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Technical Article

Strata Monitoring Investigations Around Longwall Panels Beneath the Cataract Reservoir

R. N. Singh[1] and M. Jakeman[2]

[1] Univ of Wollongong, Northfields Ave, Wollongong, NSW 2522, Australia; e-mail: raghu@uow.edu.au

[2] General Mgr, Capricorn Coal Co, Southern Colliery, PMB Fairmount, Queensland 4238, Australia.

Abstract. This paper describes the extraction of longwall panels in the Bellambi West Colliery beneath the Cataract water reservoir in the Southern Coalfields of NSW. These longwall workings were designed in accordance with the statutory conditions imposed by the Reynolds Commission of Inquiry, 1978, and worked in accordance with the conditional permission given by the Dams Safety Committee. The major conditions under which mining was permitted included: (a) submission of periodic mining plans identifying the geological structures encountered, (b) monitoring of strata behavior around mine workings and (c) water balance studies to be carried out in the mine workings beneath the water reservoir. The main monitoring program consisted of monitoring of geological structures, observation of the water seepage into the mine workings together with their sediment contents, and the measurement of surface subsidence and sub-surface strains. In addition, piezometric levels in the boreholes overlying the production districts were measured showing the fluctuation of the ground water level. Stress/deformation measurements were made on the longwall chain pillars to indicate their structural stability.

Strata monitoring during the first three years of workings under the Cataract reservoir have indicated that the surface and subsurface subsidence and the strata displacements were within permissible limits and no water inflow was encountered as a consequence of coal mining under the Cataract reservoir. Based on these studies, the life span of the mine has been extended by eight years.

Key words: Australia, Illawarra, ground strains, longwall mining, subsidence, underwater workings.

Introduction

Underground coal mining in the Illawarra region is being carried out in the Bulli Seam by 11 operating collieries producing some 18 million tonnes of coal per year. One of the main features of this coalfield is that mining is carried out in an environmentally sensitive area within the catchment area of the Sydney Water Corporation. A large amount of coal had been sterilized in barrier pillars below major water reservoirs and dams. Since 1978, coal mining has been allowed in the restricted area (in the close proximity of dams and water reservoirs), with the approval of the Dam Safety Committee.

Permission for mining under major reservoirs and dams is granted by the Dam Safety Committee under conditions based on the recommendations of the Reynold's Inquiry Commission (1976) and the Dam Safety Act (1978). In this paper, a case history is presented where permission was sought from the Dam Safety Committee to mine coal reserves under the Cataract Reservoir by the mechanised longwall mining method.

The paper describes a wide ranging monitoring program implemented by the mine operator during the first three years of the workings in order to carry out safe mining under the Cataract reservoir (Jakeman 1996). An instrumentation scheme was installed that included monitoring the surface subsidence by precise surveying, measuring ground strains and strata displacement using borehole extensometer surveys above the coal seam, monitoring of the pillar stability parameters within the coal seam, piezometric surveys in boreholes above the longwall panels, and monitoring of water inflow and pumping quantities in the longwall panels below the Cataract Dam. During the first 2.5 years, 30 km of roadways were developed in 6 longwall panels and approximately 2.5 million tonnes of raw coal was extracted from four longwall faces each being 110m wide supported by 66m wide chain pillars.

Factors to be considered for the design of mine workings under stored water

The main objective of mining under bodies of water is to safely extract as much coal as possible without disturbing the overlying strata to a degree that water inflow to the mine workings becomes excessive. There are two main possibilities relative to the inflow of water. The first is water ingress through pre-existing arrays of discontinuities or through geological structures such as dykes and faults. The second possibility is that water enters the mine through tensile zones that may be created by the sub-surface subsidence associated with longwall mining. These factors have been considered in detail in previous publications (Singh 1986; Singh 1989; Singh and Aktins 1982; Singh and Kendorski 1981; Whittaker and Singh 1978; Whittaker et al. 1979). The main considerations that govern the design of mine workings under bodies of water are:

(a) The geometry of workings and its effect on the possible development of a de-stressed zone between the mine workings and the water reservoir,

(b) Thickness of barriers between the reservoir and the workings,

(c) The nature of rock material in the barrier (mudstone, shale and claystone)

(d) Strains at the bottom of the bodies of water, and

(e) Geological features such as faults, dykes and joints forming conduits of water.

