Effects of Mines Dewatering on Poorly Consolidated Sandstone

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ABSTRACT

This paper describes the research carried out to examine the geotechnical design characteristics of the sandstone aquifers in the Collie Coal Basin under conditions anticipated during dewatering operations.

The Collie Coalfield has a long history of strata control problems. They manifest themselves in the form of localised poor roof control, surface subsidence, slope instability and mine abandonment (due to sand-slurry inrush). 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. The trial introduction of the Wongawilli method of short-wall extraction, increasing recovery to 60-70 percent, required an enhanced understanding of strata mechanics to enable confident application of engineering design.

The methodology adopted consisted of simulation of the assumed in situ conditions on triaxially confined, saturated laboratory specimens prepared from in situ core samples. Dewatering was simulated by pore pressure release followed by vertical water flow induction through the specimen. Any deterioration of the specimen and the associated volume change was monitored. The triaxial tests results were related to the texture, bulk properties, strength and deformability, permeability and wave propagation properties. These properties were used to indicate the risk of potential failure under given stress conditions.

The paper contains a description of the equipment commission, test techniques, results, analysis, and interpretation of the data obtained.

INTRODUCTION

The Collie Basin is located approximately 200 km south-east of Perth in Western Australia. It contains extensive reserves of good steaming coal which is currently being mined by both open cut and underground methods.

Deep mining in the Collie Basin has suffered from a high level of water flow and sediment in-rushes throughout its century long history. The problem of the water is compounded by the extremely weak nature of the strata overlying the Coal Seams, particularly the sandstone aquifers themselves. This combination of large quantities of overlying water in a very weak strata prevented any extensive form of secondary workings or total extraction for fear of uncontrolled goaf flooding, slurry inrushes and uncontrollable surface subsidence. 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.

In order to increase the recovery to approximately 70%, the Wongawilli method of short-wall mining has been introduced. 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 modelling of strata behaviour.

Of prime concern is the effect of pore pressure reduction and water flow induction upon strata integrity. To simulate these effects, it is necessary to perform tests under triaxial conditions of the same distribution of in situ stresses. The pore pressure effect phenomenon is not a new concept. However, investigation of the effect under triaxial conditions is relatively new. The possibility of an erosional effect due to the flow of water induced by de-watering, would tend to exacerbate any detrimental effects of pore pressure reduction. Thus its contribution must also be evaluated under triaxial conditions.

This paper contains a description of the equipment commissioned, test techniques, results, analysis and interpretation of the data obtained.

GENERAL APPRECIATION OF THE PROBLEM AND ITS IMPACT ON THE MINING ENVIRONMENT

Ground water is prevalent in the mining environment and must be taken into consideration to ensure optimum working conditions. It is not always a potential source of hazard in the work place but more of a nuisance effect. It also has a significant influence on the scope for environmental damage. Although of importance, environmental damage is not directly within the scope of this paper.

The Collie Basin, with it's thick, largely impervious sediment contains the largest single groundwater resource in the south west region east of the darling scarp in Western Australia. The Measures, which constitute a multi-layer of sandstone beds separated by confining beds of shale, mudstone and coal beds. About 75% of the succession is sandstone and grits, which are loosely cemented, although occasionally a moderately strong sandstone is found. Most sandstones, however, are not cemented at all and are known to the drillers as "drift" which could alternatively be termed "fluid sandstone".

Many of the Collie underground mines throughout this century reported problems due to "heavy" types of water often causing temporary mine closures. One of the most serious water-related problems of recent times was the forced permanent closure of the Hebe Colliery in 1965. This was caused by one of the working plates exposing a major, water-bearing aquifer via a borehole which rapidly flooded the mine. It was never re-opened as an underground mine. An interesting and comprehensive account of the water problems and mine de-watering techniques in the Collie Coal Basin has been given by Jones [1].

