A Review of the Accuracy and Reliability of Empirical Subsidence Predictions

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Summary

The prediction of subsidence effects resulting from the underground extraction of coal is undertaken prior to commencing mining operations in order to assess the likely consequences and impacts of subsidence on the natural and built environment above and in the vicinity of the mining operations. Often subsidence predictions are also undertaken for many alternative mine layouts before the appropriate layout is chosen. These subsidence predictions are used by the mine owners, consultants and stakeholders to manage the subsidence impacts on the natural and built features by providing a basis to:

- develop appropriate management plans; and
- assess whether the observed subsidence movements are developing as expected.

With a continuing increase in the awareness of and the need to protect the natural environment, and with an increasing need to extract coal beneath the built environment, there has also been an increasing demand for greater detail in the provided predictions and assessments of the effects, consequences and impacts of underground mining on the natural and built features. With this increased demand for greater detail, there must also be an understanding of the background to, and the accuracy and reliability of, the subsidence predictions that are being used for the impact assessments on the natural and built features and for the management plans developed.

This paper provides a discussion on the background to the commonly used empirical methods of subsidence prediction in NSW and provides an assessment of the accuracy of two commonly used empirical subsidence prediction methods, using monitored data from the Southern Coalfield of NSW. The methods were initially developed by:

- Dr L Holla (1985(a)), then of the Department of Mineral Resources (DMR), NSW, in a paper titled 'Surface Subsidence Prediction in the Southern Coalfield'; and
- Waddington Kay and Associates (1995) (now Mine Subsidence Engineering Consultants or MSEC) and known as the Incremental Profile Method.

1. Subsidence prediction

There are two basic approaches currently used to predict subsidence: empirical and numerical/analytical.

Numerical/analytical methods use complex mathematical representations of the overburden material and its behaviour. The challenges in determining the appropriate input parameters for the numerical/analytical methods have limited their widespread use. Empirical mine subsidence prediction techniques are more commonly used in NSW because they are convenient and quick to use. Empirical approaches rely on a large database of observed subsidence data monitored over previous mining. The main focus of this paper is on empirical methods.However, it should be remembered that empirical methods only provide reasonably accurate predictions, if:

- the mechanics of the subsidence

processes are consistent enough to allow reproducible behaviour;
- the overall size of the available monitoring database used is representative;
- the appropriate variables/factors are chosen;
- the limitations of the predictions are understood, for instance whether the method provides a reasonable average or an upper bound style prediction; and
- care is taken to recognise conditions that are outside the range of available data within the database of experience.

The more common types of empirical mine subsidence prediction methods are:
- **Graphical**, such as those advanced by the United Kingdom (UK) in developing the Subsidence Engineers Handbook, which involves plotting suites of curves showing relationships between various parameters and subsidence outcomes;
- **Upper Bound**, which involves constructing an envelope over measured maximum or worse case outcomes and predicting on the basis of that envelope; and
- **Profile Function**, which attempts to define the shape of the vertical displacement curve by a mathematical equation. This equation can represent an average or a conservative curve through the available data.
- **Influence Function**, which determines the subsided surface level based on the area of influence around the point of extraction.

2. History of empirical subsidence predictions in Australia

Up until 1980, subsidence predictions were predominantly based on the methods outlined in the Subsidence Engineers Handbook, first published by the National Coal Board of the UK in 1965 and revised in 1975. This method involved the use of a series of graphs derived from numerous field observations in UK mines, which allowed the shapes of the subsidence, tilt and strain profiles to be predicted over single mined panels.

However early mine surveyors and mine subsidence researchers identified that, in Australia, the field observations were considerably lower (up to 60% of the extracted seam thickness) compared to the predicted values using the UK handbook (up to 90% of the extracted seam thickness). Much of the variation was attributed to observations that mining in the UK had generally been conducted at much greater depth of cover, in conditions where multiple seams had previously been mined, so the rock strata was more disturbed and the loading on the rock strata was much greater relative to the available rock strengths.