Mining at Bellambi West Colliery

Bellambi West Colliery is situated in the Southern Coalfields of NSW about 14 km west of Wollongong. The mine is over 100 years old and has produced some 60 million tonnes of coal since its inception and provides nearly 300 jobs. The colliery also indirectly creates about 1000 other jobs in the area due the continuous operation of the mine. Approximately A$ 52 M per annum are injected into the local economy through employees wages, direct and indirect taxes and the purchase of goods and services. In the late 1980's, good quality coal started to be depleted in the western district of the colliery and the quality requirements of an international customer could not be met. The best quality reserves were locked up under the Cataract Reservoir as a coal reserve in the restricted zone. In 1990, the management applied to the Dams Safety Committee for permission to mine coal reserves under the Cataract Reservoir. In May 1991, the Minister of Mineral Resources permitted extraction of the first seven panels and the development of the eighth panel based on the recommendations of the Dams Safety Committee (Figure 1). The Chief Inspector of Coal Mines subsequently approved the extraction of the first seven panels by the longwall system of mining. The development of roadways in the Cataract district commenced in March 1992 and by March 1993, the development of the first longwall panel was completed. Mining in the Western District ceased completely in June 1993 and panel 501 in the Cataract District commenced production. Since then, the entire production of the colliery comes from the Cataract District (Jakeman 1996).

Conditional approval for longwall mining

In an initial plan of the first 8 faces, a 105m wide face was developed with 70m wide rib pillars. In the subsequent design, a face width of 115 m together with 65m x 100m size rib pillars was incorporated in the mine plan (Figure 1). It may be noted that the minimum depth below the surface was used to calculate the panel width. In contrast, the maximum depth of the panel was used to calculate the width of the rib pillar with widely spaced cut-throughs.

During periods of longwall extraction, the following monitoring programs were implemented:

(a) Underground seam mapping to extrapolate the known geological features that may influence the stability of the strata below the reservoir.

(b) An in-seam seismic survey using boreholes within the seam to identify any structures that may lie within but had not been revealed by previous extraction from areas around the reservoir.

(c) A detailed surface subsidence grid to accurately measure subsidence around the perimeter of the reservoir.

(d) Monitoring to measure water inflow to the mine by means of water balance studies of underground operations. The quantities of water used in the mine for dust suppression and drinking and the quantity of water pumped out of the mine during the normal operation of the mine were all measured. Any increase in the difference between water used and water pumped out could be attributed to inflow from the reservoir to the mine through arrays of mining induced fractures.

(e) In-situ strain measurement was carried out on the dam structure using strain gauges capable of measuring strain up to an accuracy of 0.1mm/m.

(f) Ground water monitoring using piezometers to measure variation in water pressures contained within the strata above the area to be extracted.

(g) Pillar loading and deformation using stress meters to ascertain whether the chain pillar remaining after longwall extraction deformed as a result of extraction.

