Long Term Subsidence Predictions in the Traralgon Township Area Due to Ground Water Withdrawal

S.J. Gray
B.E.(Hons), Grad.I.E.Aust
Engineer, Connell Wagner Pty Ltd, Brisbane
D. Nag
B.Tech(Hons), M.Sc, M.Sc, D.I.C, MASCE, M.I.E.Aust
Lecturer, Monash University, Australia

Summary Subsidence predictions for two sites in Traralgon, Victoria were carried out in 1994. A significant deviation of "actual" subsidence readings from previously predicted patterns (1987) called for the remodelling of the two sites. The site specific modelling was carried out in Traralgon at sites S12 and S20. Site S12 is located on the Princes Highway approximately 6 km east of the town centre, while S20 is located approximately 2.5 km south of the town centre. In order to make predictions of future subsidence, the models at each site were calibrated to give representative values of permeability and compressibility. In 1994 the recorded subsidence at S12 and S20 was 130mm and 275mm respectively. The modelling results show the predicted subsidence levels in 2020 at S12 and S20 to be 210mm and 320mm respectively, while at ultimate the subsidence was predicted to be 215mm and 325mm respectively.

1. INTRODUCTION

The State Electricity Commission of Victoria (SECV) pump water from surrounding underlying artesian ground water basins (confined aquifers) at the Morwell and Loy Yang Open Cut coal mines to reduce the pressure exerted on the floor of the mines during excavation. The main effect of ground water pumping is subsidence near and around the mines.

The Traralgon and Morwell townships are in close proximity to the open cut coal mines in the Latrobe Valley. Therefore, to optimise the design of mining layouts, and/or the design of new surface or subsurface structures it is important to predict future subsidence magnitudes.

Figure 1 shows a representation of equal subsidence contours due to the influence of mining. To date, the bulk of subsidence has been influenced by the Morwell mine as the Loy Yang mine is relatively new. However, as Loy Yang mine expands, its influence on Traralgon will become greater due to its close proximity to the town.

Subsidence predictions had previously been made at specific locations in the Latrobe Valley. This was part of a program to model subsidence due to aquifer withdrawal at Morwell and Loy Yang mines. Presently, five of twenty potential sites have been modelled.

This paper outlines the revised site specific modelling for the two sites, S12 and S20. They were modelled previously by Kacavenda in 1987. Remodelling was required because the observed subsidence since 1987 had deviated significantly from predictions made. Remodelling also allowed the incorporation of a new regional three-dimensional ground water model which had not been available for the 1987 study.

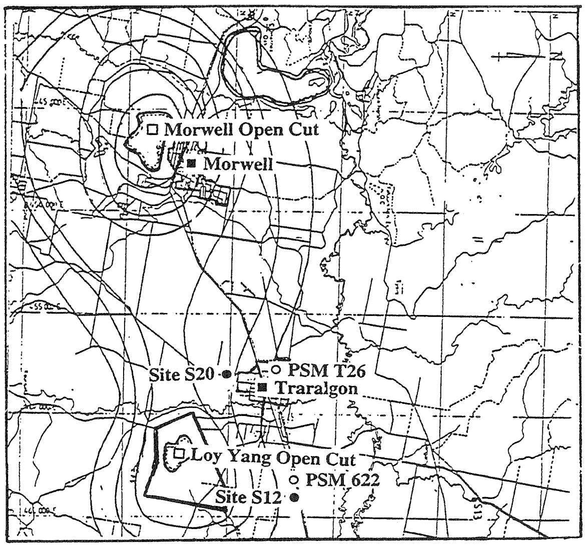

Figure 1. Equal subsidence contours

2. GEOLOGY OF THE AREA WITH STRATIGRAPHY

The Latrobe Valley is situated near the coast to the south east of Melbourne, Australia. It lies within the western portion of the Gippsland Basin. The Latrobe Valley essentially follows the eastwards dipping Latrobe Syncline and opens eastwards towards Lake Wellington near Sale.

