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ROCK MECHANICS INVESTIGATIONS FOR GAS STORAGE SALT CAVERNS AT SHALLOW AND INTERMEDIATE DEPTH

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Abstract

In order to investigate the mechanical response of rocksalt under conditions similar to those predicted around operating gas storage caverns at shallow and intermediate depth, a series of in-situ tests were conducted in an instrumented cavity 140 m below ground at a rocksalt mine in Cheshire, operated by I.C.I. Ltd.

Analysis of the experimental results indicated that the in-situ elastic modulus of salt was more than twice the value of the usually quoted laboratory value and that the Poisson's ratio of salt varied with stress, the most distinct differences being between compressive and tensile stress state. This different constitutive behaviour in tension and compression develops an extrinsic anisotropy resulting in substantial reduction of the tensile tangential stresses acting on the surface of pressurised caverns.

Furthermore, critical assessment of the time-dependent in-situ tests has shown that creep of rocksalt is within the linear viscoelastic region and it was possible to calculate the creep constants of the rheological model representing the in-situ behaviour of rocksalt.

The stability of gas storage salt caverns at shallow and intermediate depth is illustrated with an example by assessing the effect of the tensile stresses resulting from rapid gas withdrawal. The beneficial influence of the extrinsic anisotropy of salt is clearly demonstrated.

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1. Introduction

During the last twenty five years more and more effort has been invested in the use of salt caverns for underground storage of gas, as means of reducing substantially the capital demanded for storage facilities. A review of the techniques and methods involved in design of operations for underground gas storage facilities in salt caverns has been presented by Haddenhorst (1979) and one can adequately state that the accumulated experience in that field has been certainly positive.

The advantages of underground gas storage could be realised effectively provided an assessment can be made of the stability of an underground cavern for the specific loading conditions related to the actual storage operations. Furthermore an engineering appreciation of the stability of such underground caverns is impossible unless a knowledge of the physical-mechanical properties of the surrounding rock material can be established.

The successful formulation of the stability criterion for a storage cavern based on the mechanical properties of the rock, depends upon the isolation of the phenomena which are common to every situation. However there are considerable uncertainties in the prediction of the structural response of a salt cavern, particularly for long periods of time. In addition the mechanical response of salt to loading is complex, and knowledge of weaknesses and inhomogeneities in the rock mass surrounding a cavern is limited. Furthermore the primitive geostatic stress field around a projected cavern is rarely known with any degree of certainty and must be assumed in most cases. As a result, any approach to the stability of an underground gas storage cavern may be analytical in origin but to be of practical use it must be carefully checked by critical observations in an in-situ case.

During the rock mechanics investigations for gas storage salt caverns for Imperial Chemical Industries Ltd., Mond Division, there were available facilities for an "in-situ" approach to the problem and for this reason it was decided to use this opportunity and test the salt in its natural environment. The present paper reports the results of the in-situ tests performed for Imperial Chemical Industries Ltd., Mond Division, as part of the investigations carried out for the assessment of the structural response of salt caverns at shallow and intermediate depth.

2. The "In-Situ Tests"

In shallow and intermediated depth caverns the primitive geostatic stress field is comparatively low and the internal pressure of stored gas is expected to reduce the stress concentrations around the opening.

If the cavern walls are cooled relative to the surrounding rock mass, as could happen during rapid gas withdrawal, additional tensile stresses are induced in the tangential directions. These could be sufficient to lead to resultant tensile stresses and the possibility of tensile failure exists.

The effect of these tensile stresses on the cavern surface, and in particular the thermal components were the objectives of the investigation carried out by means of the 'in-situ' tests.

In developing the 'in-situ' tests to investigate the rock mechanics condition related to a gas storage salt cavern it would clearly be advantageous to simulate, as nearly as possible, the likely stress configuration of an operational cavern. For this reason an underground site was made available by Imperial Chemical Industries Ltd., Mond Division, at their Meadow Bank Rock Salt Mine at Winsford in Cheshire, where a major programme of 'in-situ' tests were conducted in an instrumented cavity.