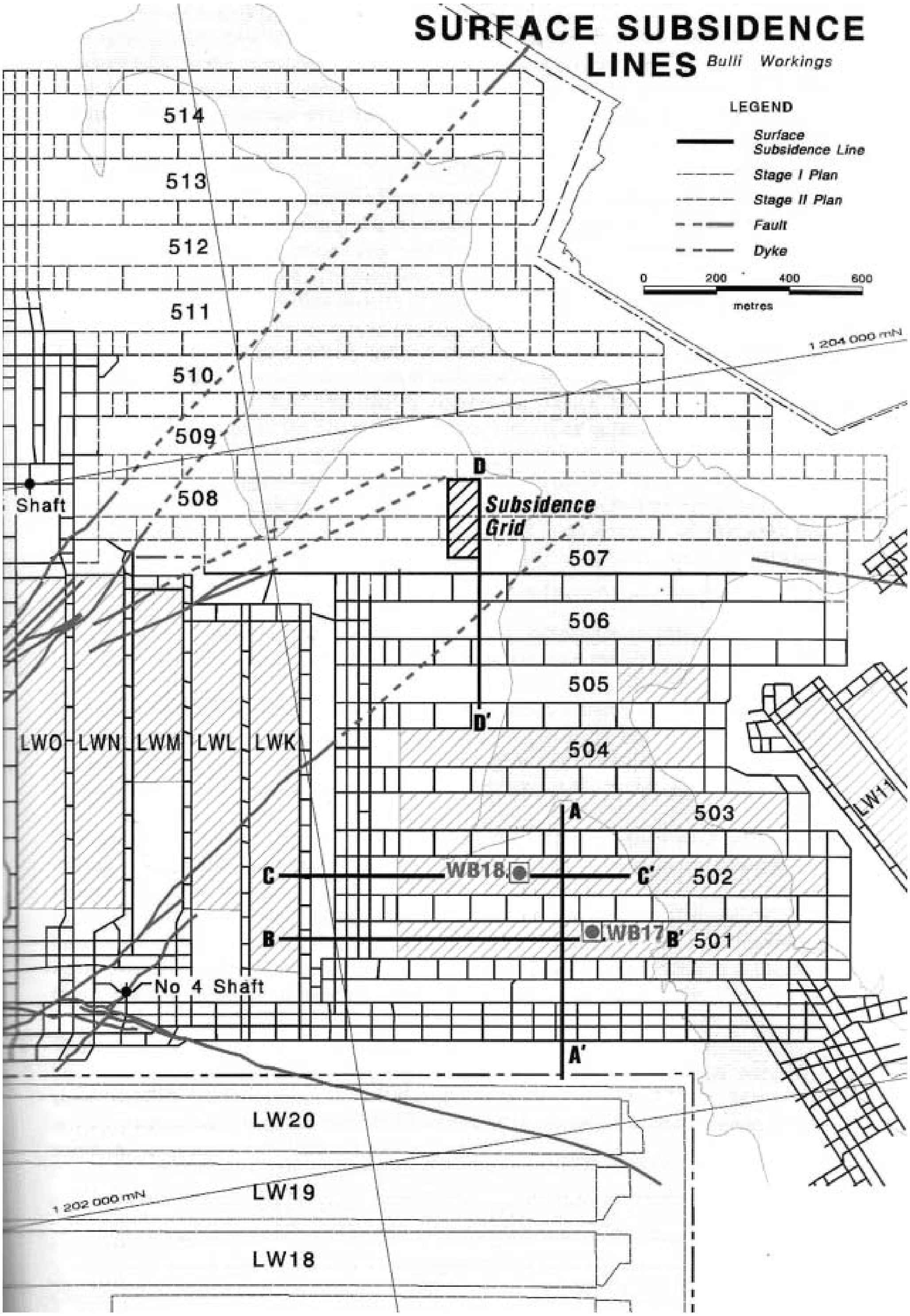

Figure 1. Layout of longwall faces under the Cataract Dam in Bellambi West Colliery

Strata monitoring investigations

Geological mapping

Surface geological mapping included aerial magnetic surveys as well as a drilling program to delineate the geological features extending from the surface water reservoir to the Bulli coal seam. A number of thin dykes consisting of altered clay were detected. Interpretation of aerial magnetic survey attributes a very small anomaly to this lineament; the westward continuation of the dyke appears to be very restricted. Underground seam mapping has kept pace with coal seam development.

Surface subsidence studies

The subsidence survey was carried out above the Cataract District by precise levelling of the survey pegs to an accuracy of ± 1mm/km, and measuring the distance between the pegs by tensioned steel bands or an electronic distance measurement unit to an accuracy of ±1 mm/ bay. Four survey lines were laid out on the surface of the Cataract District, two parallel to the direction of advance of longwall LW501 and LW502 (from right to left in Figure 1) and two lines parallel to the faces (North to South). Figure 1 shows three of these survey lines, AA', BB' and CC'. The construction of the survey stations, which were spaced 15m apart, complied with standards suitable to the surface topography, the measurement equipment and technique used, and the precision of the subsidence survey required. In order to determine the accuracy of the subsidence survey technique and the influence of non-mining factors, a number of measurements were carried out from May 1992 to June 1993 to cover all seasons. During this period, a ground uplift of 8 to 16mm was observed. The horizontal strains during the pre-mining period were up to 0.17mm/m together with some tensile strains in the cliff area up to 0.1 mm/m. These measurements were not considered significant because a surveying accuracy of 0.05 to 0.1mm/m was achieved.

Subsidence predictions

Figure 2 (a) to (c) show the results of the first 17 subsidence surveys. The extraction of Cordeaux Longwall 18 to Longwall 20 reactivated subsidence over Longwall K up to a distance of 600m from the active longwall and contributed to the uplift of the strata over the unlimited Cataract panels. The extraction of Longwall 501 and 502 also induced uplift of the strata, but with limited effect. This uplift was relatively small and for the most part within the 20mm tolerance, defining the edge of the mining induced subsidence. Figure 2 (a) shows some uplift between the extraction area of Cordeaux and Bellambi West and a maximum subsidence of 178 mm along the line AA'. During this period, a peak tensile strain of 0.407 mm/m was developed between Bellambi West and Cordeaux.

Figure 2 (b) shows the peak subsidence of 149 mm over LW 501 panel and further subsidence over Longwall K area along line BB'. In this area, total compressive strain reached a peak of 0.309 mm/m and the area between Longwall K and LW501 changed from tensile to compressive strains as the longwall moved. Figure 2 (c) shows the maximum subsidence of 154 mm along line CC', which was located above LW502. The maximum tensile strain of 0.789 mm/m was located between Longwall K and LW502. The maximum compressive strain was -0.47 mm/m located over LW 502.

The initial prediction of maximum subsidence was 200 mm, which was still higher than the measured values given below:

Line AA'--173 mm

Line BB'--156 mm

Line CC'--158 mm

This indicates that the general subsidence measurements were 80% of the predicted theoretical maximum.

Strain measurements

In the extensive period of extraction of the first four panels in the Cataract area, neither the tensile or compressive strains have exceeded 0.8 mm/m. The average strain measurements for various survey lines were:

	Compressive	**Tensile**
Line AA	0.3mm/m	0.5 mm/m
Line BB	0.2 mm/m	< 0.1 mm/m
Line CC	0.2 mm/m	< 0.1 mm/m

Accuracy in subsidence measurements

The climatic conditions do not have a significant effect on the movement of survey pegs, provided that their construction is adequate. Accuracy limitations in level measurements due to the bench mark movements used in the Cataract area are acceptable up to 5 mm. Strain measurement errors as a result of the steel band measurements are estimated to be accurate in the range of 0.05- 0.1 mm/m. In contrast, the distances measured by electronic distance measurement instrumentation are not sufficiently accurate for determining very small ground movements.

