Prediction of land subsidence caused by mine dewatering

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Abstract This paper describes the research carried out to evaluate the compaction associated with dewatering as an aid to surface subsidence prediction in the Collie Coal basin. A triaxial test technique has been adapted to evaluate the compaction characteristics of the sandstone aquifer in the Collie basin. The technique, which allows the strata stress regime to be reproduced by triaxial loading with zero lateral strain, also provides a precise evaluation of lateral stresses and consequently Poisson's ratio under in situ conditions. The paper contains a description of equipment commission, test techniques, results, and the analysis and interpretation of derived data obtained. The testing and evaluation techniques are general in nature and are applicable to field situations in locations where similar weak sandstones occur.

INTRODUCTION

The Collie basin lies nearly 200 km south-southeast of Perth in Western Australia and is 27 km long by 13 km wide, covering an area of approximately 230 km². It contains extensive reserves of good steaming coal which is currently being mined by both open cut and underground methods.

The Collie Coalfield has a long history of strata control problems. They manifest themselves in the form of localized poor roof control, surface subsidence, slope instability and mine abandonment (due to a sand-slurry inrush). Major sources of these problems include the very extensive, weak, saturated, sandstone aquifers. As a result, underground operations have been limited to room and pillar extraction, presently carried out by continuous miners and road-heading machines. Approximately 30-40% recovery by volume is being achieved by this method.

In order to increase the recovery to approximately 70%, the Wongawilli method of shortwall mining has been introduced. With this method, extensive aquifer dewatering is carried out prior to caving of the immediate roof. However, due to the porous and weak nature of the aquifers, dewatering has the potential to cause subsidence, with a significant risk of environmental instability on a large scale. This is particularly critical adjacent to townsites and industrial complexes. For safe operations and limits to surface subsidence, an engineering design was needed which would control strata deformation
with a high degree of confidence. A better understanding of strata mechanics was needed to achieve this.

The roof dewatering/depressurization procedure involved a combination of in-mine vertical roof drainage holes and conventional dewatering bores constructed from the ground surface above the mining area. A full account of the dewatering strategy may be found elsewhere (Humphreys & Hebblewhite, 1988; Dundon et al., 1988). Of prime concern is the effect of pore pressure reduction upon strata compaction. To simulate those effects it is necessary to perform tests under triaxial conditions of the same order as experienced in situ.

The pore pressure effect phenomenon is not a new concept. However, investigation of the effect under triaxial conditions is relatively new. Although rock bulk compressibility figures are generally larger for high porosities, simple compressibility porosity correlations do not exist. Furthermore, compressibility data reported for poorly-consolidated sandstone differ greatly. This paper describes the equipment and the techniques and procedures used in carrying out deformation characteristics of poorly-consolidated sandstone in Collie Coal basin.

ROCK MOVEMENTS CAUSED BY DE-WATERING IN POORLY CONSOLIDATED SANDSTONE

Land subsidence is caused by a number of mechanisms including withdrawal of fluid and the collapse of underground openings. This study is concerned with the former.

Deformations resulting from equilibrium disturbance of the aquifer rock due to water pressure decline, are either elastic or non-elastic. Elastic deformations are mostly of a negligible extent with respect to both the involved surface subsidence and the reserve of the stored water, being only of importance in respect to the variation of the rate of flow.

The extent of the non-elastic deformation are due to compaction or migration of the rock material. The former, depends on the geotechnical characteristics of the rock, and on the extent of the pore pressure reduction. The extent of migration, on the other hand, depends on the pressure gradient (the flow velocity). The compaction may cause regional subsidence, while the migration of the rock particles causes local displacement, both phenomena being dependent upon the characteristics of the aquifer rock and the extent of dewatering.

Several techniques are available for predicting subsidence due to fluid withdrawal, classed by Poland (1984) into three broad categories: empirical, semi-theoretical and theoretical. Empirical methods essentially plot past subsidence vs. time and extrapolate into the future based on a selected curve fitting technique. They suffer from a lack of well documented examples to establish their validity. Semi-theoretical methods link on-going induced subsidence to some other measurable phenomenon in the field. Theoretical techniques require knowledge of the mechanical rock properties, which are either obtained from laboratory tests on core samples or deduced from field observations. Essentially, however, theoretical techniques use equations derived from fundamental laws of physics, such as mass balance.