To reduce the hydrological hazard aquifers are often drained if necessary. This results in the in situ stress previously accommodated by the pore water pressure being redistributed to the surrounding rock particles. Although of limited significance for most mining situations, it can result in the failure of weak rock [2].

The importance of a knowledge of the effects of induced stress changes as a result of de-watering a weakly cemented sandstone aquifer has been previously referred to by Kawecki et al, [2]. The two aspects that are of primary interest are (1) deformations produced by changes in the state of stresses of the aquifer as a result of de-watering and (2) an erosional effect due to the flow of water induced by de-watering, which would tend to exacerbate any detrimental effect of pore pressure reduction.

Although seepage and drainage of both soils and hypothetical porous media have been investigated theoretically and experimentally by geotechnical engineers, drainage of poorly-consolidated rock has been neglected. There is little reference in the literature to the basic properties of rock deformation caused by migration of rock particles. Furthermore, most failure theories and experimental work are related to non-porous and low-porosity rock types, while major problems during aquifer de-watering relate to relatively weak formations such as loose sand and/or poorly consolidated sandstone as is the case in the Collie Basin.

In an analytical attempt, Nikraz [3] has shown that the migration of rock materials in poorly cemented rock are to be expected, when seepage velocity V_s exceeds the critical velocity V_{sc} :

$$V_{cs} = 5.11 \times 10^{-11} \tan \phi \, n^{4.1} \, d^2 \frac{\gamma s - \gamma f}{\gamma f} \qquad (1)$$

where V_{sc} = Critical seepage velocity (m/s)
ϕ = angle of internal friction (degree)
n = porosity (%)
d = average grain size diameter (mm)
γs = specific weight of particle (kg/m^3)
γf = specific weight of fluid (kg/m^3)

However, Nikraz [3] concluded that the critical seepage velocity calculated in this way is considerably smaller than the actual critical value, because in the layer the grain is compelled to move in a complicated conduit including rising sections and not on a plain surface. The only conclusion which can be drawn from equation (1) is that the critical seepage velocity is a function of porosity, average particle diameter and friction assuming the specific weight of both water and particle are constant. Thus the investigation of erosional effect due to flow of water induced by dewatering can only be determined by experiments.

TRIAXIAL EQUIPMENT

The scope of the research required unique triaxial testing of rock. As no commercial system was available, a system with the appropriate capabilities was designed.

An automated data capture system utilising transducers and dynamic recording were designed and commissioned. The overall system was designed to withstand a maximum predicted hydraulic pressure of 14 MPa.

While the equipment developed for use in this and in other associated programs of research was similar in principle to that described by Bishop and Hankel [4], a number of refinements had to be introduced because of the markedly higher strength and stiffness characteristics of soft rock which required the use of significantly higher testing pressures.

The system developed for this study consisted of six integrated units :

1. A triaxial cell
2. A confining pressure system
3. A pore pressure system
4. A stiff load frame and servo-controlled loading ram
5. Monitoring equipment for applied loads, water flows, and specimen deformation, and
6. Data capture and display system.

Full details of the equipment design may be found in Nikraz [3].

MODIFIED TRIAXIAL TEST

The test was designed to stimulate in situ strata conditions as it dewatered. The design approach was influenced by observed in situ deformation which ranged from roof failures to significant strata stabilisation.

The test parameters considered most significant were :

(a) The triaxial and confining stresses
(b) Pore pressure reduction rate
(c) Water head applied to induce flow through the specimen
(d) Test duration

These were standardised for the tests which consisted of six stages, namely :-

1. Specimen mounting in triaxial cell
2. Specimen saturation
3. Load application
4. Pore pressure reduction
5. Axial water flow induction
6. Time dependent testing

Only a brief description of test procedures will be presented herein but full details may be found in Nikraz [3].

Each specimen was photographed prior to testing. The specimens were then placed into the triaxial cell and saturated. Specimen permeability was determined upon completion of the saturation. Any water passing through the specimen was collected for analysis.