Strata monitoring results

Strain monitoring program on the dam was initiated by the Sydney Water Corporation to correlate the strain with the seismic network monitoring system. The strain monitoring initiated at the pre-mining stage was continued long after mining ceased in order to assess if a widespread build up of strain and tectonic movement is possible. To measure *in situ strains,* a high resolution and complex instrumentation previously used to monitor earthquakes in the San Andreas Valley in California as well as in Canberra was chosen.

In situ strains

The program involved the installation of instruments in three different boreholes, with solar powered data acquisition units installed atop each hole and connected to a computer for data collection at desired intervals. Battery back up of the solar cells allowed the system to work on cloudy days and during the night. The stored data was sent automatically by radio to a central station to be processed and analysed. The construction of the boreholes required extra care, as the actual strain measuring instruments had to be installed in borehole sections free of fissures. The cores from the above-mentioned boreholes were tested in the laboratory to determine elastic parameters to calibrate the instruments. The results from the vertical strain monitoring in the Hawkesbury Sandstone at the base of the reservoir showed very low deformation indicating only the development of elastic strains in response to mining.

Chain pillar stability monitoring

Stress monitoring of chain pillars beneath the Cataract Reservoir was undertaken at locations between LW501 and LW504. Two types of stress meters were used: hydraulic curved jacks using platens and vibrating wire rigid inclusion stress meters. The stress meters were installed at approximately mid-height of the longwall chain pillars. They were installed from the cut-through into the pillars to a depth of approximately 10m, which is beyond the stress abutment zone.

Background stress level for this depth of cover was 12 Mpa, which is consistent with the site conditions. Stress levels in the pillar generally started increasing as the longwall face approached the instrumented boreholes. This distance was about 30-40 m and consistent with the observations in the other mines in the area. Maximum stress levels were reached when the second abutment zone came from the next longwall. The stress level reached 30-32 MPa and appeared to remain constant after the longwall had passed the site by more than 100 m. Across the pillars the stress rose to a maximum of 32 MPa in a zone 10-15 m from the pillar edge. This then quickly dropped to 16 MPa at 20 m and 12 MPa at 33 m at the central part of the pillar. This confirms that the layout is conservative and the pillar had a 35-40 m wide core that remained unstressed.

Hydrology

Water Balance Studies

An automatic system to measure all water pumped into and out of the Cataract mining district was implemented for the water balance study. This system transmitted the data to a computer in the colliery's surface control room. The water flow rates both in

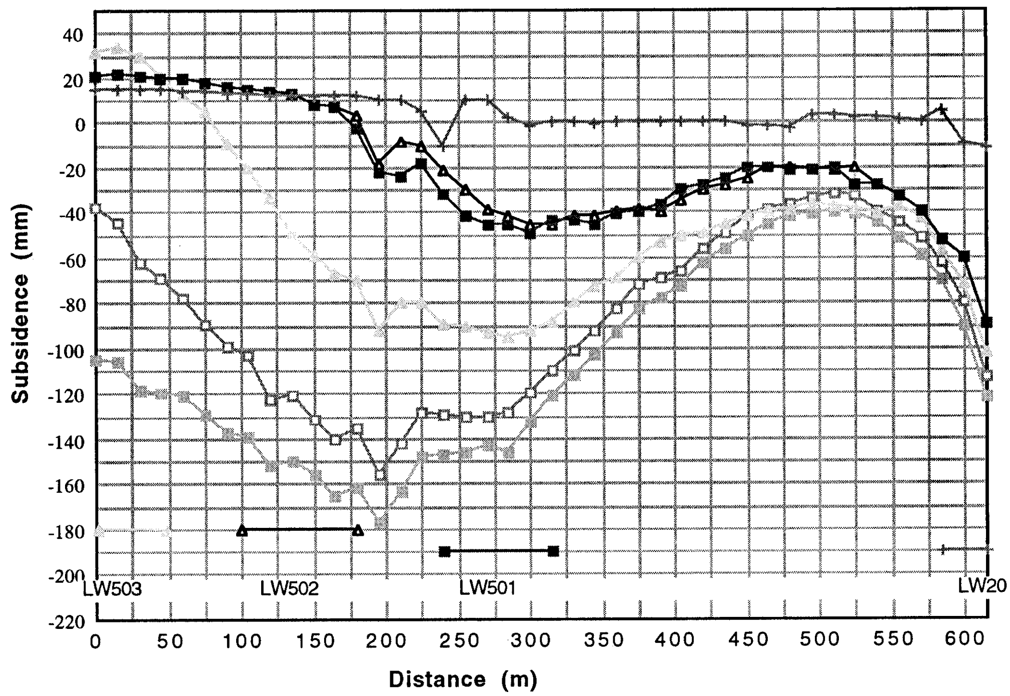

Figure 2 (a) Subsidence sections along Line AA (six surveys)