After further empirical studies, it was found that where there is a mix of sandstone and shale, siltstone and claystone strata units within the overburden and the horizontal stresses are relatively high, as is typical in Southern Coalfield of NSW, the maximum vertical subsidence for supercritical width panels in single seam conditions is between 60% and 65% of the extracted seam thickness. Where strong and massive conglomerate and sandstone strata units are commonly present in the overburden, and where the horizontal stresses are relatively low, as is typical in the Newcastle and Hunter Coalfields of NSW, the maximum vertical subsidence for supercritical width panels in single seam conditions is typically between 50% and 55% of the extracted seam thickness.

The magnitude of the maximum vertical subsidence at the surface resulting from the extraction of a longwall panel has been found to be a function of multiple factors including:
- depths of cover;
- longwall panel width;
- chain pillar width;
- extracted seam thicknesses;
- surface topography;
- proximity and extent of mining in nearby previously extracted panels;
- presence of previously mined panels in the overlying seams;
- pillar stability;
- the geology and geomechanical properties of the strata layers between the surface and coal seam as well as below the seam;
  the presence of igneous intrusions or faults; and
- the dip of the strata.

Other factors can also influence the final subsidence, for instance, the depressurisation of groundwater within near-surface sediments can lead to increased subsidence from the consolidation of these sediments, additional to the normal subsidence movements. Multi-seam mining can lead to changes in the subsidence characteristics of the overburden strata and can result in additional subsidence. Mining below open cut waste rock backfill also results in increased subsidence.

The need for Australian-based monitoring and research became very clear during the Stored Waters Inquiry in 1975 and 1976, when the NSW Department of Mineral Resources engaged the consulting services of Eric Orchard from the UK for mine subsidence advice. For this important inquiry, the NSW mining industry engaged the mine subsidence consulting services of Ken Wardell from the UK, even though Bill Kapp, who was working with BHP at that time, had published several papers on the monitoring of mine subsidence in NSW. Reynolds (1977) commented that:

> *'The Inquiry has indicated that there is a need for the Department to acquire and build up for itself experience and knowledge in the field of subsidence engineering as it relates to New South Wales conditions. For the future the Department should not be so dependent upon overseas consultants for advice in this field.'*

Early mine subsidence prediction curves were published by Kapp (1973 to 1985), Frankham & Mould (1980) and Holla (1985(a), 1985(b), 1987 and 1991(a)) that were based on Australian geological conditions. It was Kapp who identified that the maximum observed subsidence over NSW coal mines was generally 60% of that predicted using the Subsidence Engineers Handbook (1975) (National Coal Board of the UK). Kapp advised that the reduced subsidence was probably due to the higher proportion of sandstone within the overburden.

After carrying out an intensive survey monitoring program, the NSW Department of Mineral Resources (DMR) prepared the first mine subsidence empirical prediction handbook model that was more appropriate for Australian geological conditions. The handbook for the Southern Coalfield was completed in 1985 (Holla, 1985) and the handbooks for the Newcastle and Western Coalfields were completed in 1987 (Holla, 1987) and 1991 (Holla, 1991(a)) respectively.

Although the subsidence prediction methods given in these NSW handbooks are only applicable to single, isolated panels, additional research (Holla ,1988) led to publication of a paper that included a graph for predicting the maximum subsidence above a series of longwall panels. This graph is reproduced as Figure 1, where S_{max} is the maximum total subsidence, T is the average seam thickness extracted over the panels and H is the depth of cover.

