Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece
© Authors: All rights reserved, 2023
https://doi.org/10.53243/ICEG2023-31

In situ geomechanical tests used in the design of hydrogen storage salt caverns

Evan Passaris

Technical Director, Atkins Limited (member of the SNC-Lavalin Group), Edinburgh, UK, email: evan.passaris@atkinsglobal.com

ABSTRACT

Hydrogen is an energy carrier that can be produced via electrolysis utilising renewable energy sources, i.e., wind turbines. If such a system is linked to hydrogen storage, the renewable sources may be utilised to their full capacity, removing their intermittent energy production nature. The stored hydrogen could then be used for addressing the daily and seasonal peaks and troughs of the energy demand curve. Accounting for the storage volume and discharge capacity that hydrogen storage technologies have to offer, it may be concluded that the envisioned long term inter-seasonal storage can be delivered by geological storage such underground salt caverns. To investigate the geomechanical response of the UK's Triassic salt, under conditions predicted around hydrogen storage caverns, a series of *in situ* tests were carried out in a salt mine using an instrumented cavern subjected to cyclic pressures and temperatures. The cavern was a 1.2 m diameter and a 10.7 m length horizontal cylinder. The deformation of the test cavern surface and that within the surrounding rock salt was measured at three instrument stations along the length of the cavern, one central and one at either side. At each station measurements were made in three radial directions, vertical, 120° clockwise and 120° anticlockwise. Furthermore, the cavern's diametral deformation was determined with additional extensometers. The temperature in the salt surrounding the cavern was monitored employing thermistors in the extensometer boreholes. Additional thermistors monitored the temperature gradient near the cavern walls. During testing the cavern was pressurised using a compressed air system employing pressures of up to 1,400 kPa, while temperatures from -14°C to +15°C, relative to ambient rock temperature, were imposed on the cavern wall using a heat exchanger coil. The pressurisation tests were used to determine the *in situ* shear modulus of rock salt and the results indicated that the *in situ* stiffness of salt was significantly higher than the one determined by laboratory tests. Additionally, the results of the thermal loading tests were employed in determining the *in situ* Poisson's ratio of rock salt which was found to vary with stress, the most distinct differences being between the compressive and tensile stress states. Moreover analysis of the results of long-term pressurisation tests confirmed that rock salt can be modelled as a non-linear visco-elastic material which may be used in determining the creep volumetric convergence of hydrogen storage caverns. The results of the undertaken *in situ* tests provided a better understanding of the anticipated thermo-mechanical response of the salt caverns used for the storage of hydrogen.

Keywords: Triassic salt, in situ tests, salt properties, hydrogen storage, salt caverns

1 INTRODUCTION

Wind generated energies are inherently intermittent with continual fluctuations in electricity production. The availability of wind is time-dependent whereas the need of electric power is continuous, so the need for an intermediate storage of wind power may be achieved by using hydrogen as an energy carrier. Wind and hydrogen integration can be achieved by means of hydrogen storage and electrical conversion that balances the original wind energy production, allowing an approach to demand that closes the gap with conventional energies. Hydrogen has long been a potential solution for large scale power storage in renewable energy systems, whereby the renewable electricity is used for electrolysis of water in times of electricity surplus to produce hydrogen. Hydrogen can be converted back to electricity in times of electricity shortage by fuel cells or by combustion in combined cycle or simple gas turbine plants.

The considerable large volumes required to make a hydrogen storage plant economic are significant, as a result, above ground facilities are not practicable due to prohibitive costs. For this reason, hydrogen

is stored under pressure in geological formations and currently two technologies may be used for storage of large amounts of gases: underground solution mined salt caverns and porous formations. Hydrogen energy storage in underground salt caverns is an optimum solution to address the expected balancing problems in electricity grids resulting from the planned increase in wind power in the UK.

The technological concept of hydrogen storage in salt caverns is well established and hydrogen has been successfully stored in salt caverns for decades (Crotogino & Hueber, 2008). Large-scale hydrogen storage plays a crucial role in the potential future clean hydrogen economy and as such considerable research work has already been carried out in relation to the use of salt caverns for hydrogen storage (Ozarlan, 2012; Acht & Donadei, 2012; Böttcher *et al*., 2017 and Passaris & Yfantis, 2019). However, the existing research on hydrogen storage in salt caverns is based on the mechanical properties of salt derived from laboratory tests. Hence the work presented in this paper, which focuses on the *in situ* characteristics of salt, complements the previous research work. The relevant technology and the design of hydrogen storage salt caverns are based on the existing experience in the design and operation of salt caverns for natural gas storage. In the UK there exist Triassic and Permian salt beds that are adequately thick thus providing reserves of salt in several areas which may be considered for the development of hydrogen storage caverns.

2 THE TEST CAVERN FACILITY

To investigate the mechanical response of UK's Triassic salt, under conditions similar to those predicted around hydrogen storage caverns, a series of *in situ* tests were carried out in an instrumented test cavern that was constructed at Winsford salt mine in Cheshire, UK and was subjected to a series of cyclic pressure and temperature changes. The cavern's location was at the end of a blind roadway of the Moulton no. 2 mine panel driven in the salt bed, 140 m below the surface (see Figure 1).