The test stresses were increased incrementally to their predetermined values. In the absence of in situ stress measurement or indications of high lateral stress, hydrostatic stress conditions were assumed. Thus, the confining stresses were based on the depth pressure, ie.

$$\sigma_1 = \sigma_2 = \sigma_3 = 10^{-6}\, \rho.g.h. \text{ (MPa)} \qquad (2)$$

where σ_1, σ_2 and σ_3 are the major and minor principle stresses

ρ = average saturated strata density (kg/m^3)
g = gravity constant (m/s^2)
h = depth of cover (m)

Once the desired stress conditions had been attained, pore pressure reduction was achieved by opening the fine metering valve to the atmosphere, with the top pore pressure inlet closed. Any particles washed out with the water were collected.

If no failure occurred, the final volume change associated with pore pressure reduction was noted once the predetermined stress conditions had been re-attained.

A head of distilled water was then applied to the top of the specimen for 20 minutes using the specimen saturation system to stimulate the highest predicted in situ head. The water flowing out of the specimen was sampled and analysed for specimen deterioration. The permeability at the start and upon completion of the test was determined, and the final volume change evaluated.

Upon completion of the water flow test, some specimens were continued to be monitored for up to another 35 hours under the same stress conditions, except that no water flow was induced. This provided an indication as observed after 20 minutes, compared to that attained after extended exposure to changes in stress.

Upon removal from the cell, the specimen was again photographed to illustrate the extent the location for any deterioration. Any rock particles remaining on the bottom pedestal and in-line filter were also collected.

ASSOCIATED TESTS

An extensive set of index laboratory tests were performed to supplement the modified triaxial test results (see Table 1). The methodology used to determine the geotechnical properties may be found elsewhere [3].

Table 1 - Summary of Triaxial and Associated Tests

CATEGORY	TYPE	RELEVANT PARAMETERS
Modified Triaxial Tests	Pore Pressure Reduction and Water Flow Induction	Permeability, volume change and % weight particles washed out
	Creep	Volume change
Associated Tests	Strength & Deformability	Saturated uniaxial Compressive strength dry and saturated tensile strength, saturated tensile strength after modified triaxial tests and deformability modulus
	Bulk Properties	Porosity, void ratio, Saturated moisture content; and dry density
	Textures	% gravel content % sand content % clay content, median diameter sorting and uniformity coefficient
	Ultrasonic Wave Velocity	Compressional wave velocity
	Thin section	
	Packer Test	In situ permeability

RESULTS ANALYSIS AND INTERPRETATION

Thirteen specimens failed in total and failure type ranged from a single classic triaxial failure plan, to complete collapse into an elastic, soil-like consistency. Analysis of the parameters monitored suggested that porosity, coefficient of permeability, saturated compression wave velocity, uniformity coefficient, and tensile strength, might be used as indicators of potential failure [3] and [5], Degradation was observed on most specimens. This was quantified by the weight of the particles washed out from the specimen, and any that were collected from the bottom pedestal and inline filter upon completion of the tests. Due to the small weight of particles collected, in most cases it was not possible to further quantify the degradation by evaluation of the different size fractions.

Although the origin of the larger particles was readily identified by the cavities at the specimen surface, the origin of the clay sized fraction was more difficult to determine. Migration of the fines through the specimen, or from near the specimen surface could not readily be distinguished.

Most deterioration was at the specimen base, and in some cases extended significantly (0.4-0.8 in (1-2 cm)) up the specimen. This was not classified as failure, although further tests may indicate a need for a change in failure classification.

The location of the majority of the deterioration suggested the washing out of the fines that contributed to the cementing matrix. The possibility of fines migration through the specimen was supported by the deterioration of some specimens at the top. The matrix fines could realistically only have been carried in the direction of water flow. Whether these passed along the entire length of the specimens during testing could not be determined without some means of distinguishing the fines origin.