Geertsma (1966, 1973) has shown in a theoretical analysis that reservoirs deform mainly in the vertical direction and that lateral variations may be discarded if the lateral
dimensions of the reservoir are large compared with its thickness. For the
one-dimensional compaction approximation, the vertical deformation of a prism of the
aquifer material can be computed by:

$$\Delta h = C_m h \delta P$$

where $\Delta h$ is the change in the prism height, $C_m$ is the one-dimensional compaction
coefficient, $h$ is the prism height, and $\delta P$ is the change in pore fluid pressure.

This approach was adapted by Martin & Serdengecti (1984). They suggest that the
best way to obtain values of $C_m$, which in most cases is the most difficult of the three
one-dimensional compaction parameters to determine, is to measure it on core samples
in the laboratory.

The one-dimensional compaction coefficient "$C_m$" of friable sandstones can be
measured by different methods:
- indirect measurement by measuring rock compressibility "$C_b$" under hydrostatic
  load and estimating Poisson’s ratio of the rock;
- direct measurement by equipment which simulates the aquifer boundary condition
  of zero lateral displacement (such as, Oedometer cell test, or a modified triaxial cell
test).

Although the triaxial test method is laborious and time consuming, its unique
experimental conditions make it essential as they reproduce aquifer stress quite well. In
addition, the triaxial set-up has the advantage that the circumferential pressure needed
to prevent lateral stain is measurable. The Poisson’s ratio of the rock sample can
therefore be determined independently from the ratio of lateral to vertical stress.

LABORATORY-DETERMINED COMPRESSIBILITIES

The cores taken from Collie basin vary markedly in both porosity and grain correlation.
Medium to high porosities are found in consolidated and semi-consolidated sections. In
addition, the nonhomogeneous appearance of the cores suggest that rock properties vary
over short distances. Consequently, compaction is expected to vary considerably with
depth, implying that the cores must be sampled systematically at short intervals to obtain
a reliable compaction profile. As this involves compaction measurements on a large
scale, a simple, rapid, but nevertheless reliable measuring technique must be developed.

The earlier studies by Grassman (1951), Biot (1941), Geertsma (1957) and Van der
Knaap (1959) resulted in the theory of pore elasticity. They demonstrated that
compaction behaviour depends only on effective frame stress, i.e. the difference
between external and internal stresses. Nikraz (1991) has confirmed that the effective
stress theory is applicable to Collie sandstone. Therefore, to stimulate aquifer
compaction in a laboratory experiment requires application of the stress difference
instead of the actual stresses. Experimentally the most attractive approach is to load the
samples externally, keeping the pore water pressure constant and atmospheric.

The triaxial technique which was developed in accordance with this reasoning
predicts the compaction behaviour of strata due to dewatering in particular for the
weakly cemented Collie sandstone. The technique allows the strata stress regime to be
reproduced by triaxial loading with zero lateral strain, and also provides a precise
evaluation of lateral stresses and consequently Poisson’s ratio under in situ stress
conditions. The condition of zero lateral strain during triaxial compaction test is achieved by both preventing any volume change in the cell-water system surrounding the specimen and by using the modified piston and top cap (Fig. 1). This piston is of the same diameter as the sample, therefore induced the triaxial stress in the sample, not the deviator stress. Because bulk volume change was detected from pore volume changes, the pores of the specimens had to be completely saturated. For full detail of the equipment design see Nikraz (1991). The experimental procedure had two stages:

- the preparatory stage, in which the specimen was brought into an "initial" loading state prior to the test;
- the test itself, which further compacted the specimen.

In order to eliminate possible membrane penetration effects during the test and thereby cause errors in test results, the specimens were first loaded hydrostatically to a pressure of 1.25 MPa. The volume change related to this pressure was assumed as a reference point. The axial stress was then measured continuously at a constant rate until the desired axial stress was achieved. The cell pressure was adjusted simultaneously to prevent any lateral strain. However, the maximum axial stress level was confined within cell pressure limitation (maximum cell pressure limited to 12 MPa).