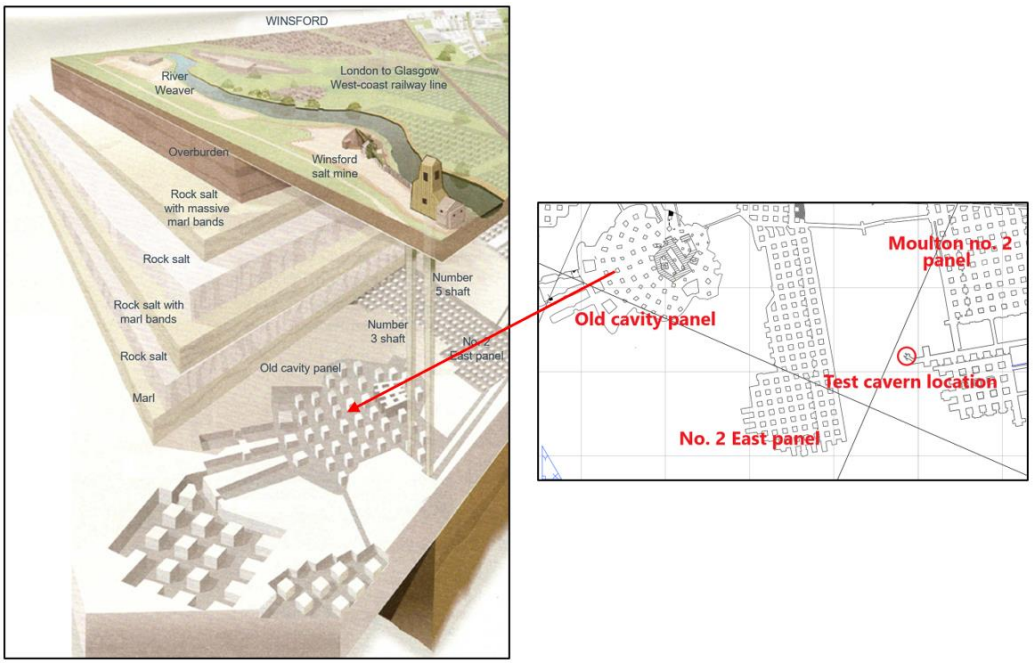


Figure 1. *Artist's impression of Winsford mine (after Girling, 2009), the test cavern location is shown in the extract of the mine's plan*

The constructed test cavern (see Figure 2) had the shape of a horizontal cylinder with a diameter of 1.22 m and a total length of 10.67 m. 7.3 m of this length being utilised as the test chamber and 0.9 m for a pressure retaining concrete plug situated 2.4 m from the mouth of the cylindrical cavern. The deformation of the test cavern surface and that within the surrounding rock salt was measured at three instrument stations along the length of the cavern, one central and one at either side. The end stations were situated at a distance of three times the cavern radius from the plug and from the blind end. As shown in Figure 2, at each station measurements were made in three radial directions, vertical, 120°

clockwise and 120° anticlockwise. The deformation profile in the walls of the cavern was determined using instrumented boreholes 3.05 meters in length. Four anchors were set in each borehole at radial distances of 0.84, 1.22, 1.83 and 3.66 m from the cavern centreline. In addition to the extensometers that monitored the radial displacements of the rock salt surrounding the test cavern, the diametral deformation of the cavern was determined using a set of extensometers arranged at the same cross-sections as the radial boreholes. The temperature profile in the salt surrounding the cavern was monitored employing miniature precision thermistors. A total of 45 temperature sensors were employed in the deformation measurement boreholes, one held against the rock surface at each of the anchors and one mounted on each of the borehole cover plates. To provide detailed information on the temperature gradient near the cavern surface, an additional 42 sensors were installed in 6 short, 51 mm diameter, boreholes aligned parallel to the deformation monitoring boreholes at points midway between the stations. These were incorporated in prepared salt cores of 305 mm length which were cemented into the short boreholes using a mixture of epoxy resin and powdered salt. In each salt core, in addition to a thermistor set at the core's end (which would correspond to the cavern's surface) 6 more thermistors were set at 6.35 mm, 12.7 mm, 25.4 mm, 50.8 mm, 101.6 mm and 152.4 mm from the end of the core.

By means of a compressed air system, internal pressures of up to 1,430 kPa were used in the tests, these being contained by the concrete plug keyed into the cavern walls. In addition, temperatures from -14°C to +15°C relative to ambient rock temperature were imposed on the test cavern wall by circulating hot or cold ethylene glycol solution through a copper pipe heat exchanger coil, set inside the test chamber.

The undertaken *in situ* tests are distinguished into two types: pressure tests comprising both short-term and long-term pressure loading and thermal loading tests which were conducted at above and below ambient rock temperature. A total of 26 pressurisation tests were carried out, comprising short-term tests lasting for 3 hours and long-term tests that lasted a maximum of 17 days. Moreover, 7 thermal loading tests were undertaken, three at elevated temperatures, three at temperatures below ambient and one test cycled below and above ambient.