The Geology of the Latrobe Valley is made up of a series of defined coal seams. In order of depth, they are the Morwell 1 coal seam, Morwell 2 coal seam and the Traralgon coal seam. They have been tilted, folded and faulted and lie on sedimentary Mesozoic basement rock. (Gloe, C.S., 1984)

The stratigraphy of each site was interpreted within the constraints of the regional ground water model. The ground water model was used to predict the future aquifer responses due to expected mining operations. These results were then used to predict subsidence using the calibrated subsidence models for each. For coupling purposes between the ground water and the subsidence models, agreement on the stratigraphic interpretation of bore data was necessary.

The ground water model was an idealisation of the Gippsland region. It was made up of a series of layers, being individual aquifers (sandy, permeable material) and separators (hydraulic separator between aquifers). The individual sites were identified in the ground water model to determine the model stratigraphy. Four pairs of aquifers and separators were defined at site S20, while six pairs were defined at site S12.

Interpretation of the ground water model enabled the stratigraphy of the subsidence model to be defined with respect to the site bore logs. Some discrepancies existed between the geological bores and the ground water model interpretation. However, this was to be expected as the ground water model was a simplification of the Latrobe Valley and could not be expected to be so finely detailed. Generally, both sites were able to accommodate the ground water model interpretation. However, at site S20, one layer was excluded as it did not adequately correspond with the site geology. Effects were limited on the subsidence results as the omitted aquifer was only influenced by pumping to a minimal extent. Figures 2 and 3 show the definition of stratigraphy for the subsidence models at sites S12 and S20 respectively.