The percentage weight of particles washed out increased with increasing volume change (see Figure 1). Whether this was as a result of the increased porosity facilitating migration or whether the increased volume change was due to the loss of particle was not clear. The latter was less likely as the weight included the larger particles that remained on the pedestal. Hence, the volume change was attributed primarily to a closure of pore spaces, which was enhanced by a weakening of the specimen, due to loss of fines from the cementing matrix.

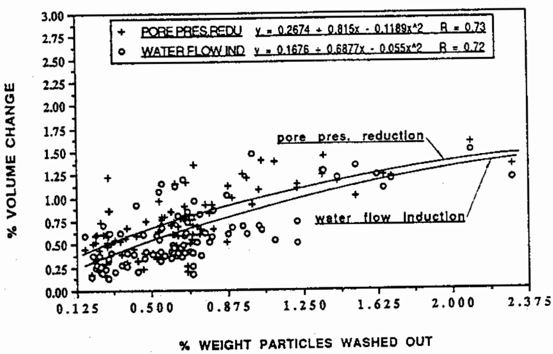

Figure 1 - Percentage of volume change vs percentage of weight of particles washed out

A simple conceptual model which explains the permeability behaviour as a result of the pore pressure reduction and the water flow induction, is one in which the quartz grains form a rigid framework which supports the externally applied stress. The pore water channels are surrounded, at least in part, by the matrix materials (clay and various accessory materials). Figure 2 schematically illustrates such a structure. The outer ring represents the quartz skeleton. The pore space, clay and accessory minerals, which are distributed between the quartz grains, are simply shown here as a single pore surrounded by the clay material.

In this model, any increase in confining pressure or reduction in pore water pressure produces a strain in region 1 which in turn induces a stress in region 2 and thus results in a strain at the pore boundary. Consequently, a smaller radius of pore may result. Furthermore, the seepage force as a result of pore pressure reduction or the water flow induction may result in washing the matrix materials in region 2 away and, as a consequence, a bigger pore radius may be obtained.

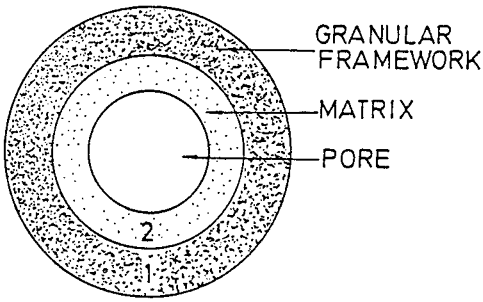

Figure 2 - Conceptual model of cylindrical capillary

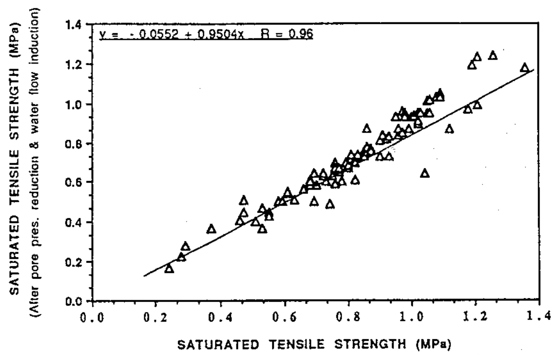

Figure 3 - Saturated tensile strength after pore pressure reduction and water flow induction vs saturated tensile strength

As indicated in Table 1, saturated tensile strength was also measured after triaxial tests. Figure 3 shows the relationship between the saturated tensile strength and saturated tensile strength of those specimens that had not failed under triaxial test (pore pressure reduction and water flow induction). There appears to be a weakening of rocks as a result of pore pressure reduction and water flow induction action. On average there is a reduction of rocks as a result of pore pressure reduction and water flow induction action. On average there is a reduction of 12% in saturated tensile strength after the triaxial test compared to the saturated tensile strength before the test. Similarly, a plot of saturated tensile strength at the end of triaxial test against the weight of particles washed out could suggest increased washing out with decreased saturated tensile strength after the triaxial test (see Figure 4). Thus, this relationship could be used to positively support the concept of weakening the rock as a result of particle migration through the specimen.