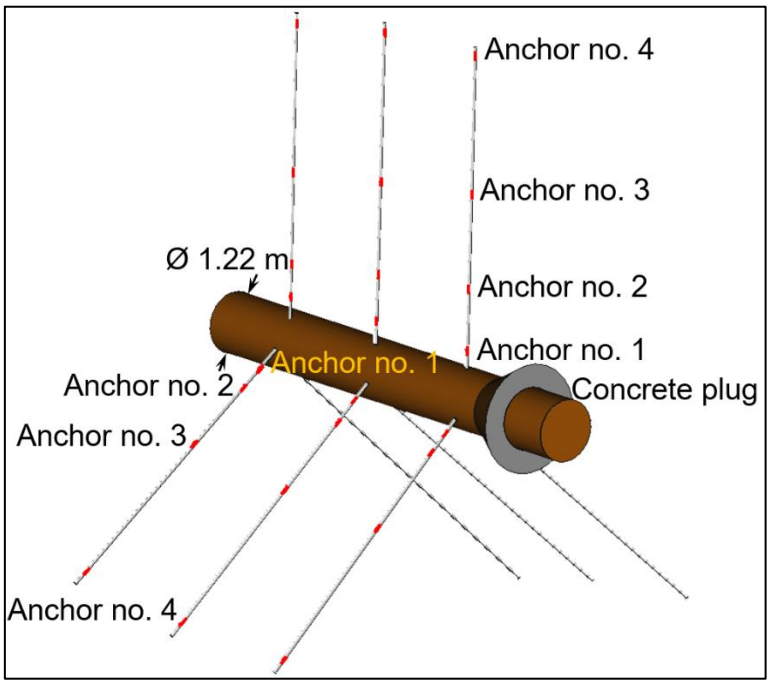


Figure 2. *Schematic of the horizontal cylindrical test cavern*

The cavern pressurisation tests were employed to investigate generally the effects of mechanical loading on the cavern walls and were specifically used to determine of the *in situ* shear modulus (G) and the creep constants of the Triassic rock salt. Additionally, the thermal loading tests were used in the investigation of the effects of thermal loading of the test cavern and were employed in particular for the determination of the *in situ* Poisson's ratio (ν) of the rock salt.

3 ANALYSIS OF THE TEST DATA

The plane strain solution for the radial deformation (u) of a hollow cylinder with infinite outer radius and internal radius r_i,subjected to an internal pressure (p) is given by (Briaud, 2013) in equation (1) as:

$$u = \left(\frac{1+\nu}{E}\right)\frac{p}{r}\,r_i^2 \tag{1}$$

where r is the radial distance, and E is the Young's modulus. Moreover, the shear modulus is a function of the Young's modulus and the Poisson's ratio as shown in equation (2):

$$G = \frac{E}{2(1+\nu)} \tag{2}$$

Therefore, taking into consideration equation (1), it is possible to obtain the shear modulus of the rock salt that surrounds the test cavern by regressing the radial deformation of the test cavern against p/r. All the short-term pressure tests have shown a good agreement with the elastic response, characterised by a marked linearity between diametral deformation and pressure and with an absence of a permanent set of the loading and unloading curves, as typically shown in Figure (3).

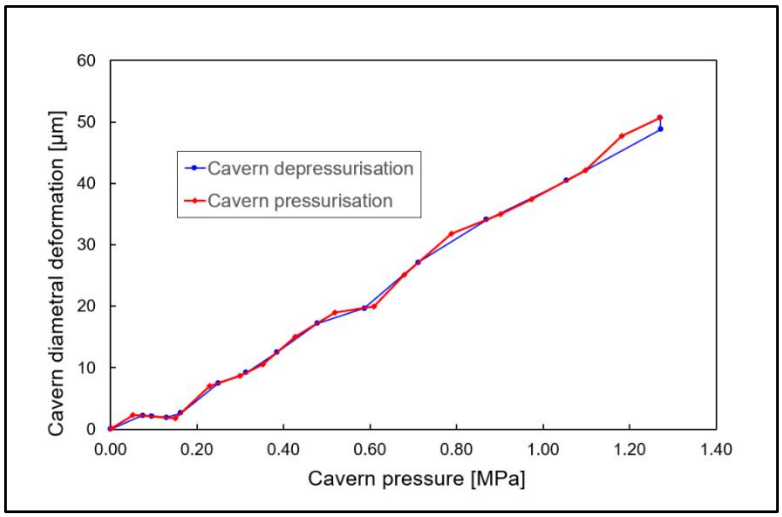
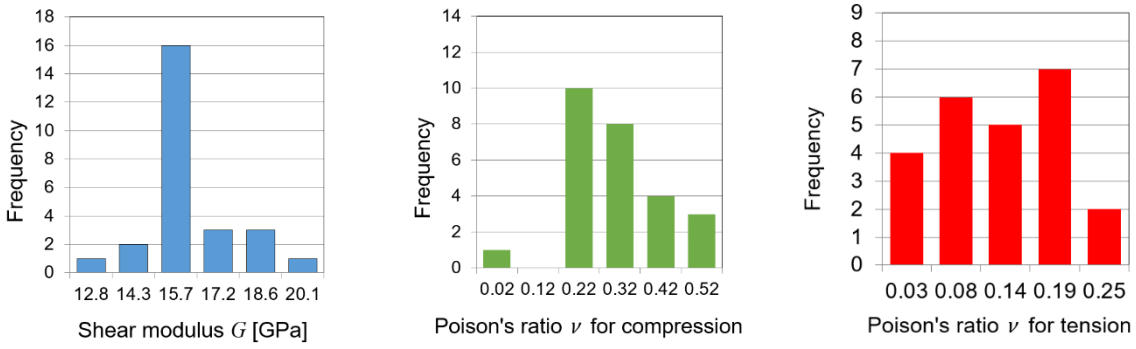


Figure 3. *Results from a short-term pressure test, maximum cavern pressure 1,294 kPa, overall mean of diametral deformation vs cavern pressure.*

The statistical analysis of the determined values of the shear modulus, derived from the short-term pressurisation-depressurisation tests, ranged between 12.8 GPa and 19.3 GPa which resulted in an average value equal to 15.45 GPa (± 1.50) and the representation of the distribution of the values of G is shown as a histogram in Figure 4a.