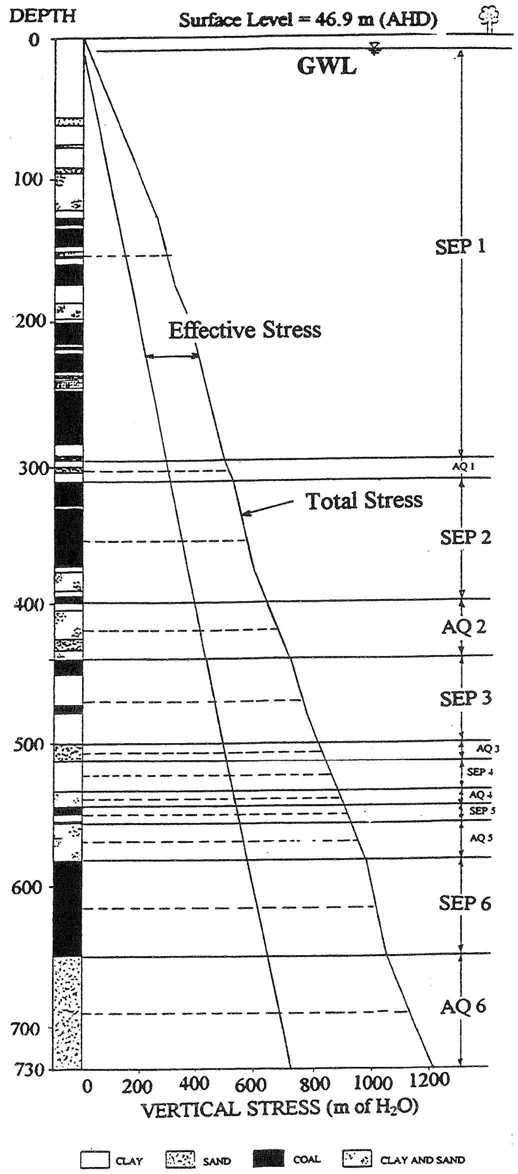

Figure 2. Site S12 Stratigraphy

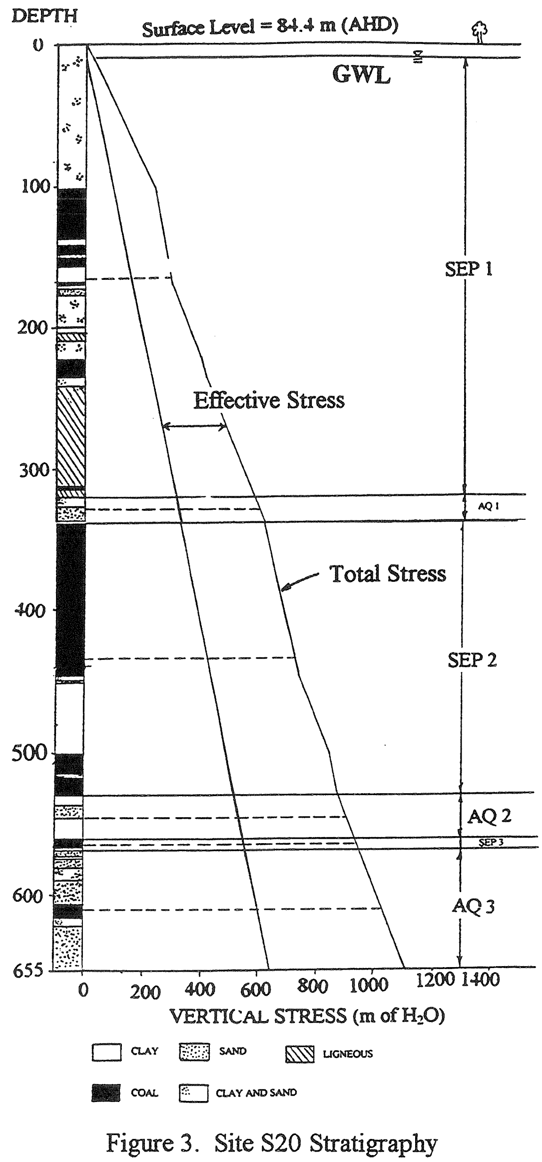

Figure 3. Site S20 Stratigraphy

3. THEORY OF SUBSIDENCE AND COMPAC PROGRAM

Subsidence is the lowering of the land surface usually attributed to processes below the ground. This study was concerned with subsidence due to the redistribution of stresses. This redistribution of stress is related to open pit mining activities such as de-watering. The major problem relating to de-watering is the effect on effective stress and the resulting deformation of soil.

The withdrawal of water from the aquifer system causes changes in pore water pressure and an increase in average effective overburden pressure, resulting in deformation of the soil.

In order to compute aquitard compaction for known changes in applied stress at an aquitard boundary, two relations are required. The first is the relation of internal effective stress to known boundary effective stress, and the second is the relation between compaction and the internal effective stress distribution. Terazaghi (1948) developed the theory of primary one-dimensional consolidation of clays. This theory is commonly used to estimate the magnitude and rate of settlement that will occur in fine-grained clayey deposits under a given change in load (stress). Helm (1975 & 76) outlines the links between effective stress and compaction.

The computer program COMPAC developed by Helm (1984) is a one-dimensional finite difference subsidence model. It was used to model the subsidence at sites S12 and S20. COMPAC computes land subsidence resulting from specified changes in hydraulic head within one or more aquifer systems. Virgin compression and elastic recompression of the clay that lies either within an aquifer system or between two aquifer systems are taken into account. The compression of permeable aquifer material (usually sand) is also calculated. Because each of the defined aquifers and separators are modelled separately the total vertical movement at ground surface as a function of time is calculated by manually summing the outputs for each layer. Back analysis with measured historical subsidence and changes in hydraulic head allows future predictions of subsidence to be made for anticipated water level changes in each aquifer. In this case the predicted changes in head were obtained from a separate three-dimensional ground water model of the region.