To check the zero lateral strain, the following relationship had to be satisfied:

$$\Delta V = \frac{A X}{1000} \text{ (ml)}$$

where $\Delta V$ is the volume change (ml), $A$ is the cross sectional area of the specimen (mm$^2$) and $X$ is the axial deflection (mm).

To determine the effect of loading history on compaction, the axial stress was released incrementally to approximately 1.5 MPa. Consequently, the confining pressure was adjusted to satisfy equation (2). The loading and unloading were repeated for
another two cycles. A total of six tests were made on specimens at strain rate of $2 \times 10^{-4}$ min$^{-1}$.

RESULTS, ANALYSIS AND INTERPRETATION

Typical axial stress/uniaxial compaction and lateral stress/uniaxial compaction are shown in Figs 2 and 3 respectively. Similar behaviour was observed in the other five specimens.

The problem of choice of loading cycle for field application has been studied by Knutson & Bohor (1963), van Kesteren (1973), Mattax et al. (1975) and Mess (1978).

![Fig. 2 Typical axial stress-strain compaction relationship with three loading cycles.](image1)

![Fig. 3 Typical lateral stress-strain compaction relationship with three loading cycles.](image2)
For fully undisturbed unloaded core material, compressibility values derived in laboratory tests should be lower than \textit{in situ} values for reservoirs that are not over-consolidated. For over-consolidated reservoirs they could be either too low or too high for \textit{in situ} application, depending on the degree of over-consolidation of the reservoir rock.

Knutson & Bohor (1963) suggest that a reasonable compressibility value may be obtained by averaging values from the first and subsequent cycle. However, from extensive laboratory and \textit{in situ} tests on relatively soft rock, Mattax \textit{et al.} (1975) suggest that the first cycle compressibility is the most realistic measure of \textit{in situ} response to changes in effective pressure that occur during reservoir depletion. However, erroneously high values of first cycle compressibility were obtained in the laboratory tests on unconsolidated sands because of systematic experimental error (caused by freezing and thawing of the sample, and some grain crushing). It was therefore recommended that about two thirds of the first cycle compressibility be taken as representative of \textit{in situ} compaction. The uniaxial compaction curves representing the six samples tested are plotted in Fig. 4 for the first loading cycles. The graph shows an almost linear compaction/stress relationship for higher stresses, so that average compaction per unit stress can be calculated for this range. Further, the compaction curves are parabolic thus there is an observed relationship:

\[
\varepsilon_1 \propto \sqrt{\sigma_1'}
\]

where \(\varepsilon_1\) is the axial strain and \(\sigma_1'\) is the axial effective stress.

To demonstrate the observed relationship the axial strains have been replotted against \(\sqrt{\sigma_1'}\) (Fig. 5). This plot provides straight lines, although it is noted that some points deviate slightly from linearity. By using the linear relationship as shown in Fig. 5, the uniaxial compaction coefficient \(C_m\) may be calculated over the relevant stress interval.

![Fig. 4 Relationship between axial strain and effective axial stress for first loading.](image-url)
Consider the simulation of dewatering operations for a typical specimen such as D156-286. Assuming an average overburden density of 2.5 t m$^{-3}$, the initial in situ hydrostatic effective stress 7 MPa would increase to 9 MPa to simulate the effects of dewatering. Hence the uniaxial compaction can be calculated by:

$$C_m = \frac{(\epsilon_1)_0 - (\epsilon_1)_f}{9 - 7}$$  \hspace{1cm} (4)

**Fig. 5** Relationship between axial strain and root of effective axial stress for first loading.

**Fig. 6** Relationship between uniaxial compaction coefficient and initial porosity for first, second, and third loading.
where \((e_1)_7\) and \((e_1)_9\) are axial strain at hydrostatic effective stresses of 7 and 9 MPa respectively, giving:

\[
C_m = \frac{(0.288 - 0.277) \times 10^{-2}}{2}
\]  

(5)

The uniaxial compaction coefficient data corresponding to first, second and third loading cycles are plotted as a function of initial porosity in Fig. 6. It appears that compaction is greater for the first loading, indicating loading history influences on compaction. However, those correlations serve to assess a reliable average field value of the uniaxial compaction coefficient, which is required for a prediction of field compaction.