(*a*) (*b*) (*c*)

Figure 4. *Frequency distribution of the determined G values (**a**) and ν values (**b** for compressive stresses and **c** for tensile stresses)*

The radial displacement u of a cylindrical hole with a radius r_i, caused by an applied temperature distribution, is given by Timoshenko & Goodier (1970) as:

$$u = \frac{1+\nu}{1-\nu}\,\frac{\alpha}{r}\int_{r_i}^{r} T\,r\,dr = \frac{1+\nu}{1-\nu}\,\alpha\,Intgr(r) \qquad (3)$$

where α is the coefficient of linear thermal expansion of rock salt, determined as being equal to 26×10^{-6} °K^{-1} and T is the temperature, which is a function of r. The temperature distribution integral $Intgr(r)$ of equation (3) was evaluated by monitoring the temperature profile of the thermal loading tests. By plotting $Intgr(r)$ against the induced radial displacement (as shown in Figure 5) the Poisson's ratio may be calculated by determining the slope $\left(\alpha\,\frac{1+\nu}{1-\nu}\right)$ of the regression line of u against $Intgr(r)$.

The statistical analysis of the determined values of the Poisson's ratio of rock salt, derived from the thermal tests that generated compressive stresses, ranged between 0.02 and 0.49 which resulted in an average value of 0.243 (± 0.11). The representation of the distribution of the corresponding values of ν, based on 23 valid test results is shown as a histogram in Figure 4b.

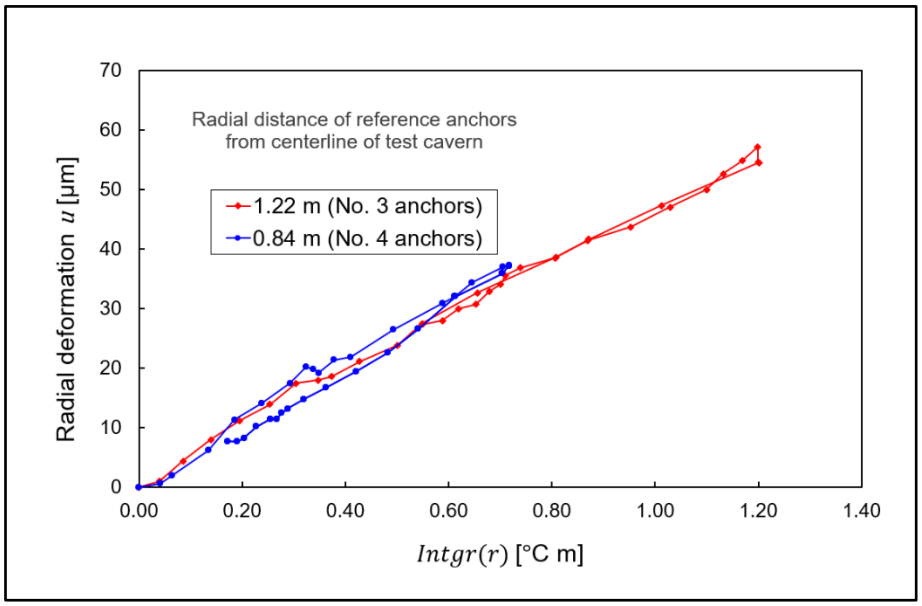


Figure 5. *Thermal loading test with T = +5°C above ambient rock temperature, overall mean of radial displacement of anchors no.3 and no.4 relative to caverns surface vs Intgr(r)*

Furthermore, statistical analysis of the evaluated values of the Poisson's ratio of rock salt, derived from the thermal tests that generated tensile stresses, ranged between 0.03 and 0.21 which resulted in an average value of 0.113 (± 0.06). The representation of the distribution of the corresponding values of ν, based on 29 valid test results is shown as a histogram in Figure 4c.

The diametral deformation observed during the long-term pressurisation tests revealed a distinct departure from linear elasticity, as is evident from the non-linear creep deformation emphasised by the red curve fitting line shown in Figure 6.

The cavern diametral deformation measurements from the pressurisation and depressurisation stages of the cavern were excluded from analysis of the creep data. Instead, following the methodology put forward by Hunsche (1981), the steady-state creep rate $\dot{\varepsilon}_{cr}$ was determined from the weighted linear regression curve fitting of the time-dependent steady-state diametral deformation that was monitored during the constant pressure period. Following this, the monitored steady-state creep deformation was modelled employing the Norton power law (Norton, 1929) which is commonly used to model the creep behaviour of salt. The Norton creep model considers that, after a short transition phase, the creep reaches a constant strain rate regime, where only an alteration of the stress state – for example the change of the geometry of a hydrogen storage cavern due to creep – may affect the rate of creep. The steady-state or secondary salt creep rate is described by the Norton creep model as:

$$\dot{\varepsilon}_{cr} = A\sigma_{vm}^{n} \quad (4)$$

where A and n are material properties, while σ_{vm} is the von Mises or Equivalent stress component defined by the following expression:

$$\sigma_{vm} = \sqrt{3J_2} \quad (5)$$

where σ_1, σ_2 and σ_3 are the principal stress components and J_2 is the second invariant of the deviatoric stress tensor given by:

$$J_2 = \frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \quad (6)$$

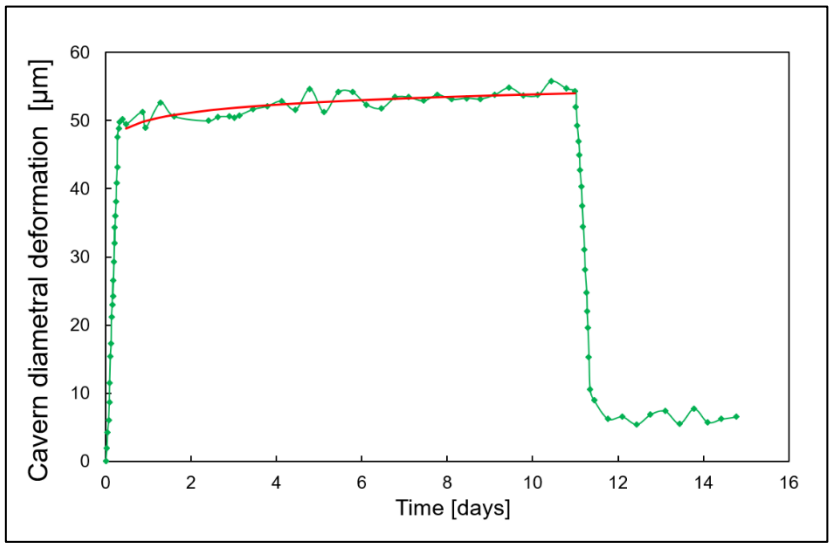


Figure 6. *Long-term pressurisation test employing an internal pressure of 1,430 kPa, overall mean of diametral deformation vs time*

Because the creep behaviour of salt rock shows a significant variation, caused by a number of factors (e.g., variations in size and distribution of secondary constituents or grain size of the rock salt matrix), the 'Bundesanstalt für Geowissenschaften und Rohstoffe' [BGR, the German Federal Institute for Geosciences and Natural Resources] developed the so-called "creep classes" to describe these variations and to categorize the creep behaviour of rock salt. Therefore, the material constant A in the Norton creep power law of equation (4) is adjusted by introducing the BGR pre-coefficient V (Plischke, 2007; Hunsche & Schulze, 2003) in accordance with equation 7:

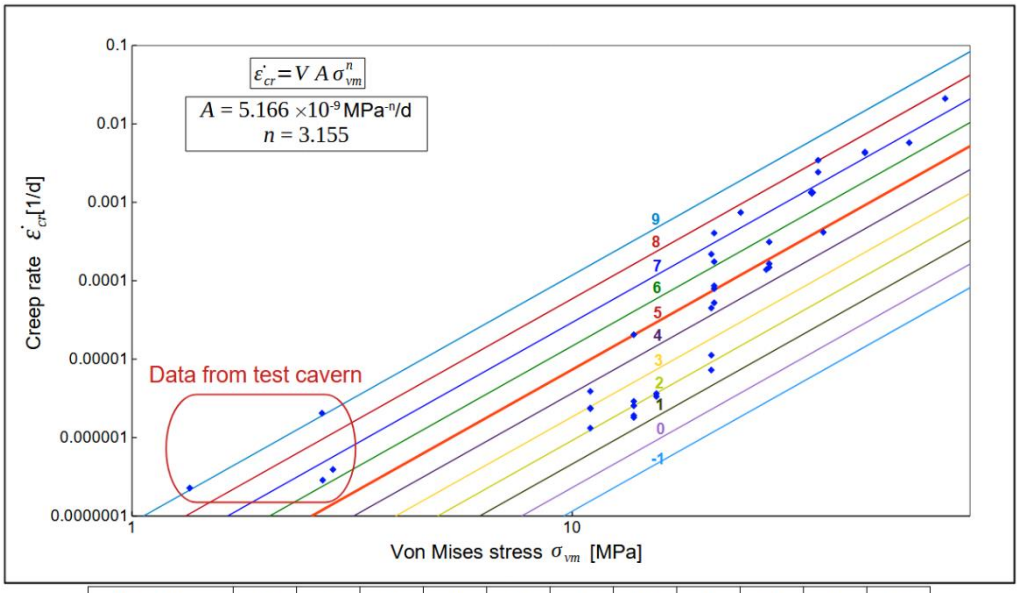
$$\dot{\varepsilon}_{cr} = VA\sigma_{vm}^{n} \quad (7)$$

with the pre-coefficient V given in equation 8, where K is the applicable creep class:

$$V = \frac{2^K}{32} \quad (8)$$

Creep class 5 (which corresponds to a pre-coefficient V equal to 1) refers to the actual experimental data obtained from the relevant creep tests. It is up to the engineering judgement of the cavern designer, to choose the appropriate creep class that may be used during the design of hydrogen storage caverns. A decision was taken to adopt a creep class equal to 5 by using the actual creep data thus avoiding to introduce any bias, effectively employing an objective approach. The creep test results are typically presented in a double-logarithmic diagram of creep rate vs the applied differential stress, which usually is expressed as the von Mises stress component. The von Mises stresses, that developed at the periphery of the test cavern during the four long-term pressurisation tests, ranged between 1,350 kPa and 2,860 kPa. The creep rate $\dot{\varepsilon}_{cr}$ results from the four long-term pressurisation tests, together with the creep rate results from a number of laboratory triaxial creep tests, carried out employing Triassic salt

specimens originating from Winsford salt mine, are plotted vs the applied von Mises stress as shown in Figure 7. The creep parameters of the Norton model, for the investigated Triassic salt, as derived from the double-logarithmic diagram of $\dot{\varepsilon}_{cr}$ vs σ_{vm} (shown in Figure 7) are: material creep parameter A = 5.166 × 10^{-9} MPa^{-n}/d, and stress exponent n = 3.155.



