What can be the future of underground storages in the context of green energy? - Geomechanical aspects

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ABSTRACT: Compressed hydrogen is classically stored in steel overground tanks. Large underground storages of compressed hydrogen are extremely few whereas the challenge today is storing liquified hydrogen at very low temperature (cryogenic). Salt caverns are used for storing compressed hydrogen in gaseous state since the 1970s but suitable salt environments are limited and heterogeneously distributed, worldwide. Thus, storing compressed hydrogen in lined rock caverns (LRC) similar to compressed natural gas (CNG) is now envisaged. Currently there is only one example of LRC for storing CNG in operation and no compressed hydrogen rock cavern has been designed yet at an industrial scale. Regarding geomechanics, the conversion of salt caverns is relatively easy but more difficult for rock caverns, due to the required steel membrane and the quality of the host rock mass. The main design criteria and preliminary geomechanical modelling required for cavern creations and challenges for the conversion are also discussed.

Keywords: hydrogen, storage, cavern, salt, conversion.

1 INTRODUCTION

In the context of the global warming and the need for green energy, the market requires an energy vector that can convey energy with a minimum emission of CO_2. In this regard, hydrogen can be one of the vectors, if its production also can be made without CO_2 emissions, such as electrolysis of water or membrane purification (Green Hydrogen). However, reforming of methane remains the majority production of (grey) hydrogen. The international demand of hydrogen will dramatically increase in the coming years and along with this demand, the storage of hydrogen shall develop (at the source, in hubs or close to the consumption centres). Various vectors can be used for hydrogen transportation and storage from pure hydrogen to more sophisticated and very promising forms such as ammonia or metal hydrated (Davoodabadi et al. 2021). This paper is limited to pure hydrogen and underground storage only.

2 HYDROGEN STORED IN SALT CAVERNS

Up to now, hydrogen is stored in tanks, both in compressed and cryogenic form (Table 1). Compressed hydrogen is stored under very high pressure (up to 70 MPa) in overground steel vessels but existing underground storages are relatively few and operated at lower pressure (15 to 20 MPa) in salt caverns (Réveillère et al. 2022). It is obvious that cryogenic storages of hydrogen have very limited prospects because of the anticipated thermal-induced damage on the host rock masses.

Thus, salt caverns, even with rather small amount of energy stored per cubic-metre (as compared to the cryogenic storages) will remain in the future adequate candidates for storing compressed hydrogen, both for new developments and conversion of existing caverns.

It is worth noting that salt is a highly heterogeneously distributed geological formation. Thus, other perspectives, more flexible, have to be contemplated. Mined caverns may constitute a good option. Technical issues imposed by high stored pressure are analysed below.

3 LINED ROCK CAVERNS

Lined rock caverns are a type of mined caverns in which a lining is added at the periphery of the caverns for tightness purpose. The concept has been initially developed in the 1980's in Sweden and validated with a pilot project in the 1990's (Stille et al. 1994) as well as in Japan in the 2000's (Okuno et al. 2009). One full-scale demonstration facility of lined rock cavern for the storage of natural gas has been built in Sweden and operated since then (Mansson et al. 2006).

Lined rock caverns are typically of silo-shaped with a spherical roof with diameter ranging between 20 m to 50 m and up to 100 m high. Horizontal tunnel can also be designed although less interesting from an economical point of view due to the less favourable volume over surface ratio. Developed for storing compressed hydrocarbons (natural gas in particular) at a limited scale (as compared to unlined rock caverns), this concept could rather easily be applied for storing hydrogen (Johansson et al. 2018).

A pilot project is currently tested in Sweden (https://www.hybritdevelopment.se).

As for salt caverns, the pressure range that can be reached in a lined rock cavern depends on the quality (strength and deformability in particular) and homogeneity of the host rock mass. However, salt caverns are generally deep, allowing more easily the pressure to reach high values. In rock caverns, the surrounding rock mass requires good characteristics and not all geological environments can represent adequate candidates for this type of facility. Although the concept can be applied to a wide range of rock types, plutonic rocks such as granitoids and metamorphic rocks such as gneiss as the perfect candidates, but even in these good geological and rock mechanical environments, technical issues imposed by the pressure level have to be solved. This point is addressed below.

4 EFFECTS OF PRESSURE CHANGES ON CAVERNS

Many aspects involving the excavation of mined caverns must be checked and of course the stability of the caverns during excavation must be achieved for the given expected geometry. Those general aspects will not be discussed here, and we will focus our paper on the specific aspects for gas storage in lined rock cavern. Two key aspects must be considered regarding the effect of pressure changes: uplift failure and integrity of the steel liner.

