 input variables ($No_{cav}$[-], $l_{cav}$ [m], GSI [-], p [MPa], d [m], D [m], t[m]) and the corresponding row, in output represents the calculated values (ε [‰], $SF_{up}$, $SF_{hor}$, Price [€]) for the input variables. To identify natural groupings in data from a large data set we use clustering technique, which allow us concise representation of relationships embedded in the data. Each input and output has as many membership functions as the number of clusters that has been identified with clustering. Sugeno-type FIS structure assigns default values and names for inputs, outputs and membership functions [9]. An example of input and output fuzzy sets is presented on Fig.2b.

#### 5.1.2 *Fuzzy rules*

Sugeno-type FIS structure map a cluster in the input space to a cluster in the output space. If the inputs to the FIS, strongly belong to their respective membership functions then the output must strongly belong to its membership function. The (1) at the end of the rule is to indicate that the rule has a weight or an importance of "1". Weights can take any value between 0 and 1. Rules with lesser weights will count for less in the final output. An example of these rules is:

IF (GSI is in1cluster1) AND (p is in2cluster1) AND (d is in3cluster1) AND (D is in4cluster1) AND (t is in5cluster1) THEN (ε is out1cluster1)($SF_{up}$ is out2cluster1)($SF_{hor}$ is out3cluster1)(PRICE is out4cluster1) (1)

#### 5.1.3 *Defuzzification*

The output of the FIS, has linear membership functions representing the clusters identified by clustering. The coefficients of the linear membership functions though are not taken directly from the cluster centers.

Instead, they are estimated from the dataset using least squares estimation technique. All membership functions in this case will be of the form $a \cdot No_{cav} + b \cdot l_{cav} + c \cdot GSI + d \cdot p + e \cdot d + f \cdot D + g \cdot t + h$, where a, b, c, d, e, f, g and h represent the coefficients of the linear membership function.

## 6 APPLICATION

Below is an example of analysis of UGS with LRC planned to place Senovo [10]. The research included a geological mapping, geotechnical field measurements (pressiometer, geophysical measurements, and hydro-geological measurements) and laboratory testing. Data obtained from geological mapping and geological inventory of the core wells, confirming act and limestone Dolomites in the eastern area of mine Senovo [11]. The UGS is planned to be constructed from 4 equal lined rock caverns in order to store 5.56 x 4 = 22.24 millions $m^3$ of natural gas. The concrete C 30/37 and structural steel S 235 are used for the construction of tunnels, cavern walls and steel lining. Steel S 400 was used for the reinforcement. Steel lining is 12 mm thick. The optimization/calculation of the UGS system comprises: determination of the rock mass parameters, geomechanical analyses, cost analysis and Fuzzy Inference System.

### 6.1 *Rock mass parameters*

The research included a geological mapping of surface, structural drilling of five deep boreholes, geotechnical field measurements and laboratory testing of samples from boreholes in order to determine their geomechanical parameters. Data obtained from geological mapping and geological inventory of the boreholes, confirming presence of limestone and dolomite in the eastern area of mine Senovo are presented in reference [11]. Rock mass parameters were determined on the basis of the generalized Hoek-Brown failure criterion [12]. By using the generalized Hoek-Brown failure criterion, all needed parameters were obtained by geological measurements in the field, laboratory testing and calculations, see Table 1. In the beginning determined were strength parameters like the unconfined compressive strength of intact rock $\sigma_{ci}$ [MPa], the geological strength index GSI [-], the intact rock parameter mi [-] and the disturbance factor D [-] as well as the intact rock deformation modulus $E_i$ [MPa].

Table 1. Hoek-Brown parameters, Mohr-Coulomb fit and rock mass parameters

| Hoek-Brown Classification | Minimum | Average | Maximum |
|---|---|---|---|
| σci [MPa] | 55 | 60 | 65 |
| GSI [-] | 41 | 46 | 51 |
| mi [-] | (9+/-3) | (9+/-3) | (9+/-3) |
| D [-] | 0.200 | 0.183 | 0.167 |
| Ei [MPa] | 40 | 55 | 60 |
| Hoek-Brown criterion | | | |
| mb [-] | 0.866 | 1.056 | 1.333 |
| s [-] | 0.0090 | 0.0016 | 0.0031 |
| a [-] | 0.511 | 0.508 | 0.505 |
| Mohr-Coulomb fit | | | |
| c [kPa] | 700 | 870 | 1000 |
| φ [°] | 37.5 | 39 | 41 |
| Rock mass parameters | | | |
| σt [MPa] | 0.057 | 0.092 | 0.15 |
| σc [GPa] | 1.5 | 2.3 | 3.5 |
| σcm [GPa] | 6.6 | 8.2 | 10.1 |
| Erm [GPa] | 5.0 | 10.0 | 15 |

### 6.2 *Geomechanical and cost analyses*

Safety factors against the rock cover uplift $SF_{up}$ and the rock failure between two caverns $SF_{hor}$ were calculated for 180 various combinations between 3 different rock mass parameters GSI (41, 46, 51), 5 different inner gas pressures p (10, 15, 20, 25 and 30 MPa), 3 different cavern depths h (150, 200 and 250 m) and 4 different cavern inner diameters D (15, 20, 25 and 30 m), see Table 2.