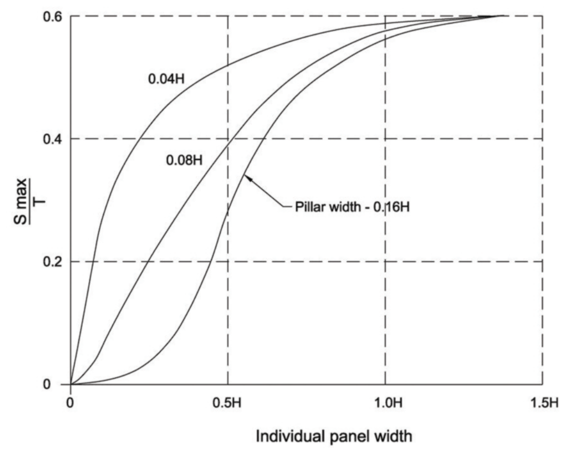

Figure 1 **Graph for the prediction of maximum subsidence over a series of panels for critical extraction conditions (after Holla, 1988)**

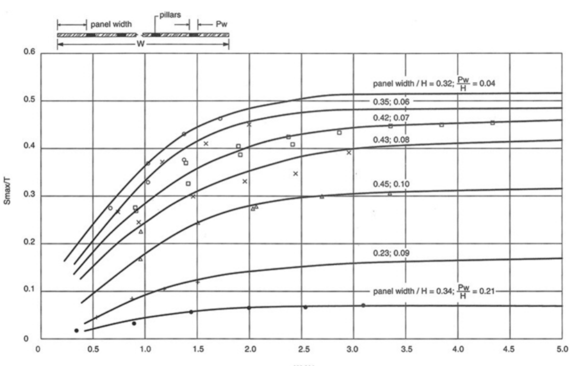

Figure 2 **Relationship between W/H ratio and S_{max}/T for multiple panel layouts**

Following further study, a revised handbook for the Southern Coalfields was produced by Holla and Barclay (2000): it includes a revised graph to predict the maximum subsidence over a series of longwall panels, as shown in Figure 2.

The handbook provides several empirical curves that were drawn through the available monitoring data for predicting the approximate shape of the subsidence profile and to predict the maximum tilt, curvature and strain above a mined area, for single panels.

Other researchers have provided empirical subsidence prediction curves to suit specific local geological conditions, including Kapp (1982 and 1984), Creech and Tobin (1991), Creech (1995), Waddington and Kay (1995), Tobin (1997) and Ditton et al (2003). These subsidence prediction curves included the limiting effects on vertical subsidence due to the presence of massive sandstones or conglomerate strata.

The Incremental Profile Method was developed by Waddington Kay and Associates (now Mine Subsidence Engineering Consultants or MSEC) following a study for BHP Collieries Division, the Water Board and AGL during the latter part of 1994 (Waddington and Kay, 1995). The purpose of the study was to develop a more detailed empirical subsidence prediction method that could be used to predict the subsidence, tilts, curvatures and strains as longwall mining occurred at Appin and Tower Collieries, and to assess the likely impacts of these subsidence ground movements on surface infrastructure.

During this study a consistency in the shapes of the incremental subsidence profiles was observed in all the measured survey lines that were located transversely across longwalls. These observed incremental subsidence profiles were determined for each longwall by subtracting the initial subsidence profile (measured prior to mining of the longwall) from the final subsidence profile (measured after mining the longwall).

The Incremental Profile Method (IPM) of subsidence prediction was then developed to predict the incremental subsidence at any point over a series of longwalls, for each longwall. The total subsidence at any stage in the development of a series of longwalls can be predicted by adding all the applicable increments. It was found that more accurate site-specific total subsidence predictions could be developed at any point over the surface by breaking the prediction process up into the small increments on a longwall by longwall basis.

The incremental subsidence profiles are usually prepared along prediction lines for the extraction of each longwall. These incremental subsidence profiles are then used to derive the incremental tilts, curvatures and strains, which can be added to show the transient and final values of each parameter as a series of longwalls are mined.