Creep Class	-1	0	1	2	3	4	5	6	7	8	9
Pre-coefficient V	1/64	1/32	1/16	1/8	1/4	1/2	1	2	4	8	16

Figure 7. *Creep of Triassic rock salt from Winsford mine*

4 EXAMPLE OF A HYDROGEN STORAGE CAVERN

By employing the rock salt properties determined in the previous section, the anticipated creep response of a hydrogen storage salt cavern is investigated accordingly by carrying out a finite difference geomechanical analysis employing the numerical modelling software FLAC (Itasca Consulting Group, 2011). The investigated cavern operates using the brine compensation method, whereby the storage facility functions under constant pressure by displacing the brine into a surface brine pond during the injection of hydrogen, from where the brine is reinjected into the cavern to displace the hydrogen during withdrawal.

The area where the cavern is located is typified by salt beds with a thickness of the order of 30 m found at depths of the order of 650 m. As a result of the relatively small thickness of the salt, the geometry of the hydrogen storage cavern is characterised by a prolate spheroidal shape with an approximate storage volume of 42,000 m^3 (see Figure 8). The symmetrical The ratio of the horizontal to the vertical geostatic stresses in the salt formation where the cavern is leached is expected to approach unity whereby the in situ stress state is assumed to be isotropic showing no differences in horizontal and vertical directions. The geostatic vertical stress resulting from the weight of the superincumbent strata was calculated as the sum of the product of the thickness and the weight density of the layers of the identified geological formations and was determined to be 16 MPa at the roof of the cavern.

In the geomechanical analysis of the investigated cavern its sump is represented as being occupied by the stored hydrogen. In real terms, the sump is filled with the insoluble materials that precipitated during the solution mining process (see Figure 8). Although these materials provide an element of support to the cavern walls, the sump of the cavern has been modelled as being devoid of such materials. This approximation lends conservatism to the analysis, although the overall response of the modelled cavern will be little influenced by the approach used to represent the pressure exerted at the sump area. Since the investigated cavern operates as a brine compensation facility, the cavern is subjected continuously to a constant internal halmostatic pressure that corresponds to the full brine head, which determined to be 7.8 MPa at the roof of the cavern.

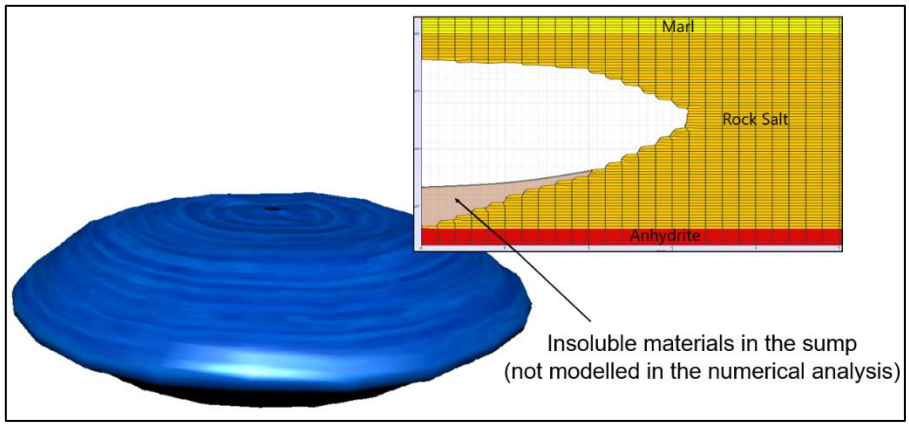


Figure 8. *The finite difference grid used in its axisymmetric numerical analysis and a 3D perspective figure of the investigated salt cavern derived from available sonar survey data.*

Assessment of the change in volume of the cavern, caused by the creep convergence, has shown that available hydrogen storage volume reduces gradually (as shown in Figure 9). Thanks to the favourable storage conditions (i.e., practically quasi-static internal pressure corresponding to approximately 50% of the applied geostatic stresses) the salt surrounding the investigated cavern will not give rise to significant cavern closure rates. Indeed, at the end of 30 years, the storage volume reduction is expected to be less than 0.4%. This rate of loss of storage volume conforms satisfactorily to the volumetric creep convergence rate identified by analysing successive cavern sonar surveys.

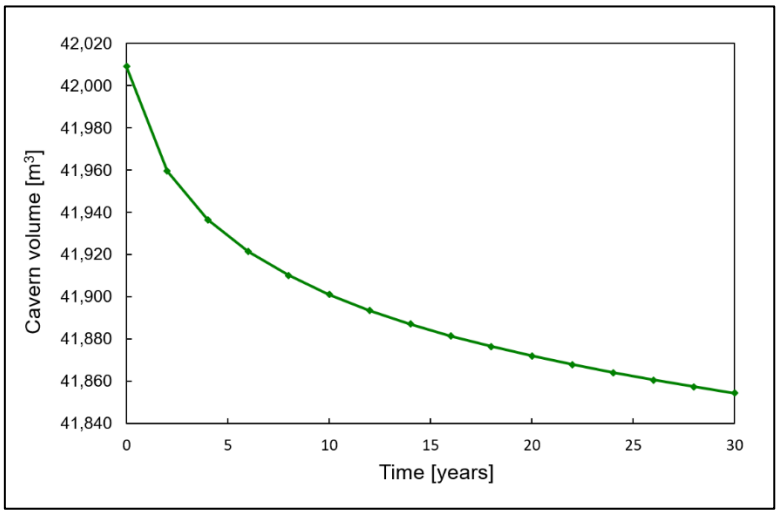


Figure 9. *History of the reduction in the storage volume of the investigated cavern, resulting from the cavern's creep convergence*

