Settlement prediction and monitoring in an area of regional subsidence

Prédiction et surveillance du tassement dans une zone de l'affaissement régional

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SYNOPSIS: To enable brown coal to be mined from open cuts in the Latrobe Valley, it has been necessary to depressurise the underlying aquifers thus causing regional subsidence over an area of 400 km² in the last 25 years. The siting of power stations on the perimeter of the economically winnable coal, where the structural geology is complex, has led to some facilities having to be located over monoclinal folds and faulted zones. The subcropping of these faults and folds is usually concealed by up to 20 m of overlying sediment. The modelling of differential subsidence across these faults due to regional groundwater withdrawal and the prediction of the effects on the Loy Yang power station structures are the subject of this paper. Field calibrated finite difference analyses have been used to predict differential subsidence across a fault and this displacement has been imposed on a boundary element model to determine its propagation to the ground surface. Preliminary analysis indicates that, if a minimum thickness of overburden is maintained between the foundations and the subcrop of the fault, then the Loy Yang power station structures have sufficient flexibility to absorb the earthmovement without distress.

1 INTRODUCTION

Development of a method which is suitable to analyse the propagation of differential subsidence to the surface was brought about by the existence of a faulted graben structure beneath the sites for the 2 x 2000 MW Loy Yang 'A' and 'B' Power Stations. These power stations are located in the Latrobe Valley on an east-west trending anticlinal dome structure some 6 km south-east of Traralgon, in the State of Victoria, Australia. Site investigations indicated a 20 m throw normal fault beneath 'A' Station and other faults sub-parallel to the antclinal axis forming a graben structure. This paper examines the effects of on-going regional subsidence in the Latrobe Valley on faults in the Loy Yang project area and how this is being modelled to enable predictions to be made of likely surface earth movements.

Regional subsidence in the Latrobe Valley has resulted from the need to extract brown coal from thick coal seams which are underlain by sub-artesian aquifers. Gloe (1976) describes how the piezometric pressures beneath the base of open cuts must be lowered to prevent floor heave. Dewatering at Morwell Open Cut, 16 km to the west of Loy Yang, has resulted in approximately 1.9 m of subsidence adjacent to the Morwell Open Cut and approximately 350 mm immediately west of the Loy Yang site by 1983 (Figure 1).

2 SETTLEMENT AND EARTHMOVEMENT MONITORING

The State Electricity Commission has carried out regional second order levelling surveys ($8\sqrt{K}$ mm nominal accuracy where K is in kilometres) on a yearly basis for 15 years. Survey pin lines have been installed in areas up to 3 km from the open cut boundaries to measure both horizontal and vertical movements. Particular care is taken to give a good coverage of survey data in urban areas. During construction of major power stations and earth dams associated with these develonments, structures are surveyed on a monthly or three-monthly basis and then on a yearly basis after completion.

Prior to development of Loy Yang, the regional benchmark surveys were allowed a free adjustment from a primary benchmark some 25 km away from the site. To ensure an adequate data base for monitoring power station structures at Loy Yang, a series of remote benchmarks were installed in near surface outcrops of basement rock approximately 6 km to the south of the site. Another group of deep marks were anchored in basement rock at depths of up to 220 m at the 'A' and 'B' power station sites (Raisbeck (1980)). At 'A' Station differential subsidence was foreseen as a factor both

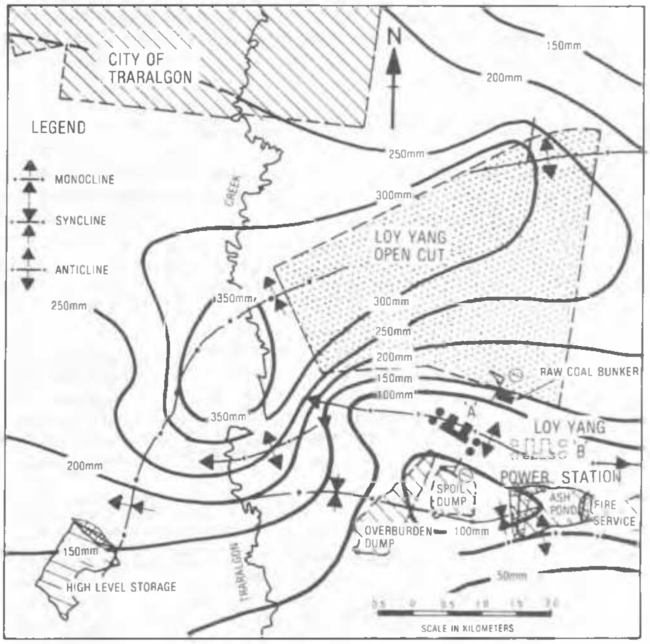

Figure 1 Project Location and Regional Subsidence Contours (1960-1983).