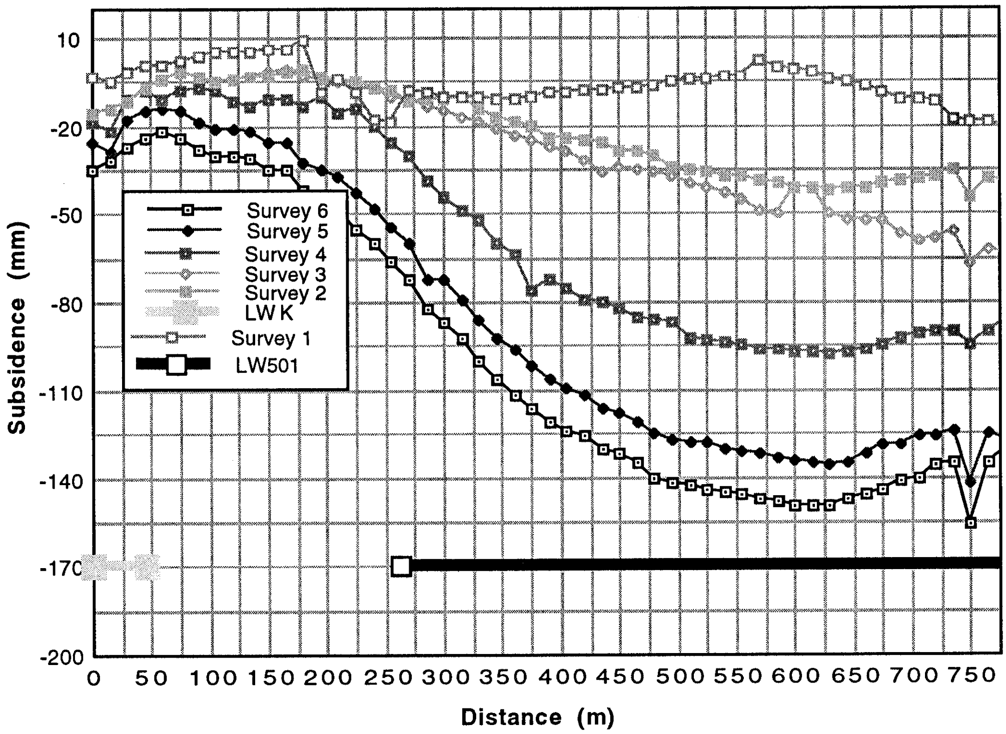

Figure 2 (b) Subsidence survey along line BB' (6 Surveys)

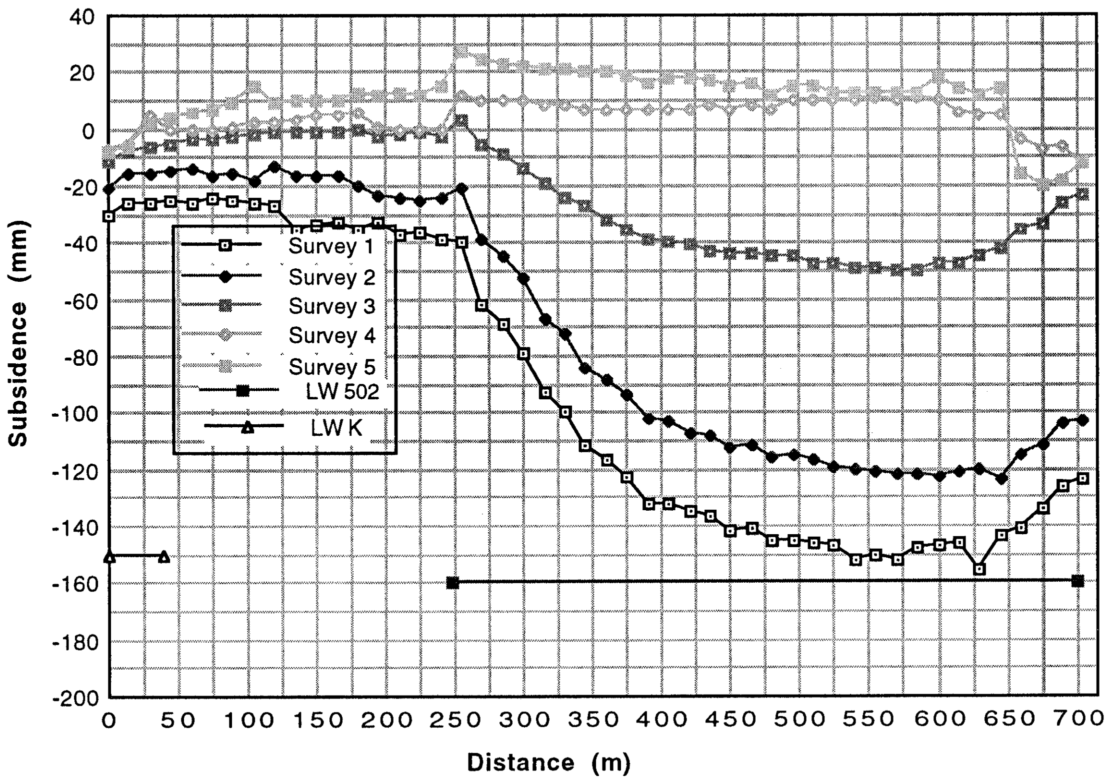

Figure 2 (c) Subsidence survey along line CC' (5 surveys)

and out were continuously indicated on a screen in the control room, which was always kept manned while workers were within the mine.