4.1 Uplift pressure

Uplift failure can be evaluated with limit equilibrium analysis (rigid cone or log-spiral model for example). The limit equilibrium analysis consists in the comparison of the load acting on the rock mass due to the gas pressure to the resistance provided by the weight of the overburden. Uplift criterion is used to determine the safe depth of the storage. The required cavern roof depth versus cavern maximum pressure for a factor of safety (FOS) = 2 with respect to the uplift failure from the simple rigid cone model is provided in Figure 2 assuming a cavern diameter of 35 m. The FOS value can be computed as follows considering that the overburden weight is the only resisting force against uplift:

$$FoS = \frac{Resistance}{Uplift} = \frac{\gamma h}{P_{cav}}\left[1 + \frac{h}{r}\tan\alpha + \frac{1}{3}\left(\frac{h}{r}\tan\alpha\right)^2\right] \tag{1}$$

in which h the roof depth of the cavern, r the cavern radius, γ the rock mass volumetric weight and α the inclination with respect to the vertical of the overburden failure.

The results (refer to Figure 1) are highly dependent of the angle α which typically ranges from 30° to 45° the lower angle corresponding to heavily fractured or weak rock mass. The required depth for storage of gas in lined rock cavern with a maximum pressure of 20 MPa should range between 95 m and 130 m. Assuming a relatively good rock mass condition with α = 38°, the cavern pressure should not exceed 25 MPa for a cavern roof depth at 120 m.

The uplift criterion for a purely cohesive rock mass obeying to the Tresca stress criterion (Carranza-Torres et al., 2017) is also shown on Figure 2 for different values of the cohesive strength ranging from 2,5 MPa to 15 MPa. It can be seen that the Tresca stress criterion against uplift failure is less sensitive to the cavern depth compared to the rigid cone model for a fixed value of the parameters (α-angle for the rigid cone model and cohesive strength for the Tresca stress criterion). The allowable maximum cavern pressure is also significantly higher for shallow cavern in the case of Tresca stress criterion compared to the rigid cone model in particular for good rock mass quality. In all cases, it can be seen however that storage at high pressure can be achieved at moderate depth as long as the rock mass quality is good.

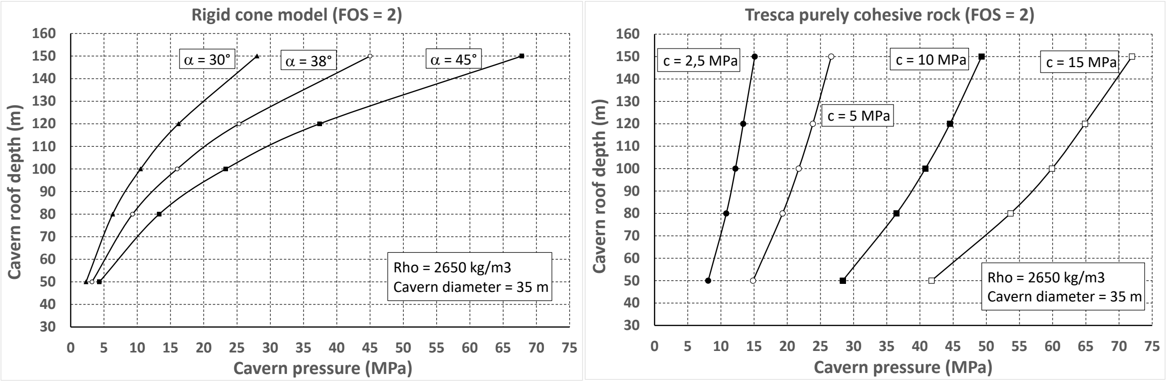

Figure 1. Cavern roof depth versus cavern pressure to achieve a FoS of 2 using the rigid cone model (left) and Tresca stress criterion (right). Cavern diameter = 35 m; rock mass volumetric weight = 2650 kg/m^3.

4.2 *Integrity of the steel liner*

The steel liner (12 to 15 mm thick) acts as an impermeable barrier to the stored gas. The choice of the steel material is a key aspect for hydrogen storage due to the well-known effect of hydrogen embrittlement. Investigation is still on-going to address this issue.

The steel liner deformation will basically follow the rock mass deformation along the cavern boundary. Therefore, tangential tensile strain will develop in the steel liner during the cavern pressurization/depressurization cycles.

