COMPACTION BEHAVIOUR OF LIGHTLY CEMENTED SANDSTONE AS A RESULT OF DEWATERING[1]

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Abstract: Deep mining in the Collie Basin has suffered from a high level of water flow and sediment in-rushes throughout its century long history. A major source of these problems is the very extensive system of weak, saturated, sandstone aquifers. As a result, past underground operations have been limited to room and pillar extraction achieving 30 to 40 percent recovery. In order to increase the recovery to approximately 70%, the Wongawilli method of short-wall mining has been introduced. Extensive aquifer dewatering was carried out to enable this mining method to be applied. The porous and weak nature of the aquifers provides a potential source of subsidence with a significant risk of environmental instability on a large scale. This is particularly critical adjacent to town sites and industrial complexes and therefore an enhanced understanding of strata mechanics to enable confident application of engineering design. Controlled strata deformation was required for safe operations and limit surface subsidence.

A triaxial technique has been adapted to evaluate the compaction characteristics of the sandstone aquifer in the Collie Basin under conditions anticipated during dewatering operations. This 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 the equipment commission, test techniques, results, analysis, and interpretation of the data obtained.

The testing evaluation techniques are general in nature and can be applied to field situations in locations where similar weak sandstones occur.

Introduction

The Collie Basin lies nearly 200 km south-south-east of Perth in Western Australia and is 27 km long by 13 km wide, covering an area of approximately 230 km^2 (fig 1). 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% to 40% recovery by volume is being achieved by this method.

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To increase the recovery to approximately 70%, the Wongawilli method of short-wall mining has been introduced. Caving of this immediate roof is integral with this method. Extensive aquifer de-watering was carried out to enable this mining method to be applied. The porous and weak nature of the aquifers provides a potential source of subsidence (due to pore closure) and strata failure (due to increasing the effective stress), as a result of pore pressure reduction upon de-watering. The proposed development of multiple seam extraction below areas sensitive to surface subsidence has increased the need to establish the strata mechanical properties. This will assist in confident application of rock mechanics principles for predictive modeling of strata behaviour.

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 and 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 studies of poorly-consolidated sandstone in Collie Coal Basin.