The cavity had the form of a horizontal cylinder with a diameter of 1.22m and a total length of 10.6m, 7.3m of this length being required for the test chamber. By means of a compressed air system internal pressures of up to 1.38 MPa were used in the tests, these being contained by an 0.8m thick concrete plug keyed into the cavity walls. In addition

- 3 -

temperatures from -13°C to +15°C, relative to ambient rock temperature were imposed on the cavity wall by circulating hot or cold ethylene glycol solution through a copper pipe heat exchanger coil, set inside the test chamber. A detailed description of the experimental site, the pressure and temperature loading systems, the deformation and temperature measurements, and the data logging system is given elsewhere (Potts et al, 1978), thus the present work is limited to the examination of the test results.

The in-situ tests can be distinguished into two types, pressure tests and thermal tests conducted at above and below ambient rock temperature. Over a period of 18 months a total of 39 tests were conducted, their duration ranging from 3 hours to 400 hours approximately.

3. Experimental Results

The pressure tests performed have been used to investigate generally the effects of mechanical loading on the cavity walls and were specifically employed for the determination of the elastic shear modulus and the rheological creep constants of rocksalt. On the other hand, the thermal tests allowed the investigation of the effects of thermal loading of the cavity and were used in particular for the determination of Poisson's ratio and the material's constant expressing the extent of the extrinsic anisotropy of rocksalt when subjected simultaneously to tensile and compressive stresses.

During the analysis of the experimental data certain assumptions were made concerning the geometry of the Cavity and the loading systems imposed. Appart from the assumptions of isotropy and homogeneity for rocksalt, a plane strain condition was employed and the principle of superposition was invoked, thus allowing the geostatic loading to be abstracted and to consider the experimentally imposed loads in isolation (Passaris, 1979).

- 4 -

3.1 Shear Modulus

All the short term pressure tests showed good agreement with the elastic response, with 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 Fig. 1.

For an internally pressurised cylindrical borehole of diameter d the diametral displacement Δd is given by Talobre (1957: 174)

$$\Delta d = \frac{1}{2u} p d$$

where μ is the shear modulus and p is the internal pressure. Consequently the shear modulus was calculated from the experimental results by regressing the diametral deformation of the cavity against the imposed internal pressure. A statistical analysis was performed on 386 experimentally determined values for the shear modulus and resulted in a mean value equal to:

This value for the shear modulus gives a modulus of elasticity ranging between 30.34 GPa and 45.51 GPa depending on the value of Poisson's ratio (ranging from 0 to 0.5) which contrasts with the usually quoted laboratory value of 12 GPa (Dreyer, 1972: 113). This variation may in part be due to the different behaviour of the rock in the "insitu" environment, but more probably is caused by the generally higher stress conditions used in laboratory tests, and the consequent unavoidable incorporation of transient creep deformation with the elastic deformation.

- 5 -



elastic response. Maximum internal pressure is equal to 1.29 kPa .

3.2 Creep Constants

The time dependent behaviour of rocks is often compared to that of rheological models, which portray the deformation response of rocks under a given loading condition. Since the use of such models implies a linear visco-elastic behaviour, one can only employ them provided that the compressive deviatoric stresses involved are not high. Indeed for gas storage caverns located at shallow and intermediate depth the corresponding deviatoric stresses are below the limit of viscoelastic linearity of salt and one can take advantage of the analytical, as opposed to numerical, creep solutions that can be developed by means of rheological linear visco-elastic models.

From the range of the available rheological models, it was shown by Potts et al (1972) that the Burger model (see Fig. 2) holds reasonably well for rocksalt originating from the same area where the present tests were conducted.

Four long term pressure tests were employed to investigate the creep behaviour of salt and experimental results of the diametral deformations with time were used to calculate the creep constants G_m , G_k , n_m and n_k (see Fig. 2) of the rheological model employed. The experimental data obtained from the four in-situ long term pressure tests have shown good qualitative and quantitative agreement with the behaviour corresponding to the calculated constants (see for example Fig. 3). A critical examination of the calculated constants showed no stress-dependence of these constants for the stress range induced during the four tests. Furthermore it was also established that there was no significant time-dependence displayed by the model constants with the exception of the viscosity constant n_m .

It was shown by Passaris (1979) that for a variation of the constant pressure time from approximately 2 to 11 days the constant n_m varied accordingly as:

- 6 -



Fig. 2 . The nheological model of Bunger used for the viscoelastic representation of the creep behaviour of nocksalt .