Moreover, correlation coefficient of 0.76 was observed in the correlation of change in tensile strength with the percentage of clay content (see Figure 5).

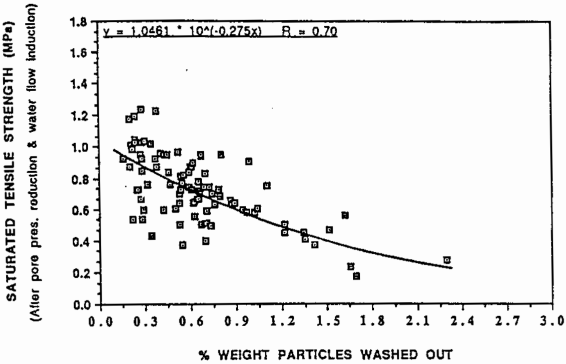

Figure 4 - Saturated tensile strength after pore pressure reduction and water flow induction vs percentage of weight of particles washed out

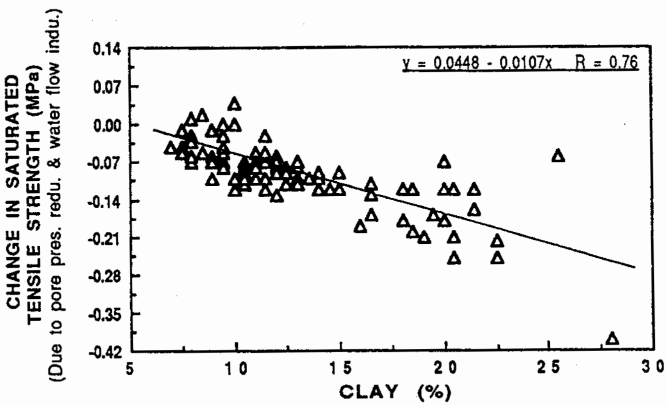

Figure 5 - Change in saturated tensile strength due to pore pressure reduction and water flow induction vs percentage clay-sized fraction

Figure 5 shows that the reduction in saturated tensile strength increases as the percentage clay content increases, which may be used to further support the concept of weakening of the rock as a result of mainly fine particles migration through the specimen.

The time dependent nature of the tests is acknowledged. Both the rate of pore pressure release and the time of water flow induction could significantly affect the results. This was demonstrated by the continued decrease in specimen volume upon extension of the water flow induction test duration of up to 35 hours.

An examination of volume changes observed under time dependent testing (see Figure 6) strongly occurred within the first 8 hours. Evaluation of the volume change observed within the first twenty minutes showed that it was consistently 82-86% of the total volume change observed at the end of time dependent testing. Hence, it reinforced the validity of limiting testing to 20 minutes in practical terms, whilst providing the means of obtaining reasonable evaluation of the total volume change that might be expected.