The equation for the vertical distribution of transient incremental effective stress within a double draining aquitard used in the COMPAC model is:

$$S_{sk}' \ \partial p'/\partial t = \partial(K' \ \partial p')/\partial z \qquad (1)$$

Where,

S_{sk}' - Skeletal specific storage of aquitard material
p' - Effective stress
t - time
K' - Hydraulic conductivity of aquitard(s)
z - vertical space coordinate

The compressibility term in this equation changes depending on the effective stress condition. If the effective stress is equal to the past maximum preconsolidation stress $S_{sk}' = S_{skv}'$. If it is less than the preconsolidation stress $S_{sk}' = S_{ske}'$, where,

S_{skv}' - Virgin Skeletal specific storage of aquitard material
S_{ske}' - Component of S_{skv}' due to aquitard skeletal compressibility

4. DATA PROCESSING - CALIBRATION AND PREDICTION PROCESSES

In order to make accurate predictions of future subsidence, the separate models were calibrated to historical aquifer drawdown and measured subsidence. Once the available data was defined and the stratigraphy interpreted the model could be calibrated. However, the calibration becomes difficult when there is a lack of reliable data (either historical subsidence or ground water). In this case, the site specific aquifer drawdown data was unreliable.

4.1 Calibration

Back analysis was used as a method of estimating the coefficients of permeability and compressibility at each site. This was carried out essentially by trial and error. It is possible to calculate the coefficients from laboratory tests, however, one single test or the average of a range of tests may not have represented the parameters required by the model. This is because the physical characteristics of the sites cannot be accurately represented in a small sample, due to the discontinuity's and non-homogeneous characteristics of soil.

The main difficulty during the calibration phase was the non-uniqueness of the parameter values. More than one combination of permeability and compressibility would yield similar subsidence results over a specified period of time. Yet, each run had a different shaped curve, being dependant on the parameters selected. In order to find the most representative set of parameters for each site, the historical subsidence data was split into eight five year time increments from 1960. The magnitude of subsidence within each of these periods was then used as a basis to determine accurate model parameters. The development of this method of using zero error curves is covered in a later section and discussed in detail by Helm (1984).

4.2 Historical Subsidence

Due to the importance of subsidence in the Latrobe Valley, the SECV monitor the level of hundreds of permanent survey markers (PSM's) each year. Some of the markers have been surveyed to as far back as the 1950's. These "base" levels enable the determination of subsidence over the past 45 years due to mining operations.

There were two main complications associated with historical subsidence data. First, the historical subsidence measurements at each site were not directly taken on the site locations. Therefore, a method of interpolation was required to define the subsidence on the actual sites. Secondly, some of the closest permanent survey markers to the modelled sites had readings that began in the 1970's, thus, making it difficult to determine the total subsidence since the 1950's.

4.2.1 Historical Subsidence at Site S12

The subsidence data for this site was derived from the three closest PSM's (622, 584 & 590). In previous modelling attempts of site S12, PSM 590 was used due to its close proximity. On further investigation of surrounding sites (622: 800m west and 584: 4km east of S12), it was found that the subsidence at PSM 590 was somewhat less than expected. PSM 622 was chosen to represent subsidence at site S12 because of its relative close proximity. All PSM's studied in this area dated back to the 1950's, therefore no adjustment was required to find the true subsidence.

4.2.2 Historical Subsidence at site S20

Five of the closest PSM's to site S20 were investigated to determine a suitable historical subsidence profile at the site. From the five, PSM T26 was found to best represent the historical subsidence. It was located approximately 2km north of the site.

Three of the PSM's, including T26, were first recorded in the 1970's and therefore conversion back to the base 1950's levels was required. Regional subsidence contours were used to determine the difference between the "base" subsidence and the recorded subsidence since 1970. The average difference for a range of years between 1970 and 1994 was used to factor the data. T26 was the most representative of the expected subsidence at site S20, both in magnitude of subsidence (based on regional subsidence contours), as well as shape of subsidence (ie similar to historical ground water drawdown patterns).

4.3 Available water level data

To calibrate the model successfully, historical water level measurements for the defined aquifers were required. Due to unreliable water level readings and data of short duration, useful field aquifer drawdown data for the two sites was unavailable.

In order to accurately calibrate the subsidence models the three dimensional ground water model was used to determine the historical water levels. The use of the ground water model was justified as it was based on accurate bore logs of the region and was calibrated with reliable regional ground water data.