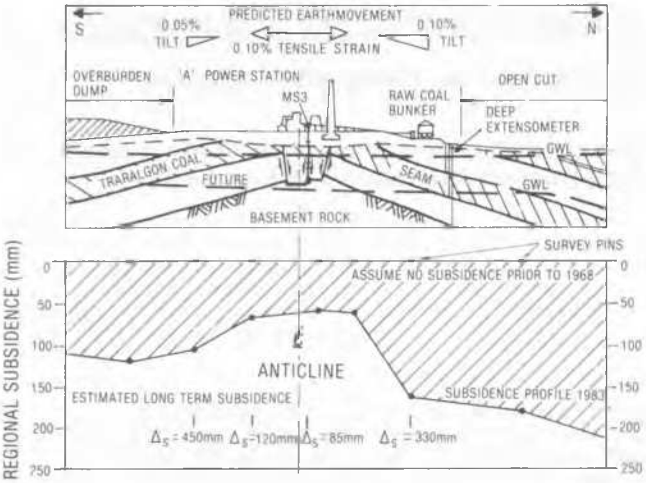

Figure 2 North-South Subsurface Section 1-1 showing Earthmovements and Instrumentation at Loy Yang 'A' Power Station.

when monitoring structural settlements and maintaining construction levels. To enable differential subsidence to be isolated, surface benchmarks were established on the same geological alignment as the major structures so that benchmarks would settle at the same regional rate. Pedler and Schneider (1984) discuss the results of monitoring 'A' Station structures during construction. Figure 2 indicates the various deep ground instruments installed at 'A' Station and at the Loy Yang Raw Coal Bunker to monitor earthmovements and settlement of structures. Of particular importance to this paper are the deep extensometers installed immediately north of the Raw Coal Bunker and the magnetic array, MS3. A fault with a throw of 20 m passes through MS3. Groundwater levels are also being monitored across the site to correlate with subsidence records. These piezometers show a current rate of drawdown at Loy Yang of between 2 m and 3 m per year. Regional subsidence was 2 mm/year at the power station and 9 mm/year at the Raw Coal Bunker in 1983 (Figure 2).

3 DESIGN ASSUMPTIONS AT LOY YANG

Subsidence at the site of 'A' Station has amounted to 60 mm over the last 15 years. With approximately 60 m of groundwater drawdown expected at the Power Station for the development of the adjacent Loy Yang Open Cut additional subsidence over the next 30 years of 85 mm is predicted at the axis of the anticline and 330 mm on the northern flank of the anticline at the Raw Coal Bunker (see Figure 2).

This differential subsidence across the anticline has already shown up in the historical data and further subsidence will lead to horizontal tensile stresses and strains in the north-south direction. To date, it has been assumed that infinitesimal tensile strains are developed across the anticline due to the draping effect of the regional differential subsidence. This strain is predicted to be approximately 0.10% across the anticlinal axis with a maximum tilt of 0.10% to the north and 0.05% to the south.

Superimposed on this infinitesimal strain is site specific differential subsidence caused by local faulting or folding. This is dependent on the strike of the fault in relationship to the overlying structure, the depth of cover over the fault, the anticipated piezometric drawdown and the soil profile to bedrock. At 'A' Station, a conservative foundation design assumption was made that the differential subsidence determined from one-dimensional (1-D) analysis of the soil profile on each side of the fault is propagated to the surface through an angle of draw equal to 70° at the unconformity between the Tertiary coal measures and the Quaternary overburden (Figure 3b). This approach may be modified at 'B' Station to account for the depth to the piezometric surface (90 m) and the relatively smaller fault throws of less than 10 m.