Simplification can be made assuming that the rock mass behaves as a linear elastic and continuous medium and that the steel liner will be submitted to the rock mass deformation (perfect bonding). In this case, the Kirsch equations of plane strain elasticity for linear elastic continuous medium and hydrostatic in-situ stress can be used for the estimation of the tangential strain (Jaeger & Cook, 1971) in the steel liner:

$$\varepsilon_\theta = \frac{P_{cont}}{2G_m} \sim \frac{P_{cav}}{2G_m}\,;\ \frac{P_{cont}}{P_{cav}} = \frac{1}{1+\frac{K_{n\_steel}}{2G_m}}\,;\ K_{n\_steel} = \frac{e}{R} \times \left[\frac{E}{1-n^2}\right]_{steel} \tag{2}$$

with G_m the rock mass shear modulus, P_{cont} the pressure at the steel liner/rock mass contact, P_{cav} the gas pressure in the cavern, K_{n_steel} the normal stiffness of the steel liner, e the thickness of the steel liner, R the radius of the cavern, E and n respectively the Young's modulus and Poisson's ratio for the steel material.

For the usual range of rock mass and steel elastic parameters and for e/R ~ 1/1000 it is found that the contact pressure remains within 95% (low rock mass stiffness) to 99% (stiff rock mass) of the gas pressure. The same approach can be used considering the presence of the ~1 m thick linear elastic concrete ring between the steel liner and the rock mass.

The maximum permissible cavern pressure to avoid entering into the plastic domain for the steel liner is highly dependent of the rock mass deformability and will range between 4.5 MPa for highly deformable rock mass to more than 25 MPa for the stiffest condition (Figure 2). For economical point of view high deformable ground must be avoided.

Although at this stage it is assumed that the fractures effect is averaged through an equivalent continuous medium with degraded deformability, it seems important in a further stage of development to introduce explicitly in the analysis the effect of pre-existing rock fractures which may cause local strain concentration on the steel liner as well as sensitivity to the initial rock mass stress condition (Johansson, 2003).

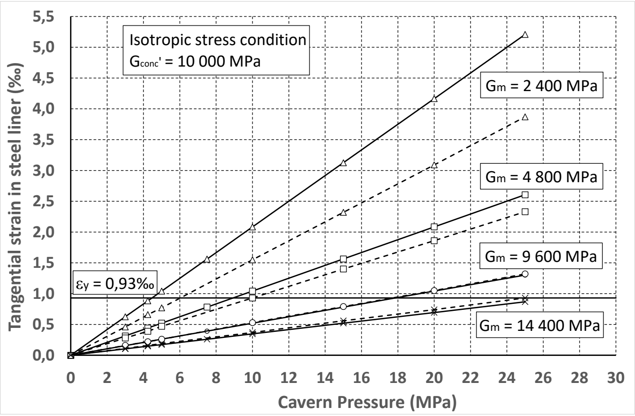

Figure 2. Tangential strain in the steel liner versus cavern pressure without (continuous lines) and with concrete effect (dashed line) for different rock mass shear moduli ($G_{conc'}$ concrete shear modulus; ε_y = 0,093% the yield strain of the steel liner).

5 CONVERSION OF EXISTING CAVERNS

A shift from fossil hydrocarbons toward hydrogen is favoured in many countries (Bai et al. 2014) but this technological change requires time, both for green production and massive storage. The development of massive underground storages has to be anticipated but in the very short term, the conversion of existing storages can be an interesting possibility. The options are limited and only two technical possibilities are foreseen: the conversion of existing salt caverns and the conversion of rock caverns.

5.1 Conversion of salt caverns

Utilizing existing salt caverns, until then used for storing hydrocarbons and specifically natural gas, and converting them into hydrogen storages represents the most attractive option, for at least two main reasons:

- Time frame: there is no site to be selected and investigated and the cavern is already excavated, which may save from 1 to 3 years overall.
- Operability: the cavern has already been operated for years and all the parameters are known, geotechnical (e.g. salt creep) or regarding the completions (casing and tubing) even though revamping could be required to adapt them to the hydrogen characteristics.