Water levels for seven increments between 1960 and 1994 were extracted for each of the aquifers defined in Section 2. These levels are shown in figures 6 and 7.

4.4 Zero error curves

The calibration required a line of best fit though the available subsidence data in order to relate the results of each model. This line was used as the line of zero error for the determination of the characteristic permeability and compressibility factors at each site. It became obvious that the lines of best fit through the subsidence data could be interpreted in many ways. Figures 4 and 5 show the historical data. The lines of best fit were chosen to best represent the subsidence, while still bearing some resemblance to the ground water drawdown shape. It was necessary to assume approximately the same shape as drawdown, so the model would calibrate. Especially as the ground water data used was generated rather that measured. If reliable physical data was available, a solid link between the two curves (ground water drawdown and subsidence) would have been expected.

In order to develop zero error curves, the fitted subsidence curves were split into eight time periods. The consolidation during these periods was found and calibrated against. This produced eight lines of zero error, with the point of intersection of all lines indicating the optimum permeability and compressibility values for each site.

The method used to define the points of zero error was systematic. An initial value of permeability (K) and the compressibility factor CR2 was chosen and the model run was executed. At this point, the consolidation at the beginning and end of each time increment was determined along with the differences in each increment. These differences could then be compared to the fitted curve differences. The final selection of K and CR2 values for each site are given in Table 1.

Table 1. Final calibration parameters

Site	Permeability (K) (m/yr)	Compressibility (CR2)
S12	0.007	0.023
S20	0.05	0.0125

Figures 4 and 5 show the consolidation in each layer and the total calibrated consolidation for sites S12 and S20. At site S12, 16 percent of the subsidence was contributed by aquifer six and a further 66 percent was contributed by separator six. At site S20, 32 percent of consolidation was contributed by separator one, while 45 percent was contributed by separator two.

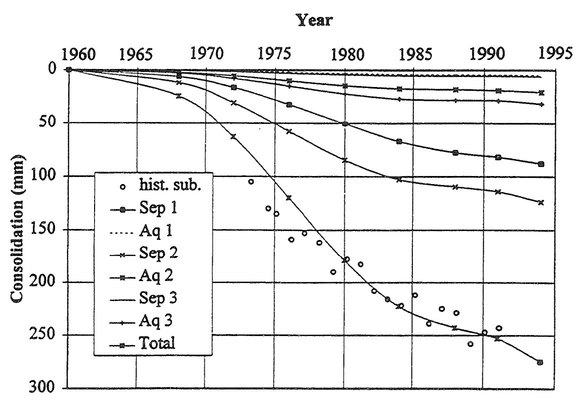

Figure 4. Consolidation at site S20

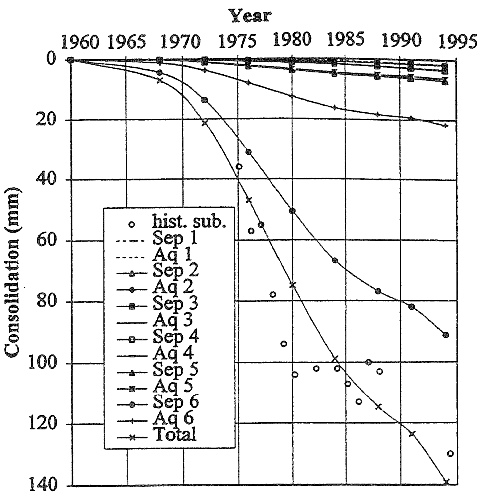

Figure 5. Consolidation of site S12

5. PREDICTIONS

Following model calibration, the prediction of future subsidence was reasonably simple. The only further data required was the predicted water levels in each of the defined aquifers. These were also extracted from the regional ground water model. The predictions of subsidence were then made for the year 2020 and ultimate.

5.1 Predicted Ground water Levels

Outputs were obtained from the regional ground water model for eight individual years between 1994 and 2020. These are shown in Figures 6 and 7 along with the historical water levels for each of the defined aquifers in section 2. Layer A represents Aq 1, layer B represents Aq 2 and so on.