The model was initially tested by comparing the predicted values of subsidence, tilt, curvature and strain against the measured values for a number of longwalls at Appin, Cordeaux, Tahmoor and West Cliff Collieries. Following that study, the method was successfully used to analyse and predict subsidence over other longwall panels within the Southern, Newcastle and Hunter Coalfields

and the Western Coalfields. These studies found that the shapes of the measured incremental profiles conformed to the patterns and magnitudes observed during the initial 1994 study.

However, it is important to appreciate that the IPM method has a tendency to over-predict the subsidence parameters because, like the method developed by Holla (1985(a)), a conservative approach was adopted in preparing the graph that is used for predicting the maximum incremental subsidence. Figure 3 shows the maximum incremental subsidence, expressed as a proportion of seam thickness, versus panel width-to-depth ratio.

3. Accuracy and reliability of empirical mine subsidence predictions

The prediction of mining-induced subsidence, tilt, curvature and strain, whether it is caused by the extraction one panel in a single seam or by the extraction of a series of overlapping multi-seam longwall panels, cannot be considered an exact science because of the many complex mechanisms involved in mine subsidence and the variability of the factors used in the prediction models.

Predictors are generally happy when the observed subsidence is similar to the predicted levels of subsidence. The observed subsidence levels are generally lower than the predicted subsidence levels, however, on occasions the observed subsidence can be higher than predicted and, in these cases, efforts are made to find out why. The inaccurate nature of mine subsidence predictions is not unique to empirical mine subsidence prediction models, as all types of subsidence models have their limitations and variations, which need to be considered when reviewing the predicted outcomes, based on previous experience.

It is important to have a clear understanding of the background to the prediction method when discussing the accuracy and reliability of subsidence