In an early study (Nikraz, 1991), the average porosity obtained from 105 samples tested as 20.77% of bulk volume. Variation in porosity between holes was considered to be minor. This, and the near linear relationship between uniaxial compaction and porosity prompted the acceptance of 20.77% porosity for the determination of an average value of the uniaxial compaction coefficient.

Based on the first loading cycle, Fig. 6 indicates a uniaxial compaction coefficient of \(3.124 \times 10^{-4}\) \((\text{MPa})^{-1}\). The effects of stress relief upon sampling are accommodated within this value. However, the second and third loading cycles exhibit elastic compaction characteristics and provide an average value of uniaxial compaction coefficient for the second and subsequent loading cycles of \(1.6409 \times 10^{-4}\) \((\text{MPa})^{-1}\).

The difference between the two values indicates the elastic component of compaction. Considering the strain-hardening and core disturbance arguments one may expect the true compaction to be somewhere in between. In view of the quite small difference between maximum and minimum values, the most practical approach seems to be to take the average as a working value, thus reducing the uncertainty to an acceptable limit. Thus, a mean value of \(2.382 \times 10^{-4}\) \((\text{MPa})^{-1}\) was used to represent the \textit{in situ} compaction coefficient.

Applying these results to a 12.5 m thick aquifer above the Collieburn No. 2, with an ultimate reduction in pore water pressure of 2.0 MPa could produce a vertical compaction of:

\[
\Delta h = -C_m h \Delta P
\]

\[
= 2.382 \times 10^{-4} \times 12.5 \times 10^3 \times 2
\]

\[
= 5.96 \text{ mm}
\]

(6)

The Poisson ratio of the specimens tested can be determined independently using the ratio of lateral to vertical stresses. The ratio of lateral to vertical stresses under isotropic conditions suggested by Teeuw (1971) is:

\[
\frac{\sigma_h}{\sigma_v} = \left( \frac{\nu}{1 - \nu} \right)^{1/n}
\]

(7)

where \(\nu\) is Poisson's ratio and \(n\) is the exponent in relationship of the uniaxial compaction/axial pressure in Fig. 6. The exponent reflects the deformation of the contact points and/or contact areas between grains (Brandt, 1955). According to Hertz's theory (Timoshenko & Goodier, 1951) for perfect spheres \(n = 2.3\), while for linear elastic media such as non-porous quartz and steel, \(n = 1\) reducing equation (7) to the well known equation:
Thus, for ideally elastic materials, a variation in $n$ reflects a change in grain sphericity at the point of contact between adjoining grains. The values of $n$ for the specimen tested range from 0.869 to 0.982. This range is higher than the value of 0.677 for spheres and indicates flatter contact surfaces.

**CONCLUSION**

Special purpose-designed triaxial testing equipment has been designed, tested and commissioned. A series of uniaxial compaction tests were performed for laboratory determination of compressibilities and in situ behaviour of the Collie sandstone. The following conclusions are drawn.

Whilst recognizing the early stages of development of subsidence prediction, some deformation has been postulated based on laboratory observations. In situ monitoring of strata deformation will be required for verification of the actual deformation mechanisms at work. It has been observed that the uniaxial compression of Collie sandstone is characterized by significant nonlinearity, hysteresis and an irrecoverable strain on unloading.

Uniaxial compaction curves have been presented for the sandstone aquifer in the Collie basin. It was found that the uniaxial compaction curves were parabolic over the major part of the stress range. This yielded the expression:

$$\varepsilon_1 \propto \sqrt{\sigma'_1}$$  \hspace{1cm} (9)  

A good correlation was found to exist between the uniaxial compaction coefficient and porosity. The correlation was quantified by regression analysis. Considering the different compaction behaviour of the specimens in the first and subsequent loading cycles, an average value for uniaxial compaction coefficient equal to 2.382 x 10^{-4} (MPa)^{-1} was obtained for an average porosity of 20.77%.

**REFERENCES**