The strains of steel lining ε were in addition calculated for 3 different thickness of the concrete wall t (2, 4 and 6 m) having thus together 180x3=540 calculations. These calculations were performed by a series of FEM analyses for the treated UGS of Senovo. These calculations were used for non-linear programming and expressed with analytical equations. Non-linear programming serves us for comparing with fuzzy results.

Fuzzy allow us to reduce number of calculations and still give us satisfied results. In this example we reduced number of calculations to 54.

Table 2. Obtained safety factors $SF_{up}$, $SF_{hor}$ and strains ε from FEM analyses

| | Input | | | | | Geomechnical output | | | Cost output |
|---|---|---|---|---|---|---|---|---|---|
| No. | GSI [-] | p [MPa] | d [m] | D [m] | t [m] | $SF_{up}$ [-] | $SF_{hor}$ [-] | ε [‰] | Cost/cav [€] |
| 1 | 41 | 10 | 150 | 15 | 2 | 8,14 | 5,93 | 2,98 | 46936615,09 |
| 2 | 41 | 15 | 150 | 15 | 2 | 5,42 | 4,00 | 6,85 | 39465455,06 |
| etc. | | | | | | | | | |
| 54 | 51 | 30 | 250 | 30 | 6 | 3,5 | 2,16 | 3,60 | 41465145,30 |

## 6.3 *Risk conditions*

Risk conditions (4)-(6) for the considered UGS system of Senovo were finally evaluated as follows and put into the Fuzzy sets optimization model. Safety factors $SF_{up,min}$ and $SF_{hor,min}$ were defined to be 2.0. The limit strain $\varepsilon_{max}$ was taken 3.5 ‰ for 1000 planed cycles of loadings.

## 6.4 *Fuzzy Inference System*

The Fuzzy Inference System of the UGS system in Senovo was performed. When executing the fuzzy system some conditions are imposed on deformations in the rock mass and structure with the limitations due to financial possibilities. The system permits to evaluate prices for different combinations of input parameters. The decision to take is illustrated in Figs. 3, 4, 5 and 6. Fig.3a shows the influence of gas-pressure and rock mass parameters on strains for given $l_{cav}$ = 75 m, D = 25 m and t = 2 m. Comparison of Figs.3a and 3b describes the impact of depth (150 m and 200 m) of cavern on strains. Comparison between Figs. 4a and 4b represent the impact of depth of cavern on the safety factor against the rock cover uplift while Figs. 5a and 5b, shows the same thing in terms of safety factor against the rock failure between two caverns.

When all conditions are satisfied we can evaluate price (see Fig.6a and Fig.6b). Other surfaces could be plotted; they serve as a decision support system for the engineer. The system allows analyzing the situation and taking the required decision regarding the feasibility of the LRC.

# 7 CONCLUSION

The Fuzzy concept for UGS with LRC is presented. For this purpose it is necessary to carry out a number of steps. First is determination the geological model of UGS region. Next is transferring the geological model into the geomechanical model. In this work the system of Hoek and Brown based on the GSI is applied. The equivalent Mohr-Coulomb strength parameters were determined. Geomechanical analysis for risk during construction and later during operation of UGS, using FEM was carried out.

FEM analyses consists a set of calculations for different data (variables) such as: mechanical properties of the soil and the LRC, the depth and the spaces between the LRC, LRC geometry and dimensions, gas pressure, etc. A Fuzzy Inference System is carried out. Uncertainties and vague information are well handled using fuzzy sets.

For lower pressures big caverns are needed with small thickness of concrete, on the other hand if the pressure is “high” this will imply “smaller” caverns with “important” concrete thickness. The prices are very sensitive in each case. The decision to take is facilitated using the fuzzy inference system proposed; we plotted some curves (surfaces) which permit visualizing the parameters on the decision to take.