However, such conversion is not straightforward and several technical points have to be controlled and/or validated such as:

- Operating pressure: unlike hydrocarbons that can be stored under gas or liquid phase, hydrogen is only stored under gas phase in salt caverns. The higher the pressure, the higher the energy stored in the cavern and thus, hydrogen caverns have to be pressurised at a maximum pressure, compatible with the depth and the in-situ stresses around the concerned cavern, with the objective to keep acceptable rock mass response and avoid the creation of fractures in the surrounding rock mass (Johannsson 2003).
- Pressure variations: as compared to hydrocarbons, hydrogen will require more frequent movements in and out of the caverns, meaning frequent pressure changes. This point has to be studied in parallel to the maximum admissible pressure.
- Temperature changes: along with pressure changes, temperature decrease will occur during rapid withdraw of hydrogen from caverns.
- Product quality: residual hydrocarbons can remain in traps impacting the quality of the stored product.

Although heterogeneously distributed, the number of existing salt caverns is extremely important, which should ease the transition from hydrocarbons to hydrogen.

5.2 Conversion of rock caverns

Converting a rock cavern (say unlined mined rock cavern) from a hydrocarbon storage (generally LPG but also liquid hydrocarbons) would require adding a lining to an existing cavern. Theoretically, the concept is feasible but practical technical difficulties must be overcome including:

- Cavern Depth: LPG rock caverns are shallow caverns (roughly 100 to 200 m depth) utilizing the concept of hydrodynamic containment to keep the product inside the caverns. Even with an added steel lining on the roof and walls, the shallow depth will reduce the maximum pressure inside the cavern, due to the deformation of the rock mass and uplift failure which is more critical for horizontal cavern compared to silo-shape cavern.
- Geology: the pressure to be applied on the lining as well as on the rock mass requires having a rather homogeneous geology around the concerned cavern. Suitable geological conditions would be a hard rock with no or very limited weak zones, due to fractures, dykes, rocks or layers of rock having a lower strength. Typically, granitic and some gneissic rock types would represent adequate candidates but even in these very good rocks, the pressure will have to be limited. Depending on the rock mass, one can consider a maximum pressure of 5 to 20 MPa for the hydrogen stored as a maximum target, say significantly above the operating pressure of LPG caverns (0.2 to 1 MPa).
- Cavern geometry: LPG or liquid hydrocarbon rock caverns have a horse-shoe- to egg- and U-shaped cross-section made of parallel caverns, linked with connection galleries. Such shapes are not the best adapted for supporting the pressure induced by the presence of hydrogen inducing stress/strain concentration in the steel liner along the cavern profile and connections which limit dramatically the allowable maximum pressure. As an alternative a cylinder the diameter of the minimum dimension of the cavern cross-section can be considered as the converted volume and the annular space filled with self-compacting concrete and the connection backfilled. Therefore, only a portion of the full capacity of the hydrocarbon storage can be converted for hydrogen storage. For this aspect, converting a room-and-pillar underground storage caverns does not seem feasible.
- Lining set up: Self-pouring concrete of the annular space rock mass/steel liner is used, as for a cavern creation, but the setting is more complicated due an unsuitable geometry with long horizontal caverns. Already difficult to set in smaller hydraulic galleries, the problem is increased with high caverns having a top heading and several benches.
- Uplift pressure: calculation has to be made as for a cavern to be created (see 4.1).

From the above, one can see converting existing rock caverns into compressed hydrogen storages requires a huge amount of work which have to be anticipated early in the conversion project, specific design aspects and construction procedures (including HSE to re-enter the caverns) with associated conversion cost that could be not necessarily cheaper than new project.

The conversion of rock caverns for storing cryogenic hydrogen can be studied because the energy stored per cubic-metre will be much higher but the problems of the very low temperature on the host rock will have to be solved. Adaptation to the lower liquid hydrogen temperature of the concept developed for LNG storage in rock caverns (Lee et al., 2005) using a highly efficient thermal insulation membrane, and drainage system to avoid water in fractures represents a real technical challenge that may be gained only if the cost is admissible for an industrial purpose.

6 CONCLUSIONS

Storing pure hydrogen underground can be done under compressed and cryogenic forms, the first being the easiest one at short and medium term. For compressed hydrogen, salt does represent the most adequate medium for cavern creation and/or conversion. The conversion of existing hydrocarbons salt caverns looks the quickest way to dispose of large volumes for hydrogen. Lined rock caverns seem the best adapted for massive compressed gaseous hydrogen storage in regional areas where salt formation is not available but careful design is required to cope with the rock mass and steel liner deformability. The concept of storing liquid hydrogen in lined rock caverns requires adaptation of the concept developed for LNG storage but is still to be studied in more details.

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