690 GPa/day 🤇 n_m 🔇 2855 GPa/day

The remaining constants of the Burger model have been determined as the mean of the individual values from every test and found equal to:

> $G_m = 32.2 \text{ GPa} \pm 6\%$ $G_k = 815.5 \text{ GPa} \pm 4\%$ $n_k = 207.2 \text{ GPa/day} \pm 4\%$

It is interesting to notice that since the constant G_m reflects the instantaneous response of salt it is expected that $\frac{1}{2}$ G_m should be equal to the shear modulus μ . Indeed the value of $\frac{1}{2}$ $G_m = 16.1$ GPa from the visco-elastic analysis compares very favourably with the independently calculated range of shear modulus 12.14 GPa $\langle \mu \rangle$ [18.20 GPa.

3.3 Poisson's Ratio

The radial displacement of a cylindrical cavity with a radius a caused by an imposed temperature distribution is given by Timoshenko and Goodier (1970) as:

$$u = \frac{1+\nu}{1-\nu} \quad \frac{\alpha}{r} \quad \int_{a}^{r} T r dr = \frac{1+\nu}{1-\nu} \quad \alpha \quad \text{Intgr} (r)$$

where v is the Poisson's ratio, \propto is the coefficient of linear thermal expansion (determined in the laboratory as being equal to 26 x 10⁻⁶ oc⁻¹ + 12%), and T is the temperature which is a function of radial distance r.

The temperature distribution integral of the above expression was evaluated by monitoring the temperature profile during the thermal tests. Consequently by plotting the expression Intgr (r) against the induced radial displacement u (as shown in Fig. 4) it was possible to calculate Poisson's ratio since the regression line of u against Intgr (r) has the slope $\propto (1 + v)/(1 - v)$.



Fig. 4 . Results of salt deformation response for an imposed temperature of 5°C above rock ambient temperature , indicating a predominantly elastic response .

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The deformation response in the thermal tests indicated a tendency to depend on the particular temperature condition applying to the surface of the test cavity. This trend was not based on significant differences in the slope $\alpha(1 + \nu)/(1 - \nu)$, but its consistency suggested it was a true reflection of the actual rock behaviour. These variations in slope of u against Intgr(r) regression line imply a variation in the Poisson's ratio, assuming an invariable σ , whereby ν is reduced with increasing temperature. However it seems most probable, in view of the small range of temperature changes involved, that ν depends upon the level of induced stress rather than directly on the temperature, a result which agrees with laboratory data (Wawersik & Hannum, 1979).

The mean value for Poisson's ratio was eventually determined as the mean of 172 results and found equal to:

 $v = 0.21 \pm 0.11$

The above value was calculated from data originating only from locations and tests where the involved stresses were compressive. As will be shown in the following section a different value for Poisson's ratio was calculated for the tensile regime.

3.4 Ratio of Extrinsic Anisotropy

It was shown (Passaris, 1978) that the tensile tangential stresses developed on the surface of an internally pressurised cylindrical hole are substantially reduced if the rock material surrounding the opening has its elastic constants in tension less than the equivalent constants in compression. Such a phenomenon takes place as a result of the stress redistribution caused by the extrinsic anisotropy resulting from simultaneous application of compressive (along the radial direction) and tensile (in the tangential direction) stresses.

- 8 -

Laboratory tests with large cylindrical specimens (diameter 608 mm, height 254 mm) of salt, having an internally pressurised concentric hole of 76 mm diameter indicated that the ratio k of Poisson's ratio in compression to Poisson's ratio in tension for salt is equal to

$$k = 3.84 \pm 1.56$$

The above value was based on the established values for shear modulus and Poisson's ratio in compression of being equal to 15.17 GPa $\pm 20\%$ and 0.21 ± 0.11 correspondingly.

With reference now to the in-situ tests, only a small number of thermal tests were conducted, which produced adequately high tensile stresses to counteract the compressive geostatic stress field and to allow the calculation of Poisson's ratio in tension. The analysis of 30 available results produced an overall figure for Poisson's ratio in tension of $v = 0.02 \pm 0.16$ implying a ratio of extrinsic anisotropy equal to k = 10.5, considerably higher than the k = 3.84 found in the laboratory tests. In fact if we use the ratio of extrinsic anisotropy as determined in the laboratory the suggested value for Poisson's ratio in tension is v = 0.05. Bearing in mind the small number of results incorporated in the in-situ mean value of Poisson's ratio and considering that a value of v = 0.05 falls well within the range of confidence and that a difference of:

v (laboratory) -v (in-situ) = 0.03

has little effect on prediction of stresses, it seems reasonable to assume a value of ν in tension equal to 0.05

4. Applications

The results given in section 3 may be used to demonstrate the influence of high tensile stresses which can develop at the end of a fast-rate gas withdrawal phase. For this purpose the case of an underground gas storage cavern with an idealised spherical shape located at a depth of 350 m is examined, by imposing a prescribed temperature distribution.