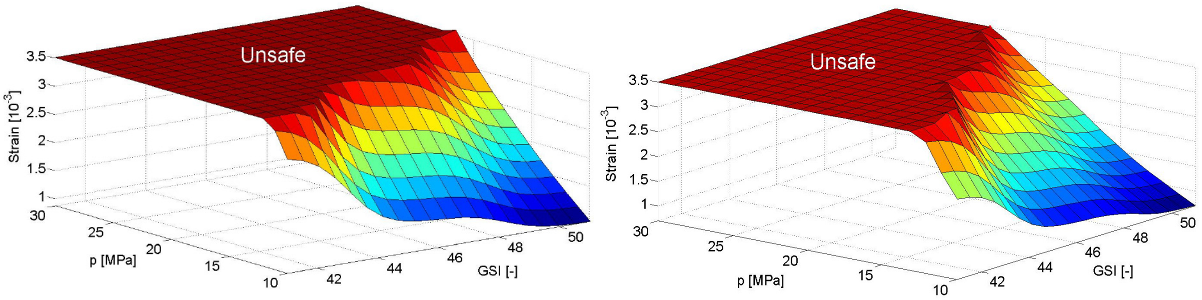


Figure 3. Strain a) d =150 m; b) d = 200m

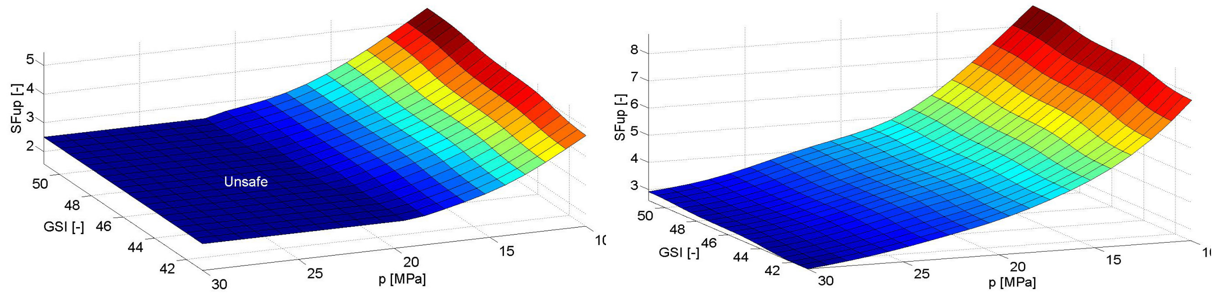


Figure 4. $SF_{up}$ safety a) d =150 m; b) d = 200m

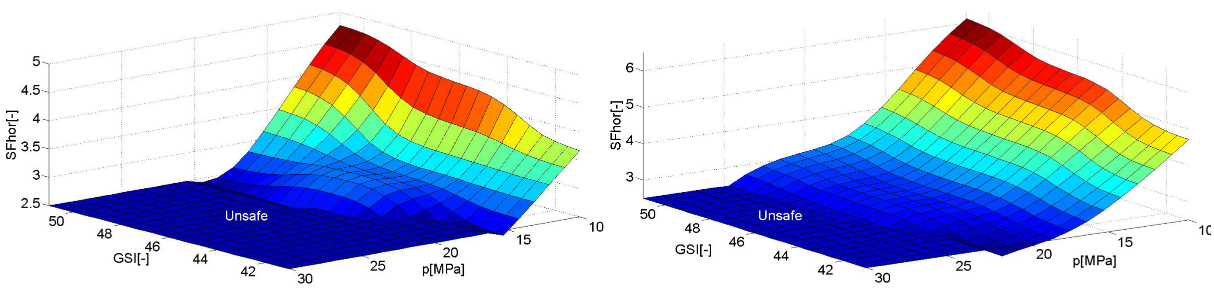


Figure 5. $SF_{hor}$ safety a) d =150 m; b) d = 200m

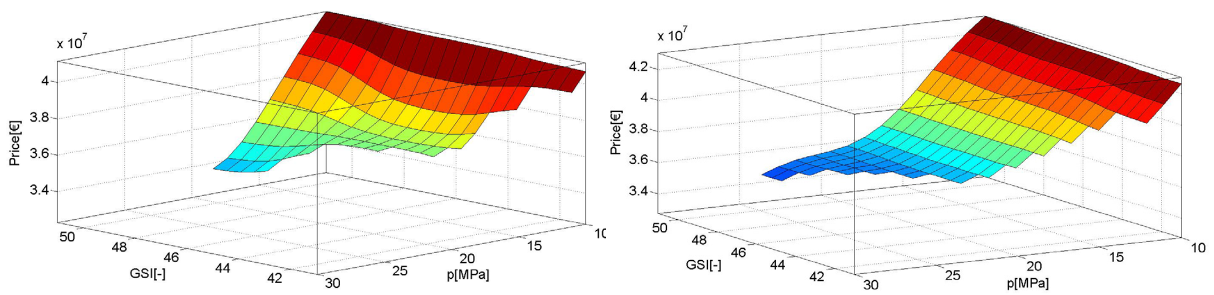


Figure 6. Price in safety area a) d =150 m; b) d = 200m

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