The quantity of water pumped out of the Cataract district was 38% of the water that was supplied to the mine workings for dust suppression, drinking and other operational reasons. Strata water dripping from the mine roof, usually at longwall take-off, does contribute to water input but it is negligible. The difference between water supply and water outflow can be attributed to the escape of water from the mine through an increase in moisture in the coal by 1% to 8%, an increase in the humidity in the mine atmosphere, and percolation through the floor.

Figure 3 shows cumulative water inflows and outflows beginning 28th August 1992. Although, Longwall 501 mining operations in the Cataract district started in June 1993, as indicated by week 44 in Figure 3, an increase in water pumped out from the Cataract district did not occur until week 72 in February 1994. This delay was thought to be due to wastewater from Longwall 501 leaving the Cataract area via the O4 roadways during June to December 1993. This was not picked up by the monitoring system due to practical difficulties. However, Figure 3 shows the outflow of water from Longwall 502 onwards, implying that the rate of water leaving the Cataract district has been consistent since the longwall operation commenced in this area. It also confirms that any water coming from drippers or through the goaf is too small to measure.

Piezometer monitoring results

The piezometer studies consisted of monitoring the water pressure in fracture zones caused by subsidence. Ground water pressure was measured at different depths prior to or during the process of mining to determine the effect of subsidence and crack propagation. The instrumentation consisted of a 200 mm diameter and 338 m deep borehole near the reservoir over Longwall 501 in which ten-compartment piezometers were installed. The piezometers measured water pressure at five levels; one in Hawkesbury Sandstone at 110m depth, three in Bulgo Sandstone at the depths of 110m, 174 m and 228m respectively and one in the Scarborough Sandstone at the depth of 328m

An additional monitoring program was also implemented, consisting of three boreholes over Longwall 502 within which single standpipe types of piezometers from three different manufacturers were embedded in a sand filter, Fig. 4 (b). Just prior to mining under the boreholes/piezometer nest, the Scarborough piezometer indicated an increase in pressure head up to 30 m. This rapid pressure rise in the piezometer was attributed to the compression of the strata immediately ahead of the longwall face.

After the passage of the longwall face, the pressures of both piezometers dropped to zero and have remained at this value ever since. The piezometer is continuing to give a signal when tested by the read out unit. This behavior indicates the propagation of vertical fractures up to 85 m above the seam floor (Figure 5). In addition, the differential bed separation above this level has been insufficient to damage the electrical connections, indicating that the Bulgo Sandstone unit is intact.