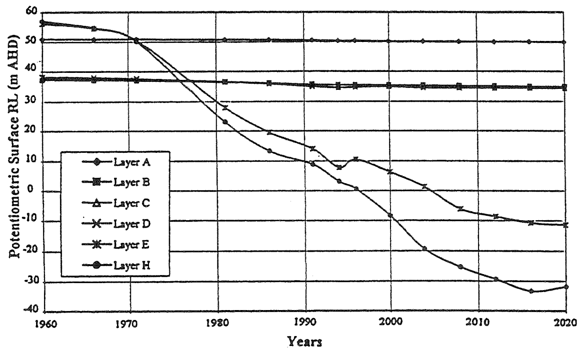

Figure 6. Potentiometric surface levels at site S12

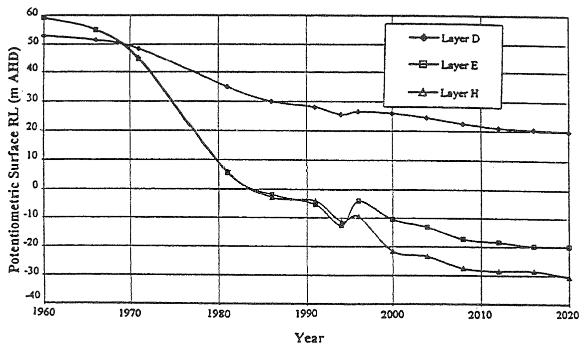

Figure 7. Potentiometric surface levels at site S20

In order to satisfy mining operations to 2020, predictions were made regarding required rates of pumping. The small rise after 1994 indicated that the predicted pumping rates were less than at the 1994 rates. If pumping reduces in the aquifers, the obvious reaction is a build up of water pressures and hence a rise in water levels.

5.2 Prediction Results

The total predicted subsidence due to the consolidation of the aquitards and separators at each site is given in Table 2. The subsidence profiles are shown in Figures 8 and 9.

Table 2. Subsidence Predictions

Site	Recorded 1994 Subsidence	Predicted 2020 Subsidence	Predicted Ultimate Subsidence
S12	130mm	210mm	215mm
S20	275mm	320mm	325mm

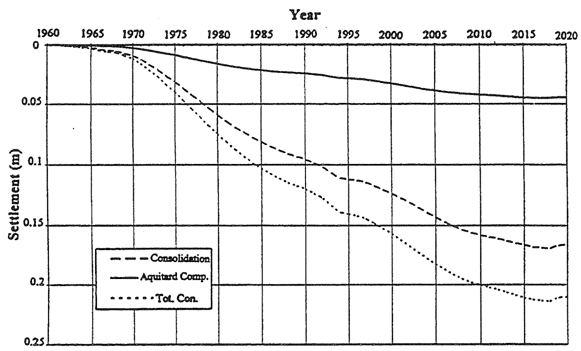

Figure 8. Subsidence from 1960 to 2020 at site S12

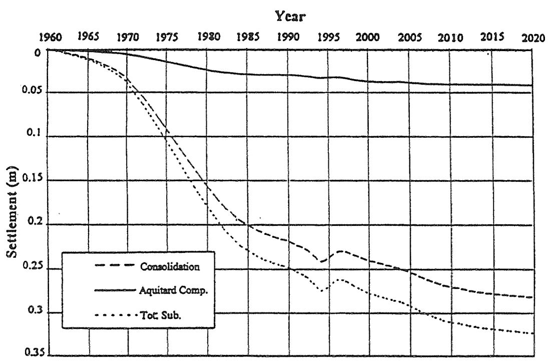

Figure 9. Subsidence from 1960 to 2020 at site S20

The dashed lines in Figures 8 and 9 indicate the consolidation of the time dependant compressible layers. That is, the separators and aquitards. The full line shows the immediate response of the highly permeable sections of the aquifers (sands), while the dotted line is the total of the previous two (ie subsidence).