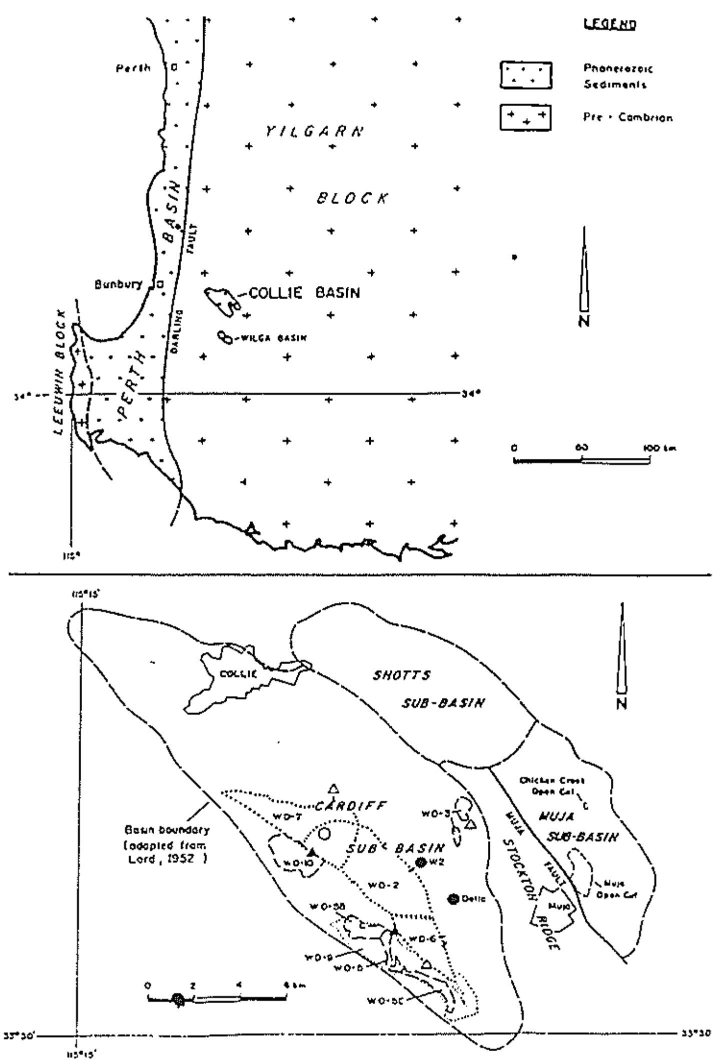

Figure 1. Collie Coal Basin, location and regional geological setting.

Regional Geology and Hydrology

The Collie Basin is comprised of two unequal lobes in part separated by a fault-controlled, basement high known as the Stockton Ridge. The basin itself consists of three sub-basins, the Cardiff, Shotts, and Muja (fig 1).

The Collie Basin sediments are mainly cyclic, high-energy fluviatile sandstones with thin gravel and conglomerate lenses. Siltstones and shales occur as overbank, lacustrine, or paludal deposits. Coal seams are remarkably uniform in thickness and composition over considerable distances.

The Collie Basin sediments can be described as saturated and weak, and have been altered through weathering or post-depositional processes. Lowry (1976) estimated that the coal measures were composed of 65% sandstone, 25% shale and claystone, and 5% coal.

The whole Collie Basin can be thought of as an interrelated groundwater system of Permian coal measures bounded by Archaean basement.

Permeable aquifers comprise fine to granular quartzose sandstones with little fines content. Moderately permeable material consists of silty-clayey sandstones. Siltstones represent the low to moderately permeable aquifers; whilst mudstone, shale, and coal layers form the system aquitards.

All coal seams in the deep mines are bounded by aquifers. In some locations aquifers are situated directly above or below the seams; however, most areas have aquitard barriers of variable thickness separating the mining seam from neighbouring aquifers (fig 2).

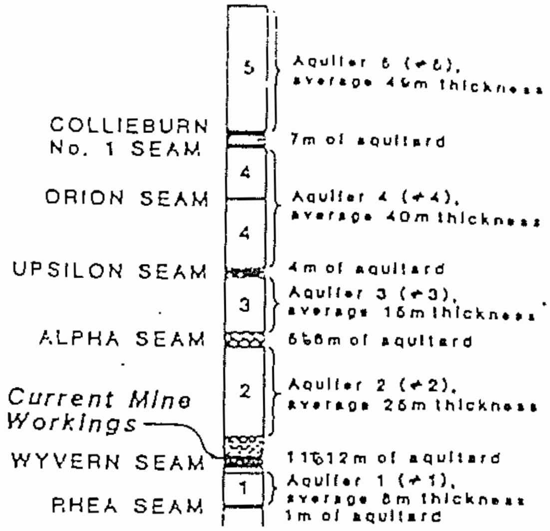

Figure 2. Generalised hydrostratigraphy.

Geomechanical Properties of the Coal Measures

The geology of the Collie Basin can vary within short intervals, both vertically and laterally. There are also marked variations within the major lithologies (sandstones, shales, siltstones, laminites). Each has a wide range of engineering properties, dependent on past and present geological processes. Table 1 below lists typical ranges of compressive strengths, elastic moduli, cohesive strengths, and friction angle for each major lithology of the Collie coal measures (Humphreys and Hebblewhite 1988). This table highlights the weak and plastic nature of Collie sediments and also illustrates that coal strengths are about two to three times greater than those of non coal lithologies. In terms of subsidence, the resistance to movement of non coals is small, and thus there is the possibility that coal seams will deform differentially and lead to bed separations at coal contact.

Table 1. Typical mechanical properties of Collie coal measures.