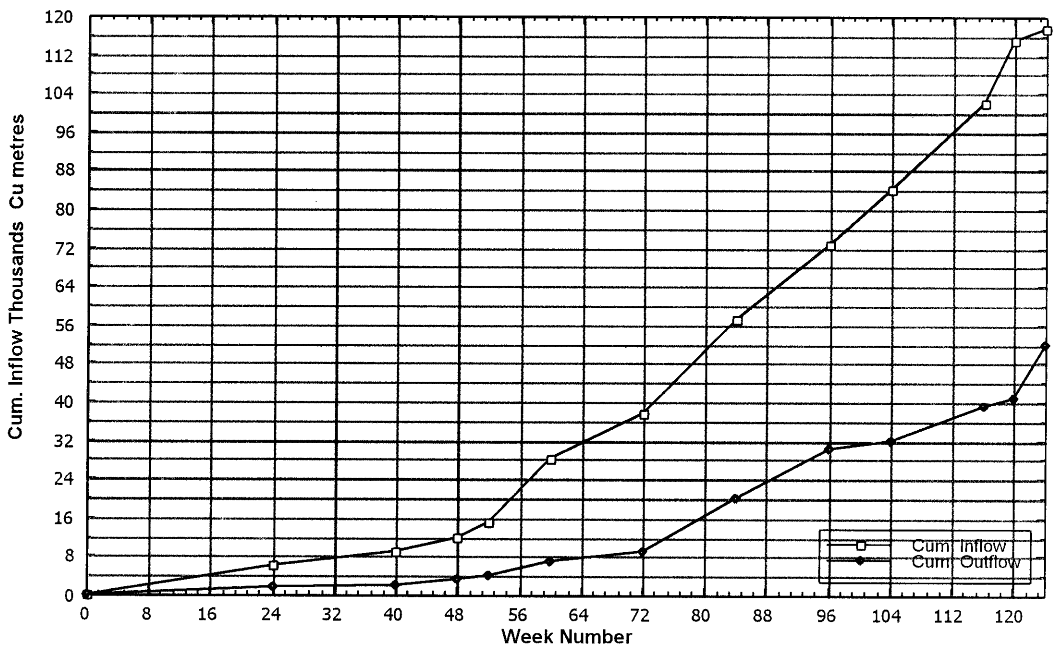

Figure 3. Water balance measurements at Bellambi West Colliery

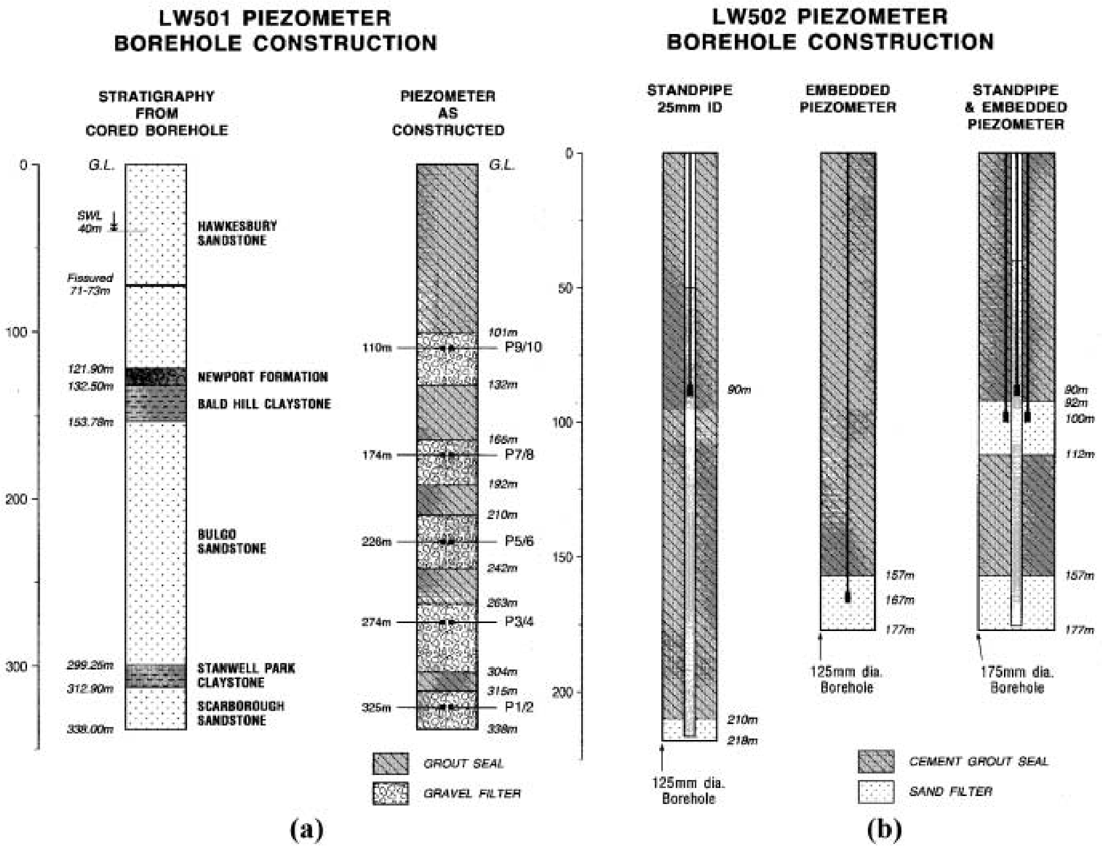

Figure 4. LW501 and LW502 borehole piezometer construction

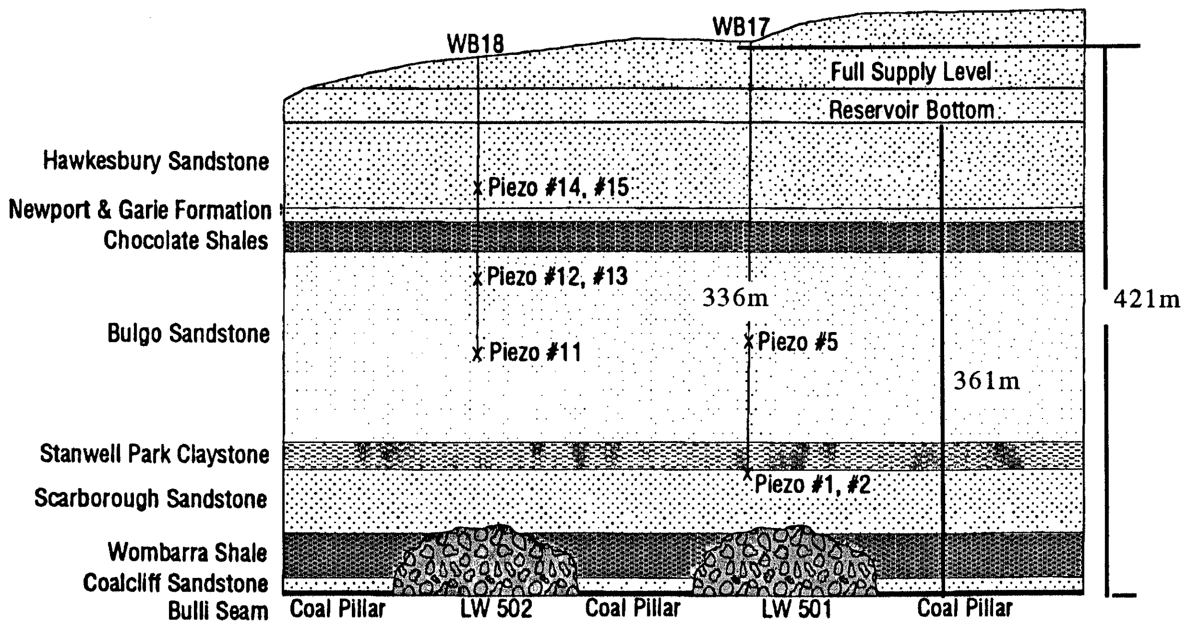

Figure 5. Piezometric survey above LW 501 and LW 502 panels

The water pressure in the Middle Bulgo Sandstone remained stable until the coal seam beneath the borehole was undermined, after which a drop of 11 m in water head was recorded. This implies that 185 m above the coal seam, a small relaxation of pore pressure occurred. The standpipe type piezometer located 185 m above the coal seam developed a small pressure drop when LW501 face line was at its closest to LW502 borehole. The other piezometers showed no clear link with the mining operations. There was a slight rise and subsequent gradual drop in pressure in the Hawkesbury Sandstone that can be attributed to seasonal changes. The piezometer in the Upper Bulgo Sandstone240 m above the seam did not record any measurable water pressure change effects.

The results of the piezometric monitoring program confirmed previous observations relating to the formation of three subsurface zones of subsidence above the coal seam and below the surface as a consequence of undermining. These are:

A zone of caving: The actual caving horizon is thought to extend up to 40m above the coal seam above Wombarra shale. However, this becomes a zone with a number of linked fractures and in term of ground water is similar. This zone extends 85 m above the coal seam in as the Cataract area and may not extend to the Bulgo Sandstone.

A zone of constrained strata: The second zone was propagated through the Mid-Bulgo level to Upper-Bulgo level. In this zone, there are slight but definite changes in the ground water pressure as a result of strata displacement due to mining. Differential vertical displacement is comparatively low at this level, as evidenced by the continuing electrical connection to the Scarborough piezometers.indicated in Fig. 4 (a). At the surface, a data logger was installed to record the data from the piezometers at desired time intervals. The data was periodically downloaded onto a portable computer for analysis.

A compression zone: The third level is that of the flexed strata without bed separation or linked fractures and this zone has very little response to undermining. This level is thought to correspond to the monitored level in the Hawkesbury Sandstone.