4 FIELD CALIBRATED SUBSIDENCE PREDICTIONS

In order to more accurately predict the differential subsidence across the fault, a study was carried out using a finite difference program, COMPAC, developed by Helm (1975/76) based on a non-linear generalisation of Terzaghi's 1-D theory of consolidation.

In this formulation, the time rate of subsidence is governed by permeability and compressibility parameters. The COMPAC model was calibrated using historically measured subsidence and known changes in piezometric levels at selected sites. Sensitivity analysis was used to narrow the possible non-unique combinations of these parameters to fit observed water level decline and subsidence. Results of this back analysis for the Loy Yang Raw Coal Bunker are shown in Figure 4. These

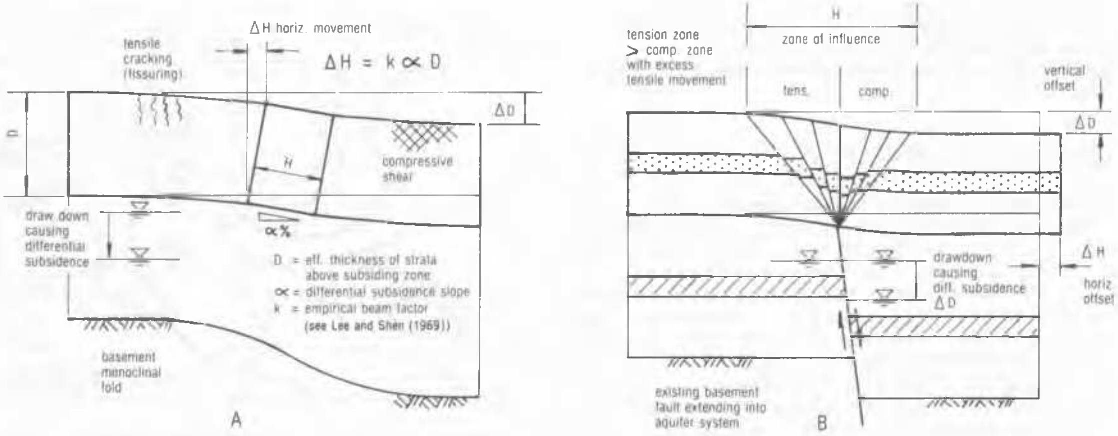

Figure 3 Surface Displacement Due to Differential Subsidence.