Lithology	UCS, MPa	Elastic modulus, MPa	Cohesive strength, MPa	Friction angle, deg
Sandstone	5.2	300	0.5	32
Siltstone	4.7	600	0.6	25
Laminite	4.7	700	0.7	25
Shale	7.0	1,200	0.8	22
Wyvem coal	19.8	2,000	2.0	42

Rock Movements Caused by Dewatering in Poorly Consolidated Sandstone

Land subsidence is caused by a number of mechanisms. Two such mechanisms are the withdrawal of fluid and the collapse of underground openings. This study is concerned with subsidence that results from the withdrawal of fluid.

The deformations resulting from equilibrium disturbance of the saturated lightly cemented sandstone aquifer 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 extents of the non elastic deformations are due to compaction or migration of the lightly cemented 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 granular 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. They have been classed by Poland (1984) into three broad categories: empirical, semi theoretical, and theoretical. Empirical methods essentially plot past subsidence versus time and extrapolate into the future based on a selected curve fitting technique. However, empirical methods suffer from the 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. Thus, the method described in this paper may be classified as a theoretical technique.

Geertsma (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 (Geertsma 1966)

$$\Delta h = C_m \, h \, \Delta P \tag{1}$$

where Δh (mm) is the change in the prism height, C_m $(\mathrm{MPa})^{-1}$ is the one-dimensional compaction coefficient, h is the prism height, and ΔP (MPa) is the change in pore fluid pressure. Readers interested in limitation of equation 1 are referred to the original work of Geertsma (1966, 1973).

A similar approach to that used by Geertsma (1966, 1973) was adapted by Martin and Serdengecti (1984). Martin and Serdengecti (1984) report that in most cases C_m is the most difficult of the three one-dimensional compaction parameters to determine and suggest that the best way to obtain values of C_m 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: (1) indirect measurement by measuring rock compressibility 'C_b' under hydrostatic load and estimating Poisson's ratio of the rock and (2) direct measurement by equipment that 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 because they reproduce aquifer stress quite well. In addition, the triaxial setup 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 stresses.

Laboratory-determined Compressibilities

The cores taken from the Collie Basin show marked variations 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 suggests that the rock's 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 adopted.

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 the compaction behaviour depends only on the effective frame stress, i.e., the difference between external and internal stresses. Furthermore, the results obtained by Nikraz (1991) confirmed that the effective stress theory is applicable to Collie sandstone. Therefore, to simulate aquifer compaction in a laboratory experiment requires the application of the stress difference instead of the actual pressures. Thus, experimentally the most attractive approach is to load the samples externally, keeping the pore water pressure constant and atmospheric.

Thus, a triaxial technique was adopted to predict the compaction behaviour of strata due to dewatering, in particular for the weakly cemented Collie sandstone. This 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 stress conditions. The condition of zero lateral strain during triaxial compaction test was achieved both by preventing any volume change in the cell-water system surrounding the specimen and by using the modified piston and top cap (fig 3). This piston was of the same diameter as the sample; it therefore induced the triaxial stress in the sample, but not the deviator stress. Because bulk volume change was detected from pore volume changes, the pores of the specimens had to be completely saturated. A full detail of the equipment design may be found in Nikraz (1991).

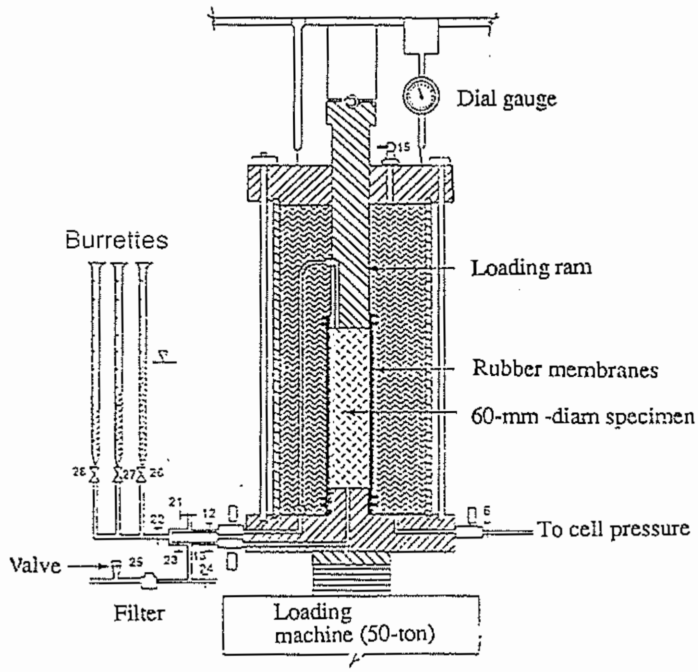

Figure 3. Arrangement of apparatus for compaction test.