The confirmation of the three zones and an estimate of their extent suggest that the strata are behaving as expected and that the disturbance of strata above the Stanwell Park Claystone is minor.

Chemical analysis

The collection and testing of water entering the mine workings under the Cataract Dam at Bellambi West Colliery was carried out to ascertain the origin of mine water. It was hoped that through chemical analysis, the source of water would be determined, thereby indicating if water was leaking from the surface water reservoir. Bellambi West Colliery is reputed to be a dry pit. Therefore identifying water entering the mine is not difficult. During the period of investigation, very little water entered the pit while mining under the Cataract Water Reservoir. The roof of the development headings and a recently driven cut-through were the major sites for water collection. Water was also collected near geological features such as dykes present in the Cataract district. The water collection sites at the longwall main gate were also utilized when water was noticed leaking from the roof. Other areas of the mine under the Cataract Dam were inspected for any sign of ingress of water but in most cases, water was not seen to be leaking from the roof.

Analysis of the limited number of water samples indicated the presence of Na, K, Mg, Fe, and Mn. as cations, and chlorides and sulphates as anions. Unfortunately, carbonate components of the water samples were not determined in the laboratory. Therefore, the source of water cannot be determined by the triangular graph method. As no consistent sources of roof water could be found around the extraction areas, the conclusions reached are that the method of mining and the design parameters employed are not causing damage to the overlying strata or to any aquifer that may inundate the mine. Taking water balance studies into account, there is no evidence of entry of water from the reservoir into the caved areas.

Conclusions

This project provided the first real opportunity to extract coal reserves under a dam or water reservoir by the longwall mining method in NSW, Australia. Thus, it was the first real instance of examining the effectiveness of the Reynolds Commission's recommendations. A comprehensive monitoring program of strata behavior has been carried out indicating that the longwall face design parameters have been set at conservative limits allowing successful longwall extractions. Thus, the life span of the mine has been extended by 8.5 years.

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