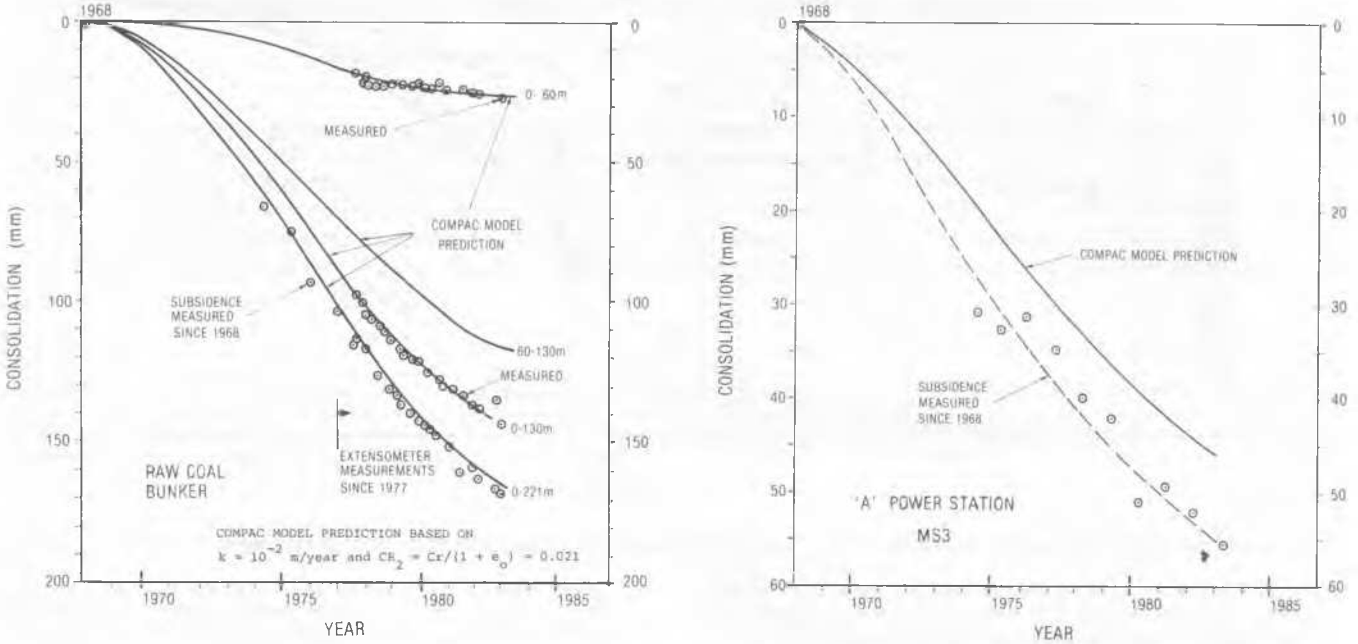

Figure 4 Predicted and Observed Subsidence versus Time at RCB and MS3 Sites, Loy Yang 'A' Power Station

show close agreement for the period 1968 to 1983 for a permeability of $k = 10^{-2}$ m/year and a CR_2 value of 0.021.

Predictions at the RCB using the field calibrated COMPAC model indicated 270 mm subsidence for 60 m drawdown. Subsidence at 'A' Station (MS3) was analysed in a similar manner; however, it became apparent that the observed drawdown was not causing the observed subsidence. Other influences including bench formation and other construction activities were considered to be contributing to the observed subsidence. Corrections for these effects based on survey data were made and a differential subsidence of 37 mm was obtained for a 60 m drawdown in water level across a fault with a 20 m throw. This compared to a differential subsidence of 40 mm calculated by 1-D consolidation analyses.

5 SURFACE DEFORMATION MODELS

The mechanism of migration of displacement through a soil medium to ultimately produce land subsidence is of considerable importance in the fields of mining, seismology, groundwater and fluid extraction. The form of this surface displacement is complicated by the presence of faults or other geological anomalies.

Figures 3a and 3b illustrate the two mechanisms that can lead to surface tensile fissures or compressive shear and the development of shear scarps emanating from deep seated pre-existing faults. These latter scarps can show up as echelon faults in the overlying soil, as plastic tensile and compressive zones defined by an angle of draw, or as a distinct projection of the original scarp to the surface. Holzer and Pampeyan (1981) studied four fissured scarp sites in the western United States associated with declining groundwater levels. The dominant mechanism was localised differential subsidence caused by horizontal tensile strains of between 0.07% and 0.10% per year at the point of maximum downward curvature over a basement rock high. Levelling across these fissures was undertaken to first order standard across benchmarks, with a nominal standard of $1.5 \sqrt{K}$ mm where K is in kilometres. Holzer and Thatcher (1978) have analysed the effects of differential subsidence on faults using computer modelling techniques developed for the study of tectonic movements. These analyses were favourably compared with field data from the Picacho Fault in Arizona.

In the current study, the land subsidence effects due to water level decline were studied using a Boundary Element program, BITEMJ (Crotty(1984)). This program has the capability of incorporating faults into the model which can represent both elastic or elastic-plastic stress-strain properties to provide realistic modelling of a discontinuous medium.

The initial application of the program was at the Loy Yang 'A' Power Station (MS3). To simplify this preliminary analysis, a dip slip movement along a vertical fault was considered. The fault extended from the piezometric surface at 92 m to the unconformity approximately 20 m below the natural surface. The Quaternary overburden materials were assigned values of $E = 60$ MPa and $\mu = 0.3$, while the Tertiary coal measures were assigned $E = 80$ MPa, $\mu = 0.4$ (Figure 5).

The differential subsidence across the fault due to the lowering of the groundwater level by 60 m was applied by a vertical relative displacement imparted to the downthrown side of the model. The hanging wall was restrained in the vertical direction. Various displacements of up to 80 mm were adopted in the study.

The influence of the strength of fault material is illustrated in Figure 5 as non-dimensional subsidence versus horizontal distance from the fault. This analysis indicates that a smooth surface displacement develops for almost any non-zero value of the angle of internal friction. The migration of the displacement to the surface is unlikely to occur in this analysis for a displacement of 80 mm imposed at a depth of 92 m except for the unlikely case where the friction angle is reduced to zero and the cohesion of the fault material is lower than 10 kPa.