At the end of a rapid gas withdrawal phase the decrease in the cavern pressure will lead to a reduction in gas temperature as a result of the Joule-Thomson effect. Fig. 5 shows a hypothetical distribution of the reduction in rock temperature which may be associated with such a gas pressure reduction.

The internal cavern pressure resulting from the stored gas is assumed as being equal to 3 MPa at the end of the withdrawal phase and the external geostatic stress acting at infinity is taken as being isotropic and equal to:

$$P_{\infty} = \frac{1}{3} \sigma_{v} (1 + 2 k_{o})$$

where the vertical geostatic stress component σ_v is calculated by the overburden gradient of 22.62 kPa/m and the ratio of the horizontal to vertical geostatic stress k_o is a function of Poisson's ratio, $k_o = v/(1 - v) = 0.266$.

To investigate the influence of the extrinsic anisotropy of rocksalt when subjected simultaneously to compressive and tensile stresses, two separate analyses were conducted where all the parameters were kept constant and only the ratio of extrinsic anisotropy varied by assuming values of k = 1.0 and k = 3.84.

For an isotropic behaviour i.e. for k = 1.0 the distribution of the tangential stresses for the specific example under consideration is given in Fig. 6. One can see in Fig. 6 that high tensile **stresses** of



Fig. 5 : Example of a hypothetical temperature distribution expected to develop at the end of a fast-rate gas withdrawal phase in an underground gas storage cavern .

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Fig. 6 : Tangential stress distribution as calculated for a 20 m radius spherical storage cavern in salt with a ratio of extrinsic anisotropy equal to 1.0 .

the order of 3.9 MPa are developed on the surface of the cavern and a tensile zone exists penetrating the rock mass to a depth of approximately 0.3 m. In this case the relatively high tensile stresses represent a critical factor in the development of tensile failure conditions of salt, extending in the rock mass up to a distance of 0.15 m from the cavern surface. However since it was established experimentally that rocksalt posseses an extrinsic anisotropy, a repeat of the analysis, this time employing k = 3.84 demonstrates a dramatic reduction in the magnitude of the tensile stresses as shown in Fig. 7. Although the extend of the tensile zone (see Fig. 7) remains the same as before (i.e. 0.3 m) the actual magnitude of the tensile stress on the cavern surface is reduced by approximately 80% down to 0.85 MPa. These results clearly suggest that the existance of extrinsic anisotropy in salt has a positive influence in cavern stability against tensile failure. Furthermore the fact that the values observed under in-situ conditions for the ratio of extrinsic anisotropy were higher than k = 3.84, adds an extra factor of safety by reducing even further the magnitude of the tensile stresses involved.

Both previous analyses were conducted by assuming the ratio of horizontal to vertical geostatic stress, as being equal to $k_0 = 0.266$. However the assumption that k_o is a function of Poisson's ratio although applies successfully to real geological situations, is not often employed for the case of evaporites where Heim's rule is customarily invoked. Heim suggested that the inability of rock to support large stress differences together with the effects of time-dependent deformation of the rock mass, can cause lateral and vertical stresses to equalise over periods of geological time, hence $k_0 = 1.0$. By employing such an assumption to the previous example the resulting tangential stress distribution, as shown in Fig. 8, is entirely in the compressive stress regime with tangential stresses of the order of -1.9 MPa developing on the cavern surface. Clearly, in this case, the existence of extrinsic anisotropy of salt is not affecting the results since the geostatic stress field is not allowing the formation of a tensile stress zone around the cavern, thus precluding the consideration of any tensile failure of salt.

- 11 -



Fig. 7 . Tangential stress distribution as calculated for a 20 m radius spherical storage cavern in salt with a ratio of extrinsic anisotropy equal to 3.84 .



Fig. 8. Tangential stress distribution as calculated for a 20 % radius spherical storage cavern in salt where the geostatic stress field is assumed isotropic .

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