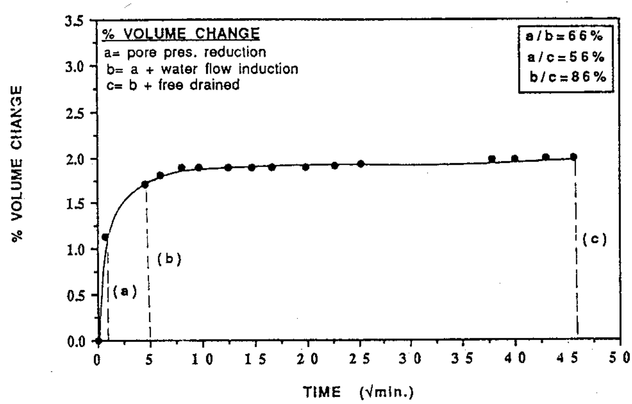

Figure 6 - Time dependent total volume change of D156-285.38

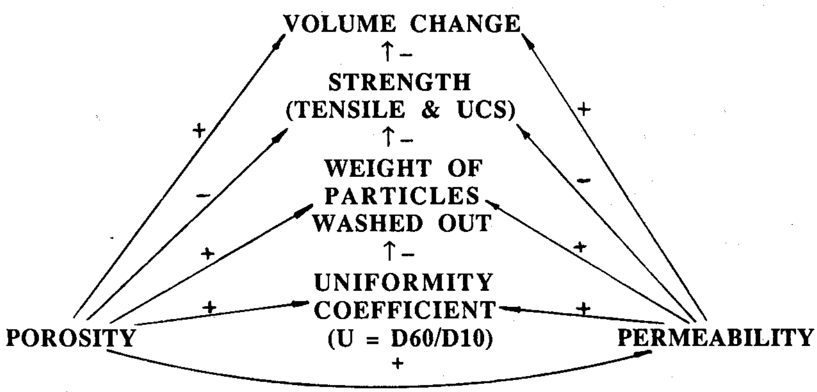

Figure 7 - Effect of causal factors on volume change

Finally, the inter-relationship between the volume change and associated parameters can be summed up in the form of a schematic "cause and effect" diagram [6] in which some prior knowledge of the factors exist (see Figure 7). In such a system, the effects of one variable on another are indicated by an arrow : positive correlations are show by a plus sign, negative ones by a minus sign.

PROGRESS TOWARDS MATHEMATICAL PREDICTIVE CAPACITY OF SUBSIDENCE

It is postulated at this stage, that subsidence could be induced by one of the three mechanisms:

(a) Any reduction in volume of the strata is represented in-situ entirely as a lowering of the surface, i.e. the overlying strata flows to fill any voids formed by the three dimensional contraction of the strata on dewatering.

Example : Consider a 1 metre cube of rock. A percentage volume reduction of 1% would result in a reduction in volume of 0.01 m^3. The plan area of the cube would be maintained. Thus the reduction of 0.01 m^3 would result in a vertical compaction of 1 cm.

(b) The reduction in volume is achieved without strata flow. This would result in opening up of any discontinuities present (provided no strata failure occurs). Thus increased flow would be possible along these enlarge conduits and any erosional effects at the discontinuity surfaces would be exacerbated.

Shrinkage at the surface would be minimal as it lies above the water table.

(c) A combination of (a) and (b). This could explain some of the observed subsidence in the Collie Basin. Some de-watered areas have not yet produced any subsidence. Others have undergone high localised subsidence, normally attributed to failure of pillars in worked areas. This could have been partially due to the formation of significant voids near the surface by mechanism (b).

Lack of observed subsidence in situ, and the degradation observed in the laboratory, indicate this mechanism, as the most likely of the three.

CONCLUSIONS

An appropriate triaxial test procedure has been established for the purpose of simulating the in situ reaction of saturated strata to dewatering operations.

Failure of the sandstone was seen to be possible during simulated de-watering. Fourteen percent of the specimens failed and the failure type range from the classical single shear plane failure associated with the standard triaxial testing, to collapse of the specimen into a clastic, soil-like consistency.

The rock degradation was observed and quantified by the weight of particles washed out from the specimen. The possibility of fines migration through the specimen was supported by the deterioration of some specimens at their supper surface.

The strengthening effect of de-watering was indicated by the saturated tensile strength test results. Approximately 12 percent reduction in saturated tensile strength recorded due to simulated de-watering. This reaction tended to increase with increase in specimen clay content.

The volume change was generally observed to be a decrease and specimen failure was accompanied by a large volume decrease. In the absence of failure, approximately equal volume changes were observed during pore pressure reduction and subsequent water flow induction.

The time-dependent nature of the strata deformation has been observed. An examination of volume change under time dependent testing suggested the majority of volume changes occurred within the first 8 hours. 82-86% of specimen volume change occurred within the first twenty minutes (pore pressure reduction and water flow induction test period).

Finally, a simple conceptual model which explains the permeability behaviour as a result of the pore pressure reduction and the water flow induction has been proposed.

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