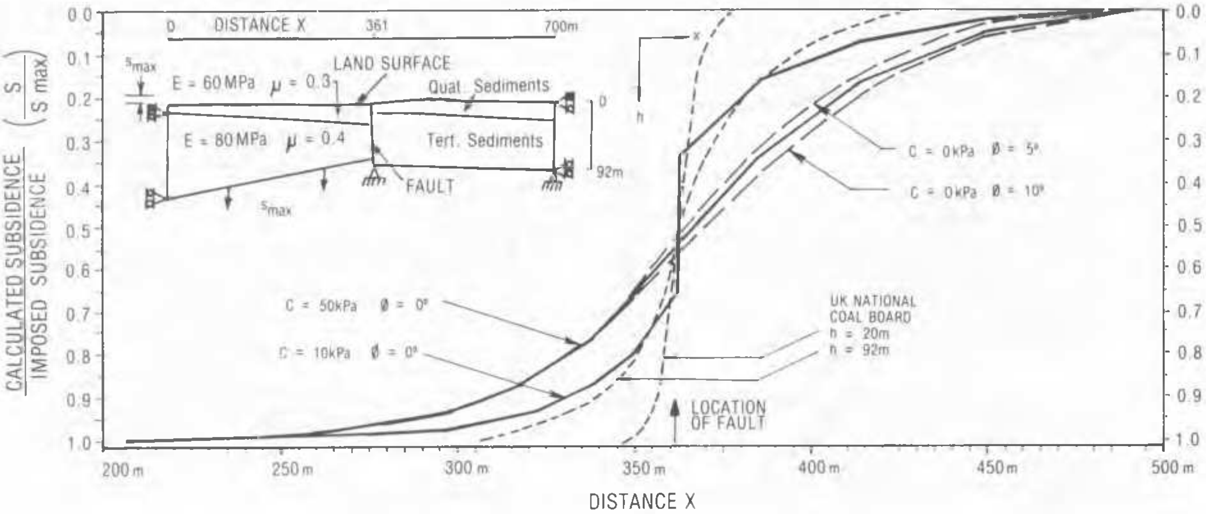

Figure 5 Land Surface Subsidence Profiles for Variable Strength Parameters in Fault Zone.

Land Surface profiles based on UK National Coal Board (NCB) recommendations are also annotated in Figure 5. The flatter curve is based on assuming the origin of differential subsidence to be co-incident with the existing water table at a depth of 92 m. The more pronounced curve corresponds to assuming the source of differential movement emanates from the unconformity at a depth of 20 m. The model analyses indicates that the NCB curve for a depth of 92 m corresponds to the minimum strength anticipated on the fault and it is unlikely that the 20 m NCB curve would apply.

The migration of displacement to the land surface to form an abrupt scarp has been shown to be related to the geometry of the imposed displacement and the thickness of the overlying stratum. Scott and Schoustra (1974) indicated that yielding of the soil at the ground surface requires considerable fault displacement in bedrock in relation to the depth of the overlying soil. This was estimated to be of the order of 2.25% of the depth of burial. The maximum displacement at Loy Yang is of the order of 0.8% which supports the smooth profiles obtained in the current analysis.

With the low rates of earth movement experienced at Loy Yang, it has been difficult to obtain confirmatory field data. However, larger earth movements have been recorded at other sites in the Latrobe Valley which are to be analysed in future stages of this study.

6 CONCLUSION

The application of the COMPAC model to the Latrobe Valley has enabled field calibrated parameters to be selected that reflect observed subsidence history due to groundwater withdrawal. The calibrated model compressibility parameters have shown close agreement with laboratory determined values.

This field calibrated system has been combined with a regional groundwater model of non-equilibrim fluid flow to increase the confidence of subsidence prediction in the Latrobe Valley.

The influence of differential subsidence across faulted structures has been examined using a boundary element approach to calculate the deformation through the medium to land surface. For the magnitude of predicted differential subsidence at the Loy Yang A Power Station, the likelihood of slip along the fault causing an abrupt scarp at the land surface is considered remote. Smooth land surface profiles, with lower curvatures than obtained by empirical methods proposed by the NCB, are predicted.

7 ACKNOWLEDGEMENTS

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