Assessment of the minimum principal stress distribution at the end of 30 years of the numerical geomechanical modelling, provided evidence that no tensile stresses develop in the salt that surrounds the cavern and as such the walls of the investigated cavern remain everywhere in compression. Furthermore, the distribution of the von Mises stress around the investigated cavern at the end of 30 years of hydrogen storage operations, indicated that most of the salt mass that forms the immediate surrounding of the cavern is subjected to low shear stresses less than 5 MPa. Consequently, provided that the internal pressure in the investigated salt cavern is maintained equal to the halmostatic head, the geomechanical integrity of the cavern and its ability to contain the stored hydrogen is attainable

5 CONCLUSIONS

The results of the undertaken tests may be separated into two main areas of interest: first, the 'time-independent' response of rock salt which is expressed by its shear modulus and the Poisson's ratio that

have been determined by employing linear elastic relationships and, second the 'time-dependent' response of rock salt which is illustrated by the Norton power law parameters which have been determined by employing a non-linear viscoelastic creep analysis.

Comparison of the determined *in situ* shear modulus of rock salt (G = 15.45 GPa) with the respective value derived from laboratory tests, i.e., 7.9 GPa (Taggart, 1984) indicates that the *in situ* stiffness of salt rock is significantly higher than the one resulting from laboratory tests. This variation may, in part, be due to the different behaviour of rock salt in the in situ environment but, more probably, it is caused by the generally higher stress conditions used in the laboratory tests, and the consequent unavoidable incorporation of primary creep deformation in the elastic movement. Moreover, the Poisson's ratio for rock salt was found to vary with stress, the most distinct differences being between the compressive and tensile stress states. In particular, the Poisson's ratio derived from the *in situ* tests that generated tensile stresses, resulted in an average value equal to 0.113. In contrast the Poisson's ratio derived from the tests that generated compressive stresses was determined as being equal to 0.243, this being of equal magnitude with the respective value derived from laboratory tests, i.e., 0.27 (Taggart, 1984). Similar results, whereby the Poisson's ratio has different values in compression and in tension, have also been presented by a number of researchers for rock materials such as sandstone, granite, mudstone, granitic gneis and rock salt, (Qiang *et al*., 2008; Yu et al., 2005; Passaris, 1978). This identified difference may be attributed to the anisotropic response of some rocks because they are less stiff in tension than in compression (Sundaram & Corrales, 1980) and/or to the extrinsic anisotropy and develops when state of stress is tension or mixed tension and compression (Passaris, 1978 and Stimpson & Chen, 1993).

The determined *in situ* shear modulus and Poisson's ratio give a value of 39.1 GPa for the Young's modulus in compression. This Young's modulus is much higher than most laboratory determined values for rock salt which typically vary between 20 GPa and 25 GPa. This variation may, in part, be due to the different behaviour of the rock salt in the *in situ* environment but, more probably, it is caused by the generally higher stress conditions used in the laboratory tests, and the consequent unavoidable incorporation of primary creep deformation in the elastic movement.

The calculated stress exponent n = 3.155 of the Norton creep law, which was identified in the analysis of the creep response of the investigated Triassic salt, falls within the typical range of values determined for a number of rock salts: n = 5.0 (Brückner *et al*., 2005), n = 4.0 (Karimi-Jafari, 2016), and n = 3.1 (Brouard & Zakharov, 2021).

Investigations carried out by Mellegard & Düsterloh (2012) indicated that applying cyclic loadings on rock salt did not cause any appreciable change in the salt behaviour that could not already be characterized using noncyclical loadings. In other words, rock salt is not more prone to damage (microcracking) under cyclic loading than it is under static loading at comparable stress levels. This conclusion is considered robust, because the same testing results were obtained independently by both the American geoscience consultants RESPEC and Clausthal University of Technology in Clausthal-Zellerfield, Germany. Consequently, the mechanical characteristics derived from the testing of the instrumented cavern are acceptable as appropriate input for the design of hydrogen storage salt caverns which will be subjected to long-term cyclic loading. However, the conclusions of the work presented here are based on tests carried out on a single site. As a result, consideration should be given to the fact the results may not be applicable to other sites with different geological conditions. It is interesting through to notice that comparison of the results of rock mechanics tests carried out by different researchers, employing UK's Triassic rock salt cores from various Cheshire sites, i.e., Taggart (1984) who used salt cores taken from Winsford mine, Düsterloh & Lux (2007) that utilised cores taken from borehole H401 in Holford and Hadj-Hassen (2009) who employed cores from the exploratory borehole in Hill Top Farm site at Warmingham, indicates that the differences of the determined geomechanical properties from various sites are not statistically significant.

REFERENCES

Acht, A. & Donadei, S. (2012) Hydrogen storage in salt caverns, State of the art, New developments and R&D projects, Solution Mining Research Institute, Fall 2012 Conference, 1−2 October, (43-56). Bremen, Germany.

Böttcher, N., Görke, U.-J., Kolditz, O. & Nagel, T. (2017) Thermo-mechanical investigation of salt caverns for short-term hydrogen storage, Environmental Earth Sciences, 76(98), 1-13.

Briaud, L.-L. (2013) The pressuremeter test: Expanding its use, Ménard Lecture, In P. Delage, J. Desrues, R. Frank, A. Puech & F. Schlosser (Eds.), 18th International Conference on Soil Mechanics and Geotechnical Engineering, (pp. 107-126). Paris, France.