The experimental procedure comprised two stages: (1) the preparatory stage, in which the specimen was brought into an "initial" loading state prior to the test, and (2) the test itself, which further compacted the specimen.

To eliminate possible membrane penetration effects during the test and thereby avoid 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).

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

$$\Delta V = (A\,X)/1000 \tag{2}$$

where ΔV = volume change (mL),
A = cross sectional area of the specimen (mm^2),
and X = 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 $2 \times 10^{-4}\text{min}^{-1}$.

Results Analysis and Interpretation

Measurements were made on six core samples taken from four locations in the Collie Coal Basin (table 2).

Table 2. Sandstone properties.

Sample	Location	Depth, m	UCS, MPa	Initial porosity, %	Permeability, 10^{-8} m/s
1	D156	286.00	3.351	20.50	36.22
2	D157	262.88	5.895	17.65	18.33
3	D157	264.26	5.201	18.05	20.62
4	D157	266.70	4.783	18.78	21.64
5	D158	259.30	3.481	22.09	34.07
6	Western 6	125.00	2.311	23.10	41.311

Typical axial stress-uniaxial compaction and lateral stress-uniaxial compaction are shown in figures 4 and 5 respectively. Similar behaviour was observed in five other specimens.

The three significant features of the stress-uniaxial compaction curves are their non linearity, hysteresis, and irrecoverable compaction on loading. Microstructural changes that produce permanent strain are a likely source of cycling effects. For example, assume that a microstructural element such as an asperity contributes to the elastic response of a rock by separating two grains. If the asperity is crushed subsequently at a high pressure, then later strain curves will be different because of the absence of the asperity. The unloading to atmospheric pressure is believed to have a significant role in stress cycling effects. When cracks are created and asperities crushed, they are probably pinned because of the high confining pressure. However, when the confining pressure is released, the microstructure can deform along new degrees of freedom and thus behave differently when reloaded. Other likely mechanisms that produce permanent strain are displacement of fines and clay minerals, and frictional sliding on grain contacts (Brace et al 1966, Batzle et al 1980).

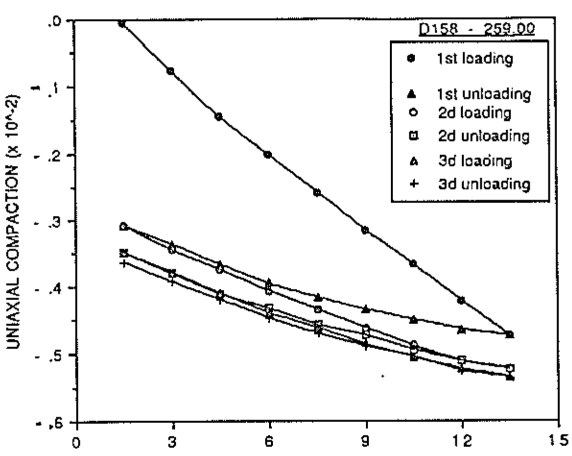

Figure 4. Typical axial stress-strain compaction relationship with three loading cycles.

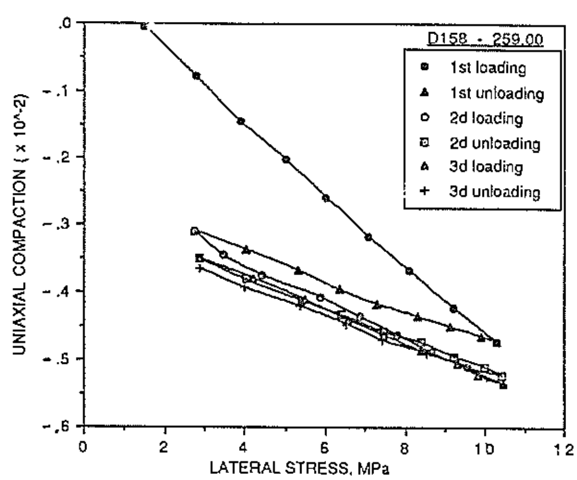

Figure 5. Typical lateral stress-strain compaction relationship with three loading cycles.