5.3 Discussion of Predictions

The results in Table 2 highlight the influence of the high value of permeability derived in the calibration process. Its high value caused more short term (immediate) subsidence and less residual (time dependant) subsidence to occur.

The small difference in the predicted subsidence between 2020 and ultimate was indicative of the high value of permeability. The final changes in aquifer pressure had a large immediate effect on subsidence and therefore only small amounts were calculated after the year 2020.

Essentially, the results are open to interpretation. The values of permeability and compressibility are not representative of lab results and therefore the characteristics of the consolidation curve may be inappropriate for each site. However, the calibrations do give an accurate representation of historical subsidence and therefore one would assume the same for future subsidence.

The predictions made are the most accurate predictions to date. The calibration process has produced curves that fit the available subsidence data. Improvements to the ground water modelling process and the addition of further subsidence data has helped facilitate this.

The reliability of the models are subject to the accurate interpretation of the strata and having reliable field data. The strata can be defined through the use of bore logs, the subsidence measurements are relatively reliable and the improved ground water modelling techniques have enhanced the reliability of the ground water information. Taking this into account, the predictions made are the best possible representation of subsidence for the future.

The subsidence estimates for the year 2020 were smaller than the previous predictions made by Kacavenda in 1987 (245mm at site S12 and 540mm at site S20). These results seem reasonable because the previous predictions had deviated rapidly above the actual subsidence during the early 1990's.

5.4 Future Monitoring

The predictions made in this project will be monitored over the coming years to determine the reliability of the models. If the expected trends in ground water pumping are reliable it would be reasonable to assume that the predicted subsidence at each of the sites has been modelled accurately. If the expected subsidence turns significantly from the predictions then re-calibration of the models are required. However, five to ten years of data could be required before an accurate trend in the subsidence is identified. Yearly subsidence readings can be quite inconsistent from year to year. Shallow influences such as a high rainfall or the growth of vegetation in an area can artificially influence the subsidence readings.

6. CONCLUSIONS

The computer modelling of time-dependent ground movement at two sites (S12 and S20) near Traralgon township, due to ground water withdrawal at Morwell and Loy Yang mines was undertaken.

The models at sites S12 and S20 were successfully calibrated to give representative values of permeability and compressibility. The predictions made are the most accurate to date due to additional historical subsidence data and more accurate ground water modelling techniques.

The use of the regional ground water model to provide the historical ground water levels proved to be an acceptable method of calibration. However, monitoring the future subsidence levels in the next ten years should determine the reliability of this calibration method.

7. ACKNOWLEDGMENTS

The Authors wish to acknowledge the valuable input during this project with Slavco Kacavenda, Chris Daniels and Jin Zang of Geo Eng Pty Ltd. All historical data, computer programs, as well as the main project outline were provided by Geo Eng.

8. REFERENCES

Gloe, C.S. (1984). *The Geology, Discovery and Assessment of Brown Coals of Victoria,* Aus I.M.M Monograph Series No 11 - Victoria's Brown Coal, AusIMM, pp. 77-109.

Helm, D.C. (1975). *One Dimensional Simulation of Aquifer System Compaction Near Pixley, California, 1: Constant Parameters*, Water Resources Research, Vol 11, pp. 465-578.

Helm, D.C. (1976). *One Dimensional Simulation of Aquifer System Compaction Near Pixley, California, 2: Stress Dependant Parameters*, Water Resources Research, Vol 12, pp. 375-391.

Helm, D.C. (1984). *Latrobe Valley Subsidence Predictions, The Modelling of Time-Dependant Ground Movement Due to Ground Water Withdrawal,* Report to SECV, Report No. DD195 - GD9.

Kacavenda, S. (1987).*Latrobe Valley Subsidence Predictions - Traralgon Township*, SECV Fuel Department, Report No. DD221.

Terzaghi, K. & Peck, R.B. (1948). *Soil Mechanics in Engineering Practice*, John Wiley, New York.