Brouard, B. & Zakharov, V. (2021). Creep-closure rate and induced subsidence in a cluster of salt caverns, Solution Mining Research Institute, Fall 2021 Conference, 20-21 September. Galveston, Texas, USA.

Brückner, D., Popp, T. & Schreiner, W. (2005). Geotechnical experiences in flooding underground openings in salt formations, Solution Mining Research Institute, Fall 2005 Conference, 2-5 October. Nancy, France.

Crotogino, F. & Hueber, S. (2008). Energy storage in salt caverns / Developments and concrete projects for adiabatic compressed air and for hydrogen storage, Solution Mining Research Institute, Spring 2008 Conference, 28-29 April. Galveston, Porto, Portugal.

Düsterloh, U. & Lux, K.-H. (2007) Rock mechanical investigations on the strength and creep behaviour of salt and marl core samples from the Holford H401 location, Clausthal University of Technology. Clausthal-Zellerfield, Germany.

Girling, R. (2009). Journey into our underworld, The Sunday Times Magazine, Times Newspapers Ltd, London, 25 January 2009, 40-45.

Hadj-Hassen, F. (2009). Geomechanical characterization of the claystone and salt core samples from Hill Top Farm site, Report R090215FHAD, Centre de Géosciences, Groupe Hydro-Géo-Ingénierie, Mines Paris and ARMINES. Fontainebleau, France.

Hunsche, U. (1981) Results and interpretation of creep experiments on rock salt. In H. Reginal Hardy, Jr. & M. Langer (Eds.), 1st Conference on the mechanical behaviour of salt, The Pennsylvania State University, November 9-11 (159-167). Trans Tech Publications, Clausthal-Zellerfeld, Germany.

Hunsche, U. & Schulze, O. (2003) The dilatancy concept – A basis for the modelling of coupled TM-H processes in rock salt. In C. Davies & F. Bernier (Eds.), European Commission CLUSTER conference and workshop on the Impact of the excavation disturbed or damaged zone (EDZ) on the performance of radioactive waste geological repositories. Luxembourg, Belgium.

Itasca Consulting Group Inc. (2011) Fast Lagrangian Analysis of Continua, version 7.0, User's manual, Minneapolis, Minnesota, USA.

Karimi-Jafari, M. (2016). Thermodynamic simulation of gas caverns with GUSTS V.2, Solution Mining Research Institute, Fall 2016 Conference, 25-28 September, (pp. 67-86). Salzburg, Austria.

Mellegard, K.D. & Düsterloh, U. (2012). High frequency cavern cycling – Phase 2: Cyclical loading effects on the dilation and creep properties of salt, Research report RR2012-2, prepared by RESPEC, Rapid City, SD, USA and Clausthal University of Technology, Clausthal-Zellerfield, Germany, for Solution Mining Research Institute, Clarks Summit, PA, USA.

Norton, F. H. (1929). The creep of steel at high temperatures, New York: McGraw-Hill.

Ozarlan, A. (2012) Large-scale hydrogen energy storage in salt caverns, International Journal of Hydrogen Energy, 37, 14265-14277.

Passaris, E. & Yfantis, G. (2019) Geomechanical analysis of salt caverns used for underground storage of hydrogen utilised in meeting peak energy demands, In A. Ferrari & L. Laloui (Eds.), International Symposium on Energy Geotechnics 2018, 26-28 September 2018, (179-184). Lausanne, Switzerland.

Passaris, E.K.S. (1978). The extrinsic anisotropy of rocksalt when subjected simultaneously to tensile and compressive stress fields. In A.H. Coogan & L. Hauber (Eds.), 5th International Symposium on Salt, Hamburg (477-485). Northern Ohio Geological Society, Cleveland, USA.

Plischke, I. (2007). Determination of mechanical homogenous areas in the rock salt mass using creep properties for a classification scheme, In M. Wallner, K. -H. Lux, W. Minkley & H. R. Hardy, Jr. (Eds.), The mechanical behavior of salt—Understanding of THMC processes in salt, 6th Conference on the mechanical behaviour of salt 'SALTMECH6', (pp. 321-326). Hannover, Germany.

Qiang, X., Xianbin, Y. & da Gama, C.D. (2008) Experimental study on deformation behavior of rock under uniaxial compression and direct tension, paper no. ARMA 08-188, 42nd US Rock Mechanics Symposium, American Rock Mechanics Association, 3(753-757), San Francisco, California, USA.

Stimpson, B. & Chen, R. (1993) Measurement of rock elastic moduli in tension and in compression and its practical significance, Canadian Geotechnical Journal 30(338-347).

Sundaram, P.N. & Corrales, J.M. (1980) Brazilian tensile strength of rocks with different elastic properties in tension and compression, International Journal Rock Mechanics Mining Sciences & Geomechanical Abstracts, 17(131-133).

Taggart, N.P. (1984) Evaluation of a rheological monitoring system based on mathematical statistics for a rock salt mine, PhD Thesis, University of Newcastle upon Tyne. Newcastle upon Tyne, UK.

Timoshenko, S. P. & Goodier, J. N. (1970). Theory of elasticity. 3rd ed., New York: McGraw Hill.

Yu, X., da Gama, C.D., Na, Y., Wang, Q.& Xie, Q. (2005) Deformation behaviour of rocks under compression and direct tension, The Journal of The South African Institute of Mining and Metallurgy, January 2005, (55-62).