The problem of choice of loading cycle for field application has been studied by Knutson and Bohor (1963), van Kesteren (1973), Mattax et al (1975) and Mess (1978). The work of Mess (1978) suggests that for fully undisturbed unloaded core material, compressibility values derived in laboratory tests should be lower than in situ values for reservoirs that are not overconsolidated. For overconsolidated reservoirs they could be either too low or too high for in situ application, depending on the degree of overconsolidation of the reservoir rock.

It is suggested by Knutson and Bohor (1963) that a reasonable compressibility value may be obtained by averaging values from the first and subsequent cycle. However, in extensive laboratory and in situ tests on relatively soft rock, Mattax et al (1975) suggested that the first cycle compressibility is the most realistic measure of in situ response to changes in effective pressure that occur during reservoir depletion. It was mentioned, however, that erroneously high values of first cycle compressibility are obtained in 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 in situ compaction.

The uniaxial compaction curves representing the six samples tested are plotted for figure 6 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, it is noted that the compaction curves are parabolic. Thus, there is an observed relationship:

$$\varepsilon_1 \ \alpha \sqrt{\sigma_1'} \tag{3}$$

where ε_1 = axial strain

and σ_1' = axial effective stress.

To demonstrate the observed relationship, the axial strains have been replotted against σ_1' as shown in figure 6. This plot provides strain lines, although it is noted that some points deviate slightly from linearity. By using the linear relationship as shown in figure 7, the uniaxial compaction coefficient, C_m, may be calculated over the relevant stress interval.

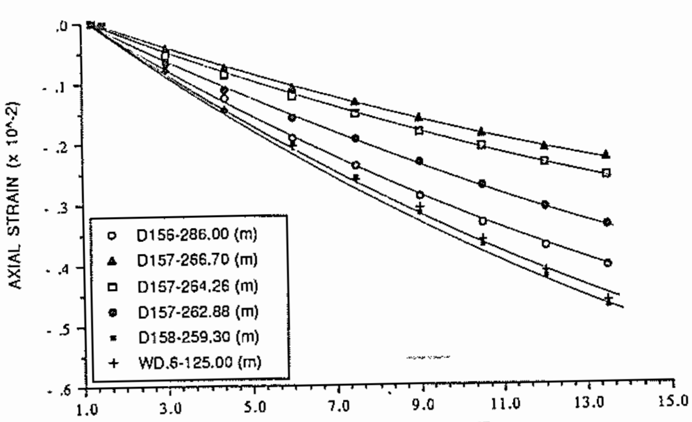

Figure 6. Relationship between axial strain and effective axial stress for first loading.

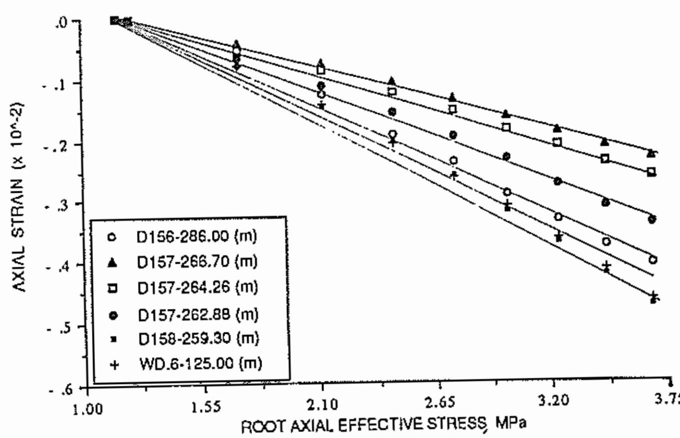

Figure 7. Relationship between axial strain and root of effective axial stress for first loading.

Consider the simulation of dewatering operations for a typical specimen such as D156-286. Assuming an average overburden density of 2.5 st/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

$$C_m = \frac{(e_1)_9 - (e_1)_7}{9 - 7} \tag{4}$$

where $(e_1)_7$ and $(e_1)_9$ are axial strain at hydrostatic effective stresses of 7 and 9 MPa, respectively.

$$C_m = \frac{(0.288 - 0.277) \times 10^{-2}}{2} \tag{5}$$

The uniaxial compaction coefficient data corresponding to first, second, and third loading cycles are plotted as a function of initial porosity in figure 8. 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, although 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, figure 8 indicates a uniaxial compaction coefficient of 3.124×10^{-4} (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 1.6409×10^{-4} (MPa)$^{-1}$.

The difference between 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 2.382×10^{-4} (Mpa)$^{-1}$ was used to represent the in situ compaction coefficient.

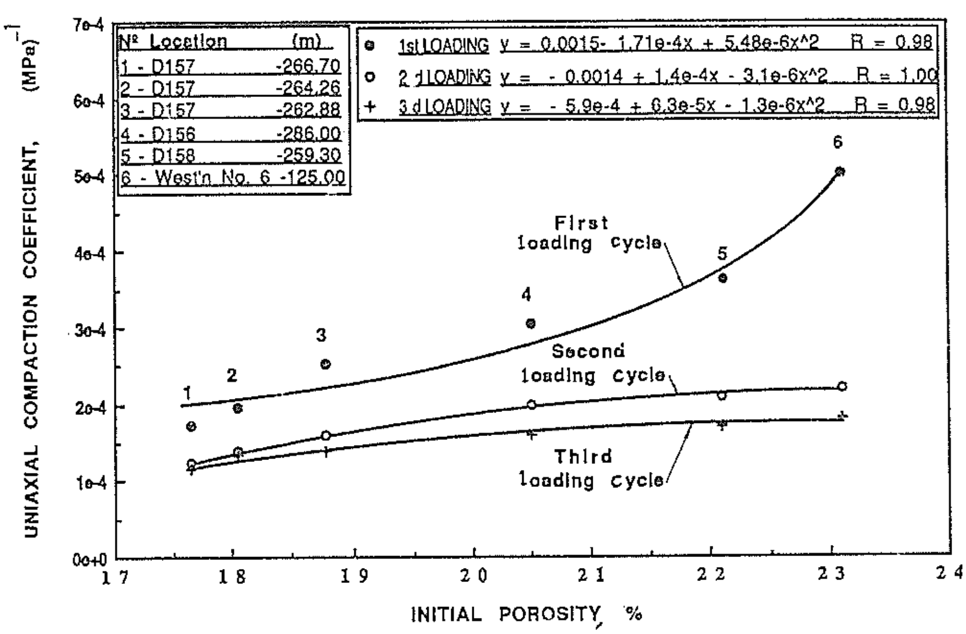

Figure 8. Relationship between uniaxial compaction coefficient and initial porosity for first, second and third loading.

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

$$\Delta h = C_m \, h \;\; \Delta P \tag{6}$$

$$= 2.382 \times 10^{-4} \times 12.50 \times 10^3 \times 2.0$$

$$= 5.96 \text{ mm}$$

The Poisson's 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

$$\frac{\sigma_h}{\sigma_v} = \left(\frac{\nu}{1 - \nu}\right)^{1/n} \tag{7}$$

where ν is the Poisson's ratio and n is the exponent in relationship of the uniaxial compaction-axial pressure in figure 4. The exponent reflects the deformation of the contact points and/or contact areas between grains (Brandt 1955). According to Hertz's theory (Timoshenko et al 1951) for perfect spheres $\nu = 2/3$, while for linear elastic media such as nonporous quartz and steel, $\nu = 1$, reducing equation 7 to the well known equation,

$$\frac{\sigma_h}{\sigma_v} = \frac{n}{1 - \nu} \tag{8}$$

For ideally elastic materials, a variation in ν thus 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.

While 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

$$\varepsilon_1 \; \alpha \sqrt{\sigma_1'} \tag{3}$$

A good correlation was found to exist between 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 2.382×10^{-4} (MPa)$^{-1}$ was obtained for an average porosity of 20.77%.

Literature Cited

Batzle, M.L., G. Simmonds, and R.W. Siegfried. 1980. Microcrack closures in rocks under stress: direct observation. J. Geophys. Res. 85:7072-7090.
http://dx.doi.org/10.1029/JB085iB12p07072

Biot, M.A. 1941. General theory of three-dimensional consolidated ion. J.App.Phys. 12:155-162.
http://dx.doi.org/10.1063/1.1712886

Brace, W.F., B.W. Paulding, and C. Scholz. 1966. Dilatancy in the fracture of crystalline rocks. J.Geophys Res. 71(16):3939-3958.
http://dx.doi.org/10.1029/JZ071i016p03939

Brandt, H. 1955. A study on the speed of sound in porous granular media. J.Appl.Phys. 22:479.

Dundon, P.J., D. Humphreys, and B. Hebblewhite. 1988. Roof depressurisation for total extraction mining trials, Collie Basin, Western Australia. p. 743-752. In 3rd International Mine Water Congress (Melbourne, Australia).

Grassmann, F. 1951. "Uber die Elastizitat Poroser Medien", Vierteljahrschrift der Naturforschenden Gesellschaft in zurich, 96(1): Sec. 1-51.

Geertsma, J. (1957). The effect of fluid pressure decline on volumetric changes of porous rock. Trans.AIME. 210:331-430.

Geertsma, J. 1966. Problems of rock mechanics in petroleum production engineering. p. 584-594. In Proceedings, First Congress of the International Society of Rock Mechanics, Lisbon, Vol 1.

Geertsma, J. 1973. Land subsidence above compacting oil and gas reservoirs. J.Petrol.Technol. 25:734-744.
http://dx.doi.org/10.2118/3730-PA

Humphreys, D., and B.K. Hebblewhite. 1988. Introduction of total extraction mining in conjunction with strata dewatering at Collie, Western Australia. Coal. Australian Coal Min.Tech. and Res. 19:45-56.

Lowrt, D.C. 1976. Tectonic history of the Collie Basin, Western Australia. Geol. Soc. Australia J. 23:95-104.
http://dx.doi.org/10.1080/00167617608728923

Knutson, C.F., and B.F. Bohor. 1963. Reservoir rock behaviour under moderate confining pressure. In Rock Mechanics, Proceedings, 5th Rock Mechanics Symposium. Macmillan, New York.

Martin, J.C., and S. Serdengecti. 1984. Subsidence over oil and gas fields. p. 23-34. In T.L. Holzer. (ed), Man-induced land subsidence. Rev.Eng. Geol. VI, The Geol Soc. of America.

Mattax, C.C., R.M. McKinley, and A.T. Clothier. 1975. Core analysis of unconsolidated and friable sands. J.Petrol.Technol. p.1423.

Mess, K.W. 1978. On the interpretation of core compaction behaviour. p.76-91. In K.S. Surendra (ed), Evaluation and prediction of subsidence. Am. Soc. of Civil Eng.

Nikraz, H.R. (1991). Laboratory evaluation of the geotechnical design characteristics of the sandstone aquifer in the Collie Basin. Ph.D. Thesis, Curtin University of Technology, p. 317.

Poland, J.F. 1984. Guide to the study of land subsidence due to ground-water withdrawal. United National Educational, Scientific, and Cultural Organisation, Paris.

Timoshenko, S., and J.N. Goodier. 1951. Theory of elasticity. McGraw-Hill, New York.

Van der Knaap, W. 1959. Non-linear behaviour of elastic porous media. Trans. AIME. 216:179-187.

Ven Kesteren, J. 1973. Estimate of compaction data representative of the Groningen Field. Verhandelingen Mijnbouwkundig Genootschap. 28:33-42.