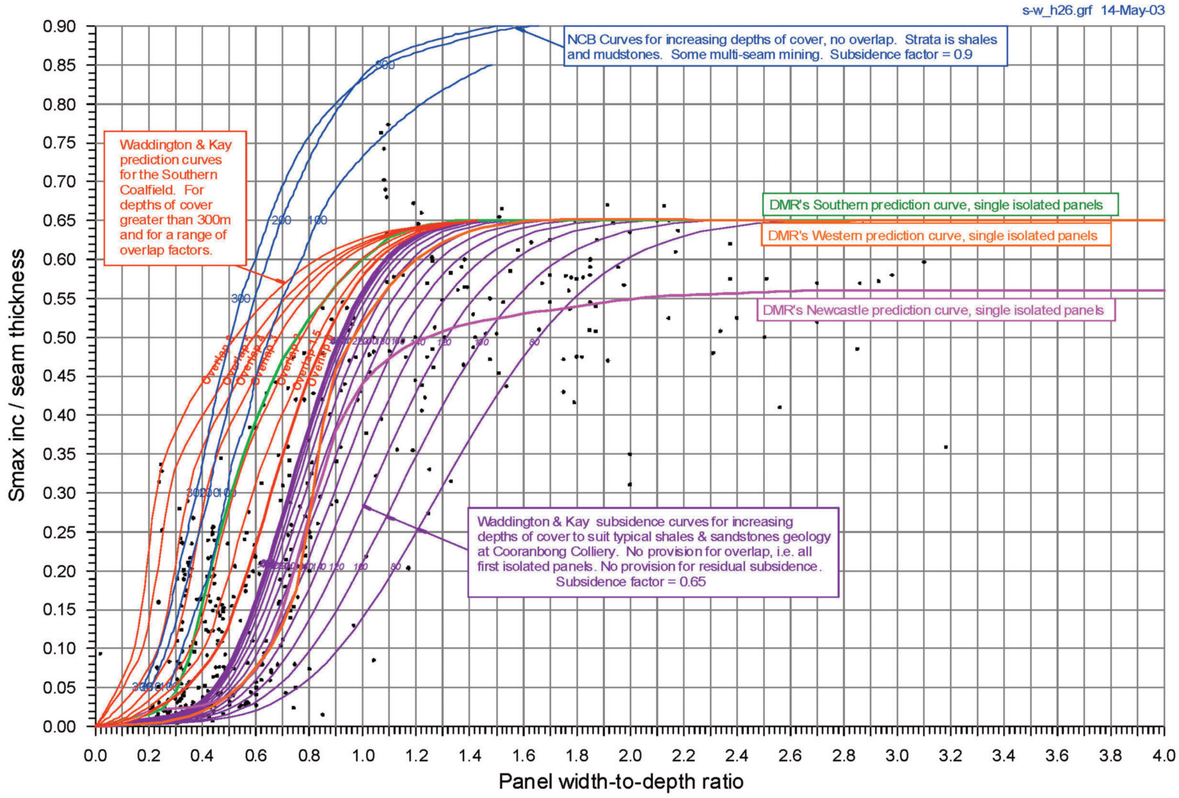

Figure 3 **Prediction curves for maximum incremental subsidence**

predictions. With any method used for the prediction of the maximum vertical subsidence, there will be limitations on the method's ability to make accurate predictions, given the inherent variability of information used in the prediction models.

The natural variability in the types and properties of the overburden material above and immediately below an extracted longwall can cause a significant variation in the predicted subsidence above an extracted longwall.

Similarly, there are limitations to the geometric information used in models. For example, the extracted seam thickness is often based on mapped contours that have been interpolated between exploration locations and the actual seam thickness extracted varies throughout a longwall due to the tolerances of the cutting equipment and the roof and floor conditions encountered during extraction. A variation in the extracted seam thickness from the interpolated seam thickness of, say, 100mm to 200mm could result in variability of the predicted subsidence by approximately 50m to 100mm.

The International Organisation for Standardization (ISO) defines accuracy by the terms 'trueness' and 'precision' (ISO 5725-1). Trueness refers to the closeness of the mean of a measurement result to the actual, or true, value and precision refers to the closeness of agreement within individual results. These are represented graphically in Figure 4.

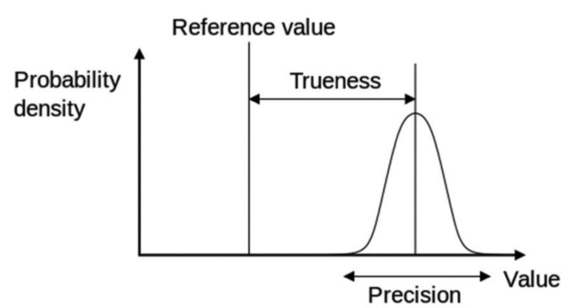

Figure 4 **Accuracy according to ISO 5725-1**

In the determination of predicted maximum vertical subsidence, the subsidence engineer aims to prepare predictions that are as true and precise as is reasonably practicable. However, in doing so there must be a realistic appreciation of the precision that can be achieved using any predictive method.

A review of the reliability of subsidence prediction methods in NSW was undertaken and presented in a paper by Dr Lax Holla (1991(b)). Of 14 cases presented in the paper, predictions of maximum total subsidence did not differ from observed subsidence by more than 11%, with average differences of less than 7%. The perspective on accuracy of predictions was emphasised in the paper where Holla stated:

> *'Those who argue that subsidence prediction should be done accurately to the nearest millimetre appear to believe that the subsidence prediction as an academic exercise is an end in itself. They lose sight of the fact that the prediction is only a means towards the end objective of assessing damage arising from the predicted subsidence';* and

> *'Available methods for predicting subsidence, their limitations and advantages are dealt with. The difficulties in achieving "accurate" predictions are highlighted. At the same time the need for and usefulness of such "accurate" predictions in all cases is questioned. The concept of adequacy of prediction rather than accuracy is emphasised'.*

4. Conservatism

In the preparation of management plans for subsidence impacts on natural and built features, contingencies are included in management plans in the event that predicted or targeted subsidence movements and impact assessments are exceeded. It is therefore desirable for observed subsidence values to be less than predicted. For this reason, the development of empirical methods for prediction of maximum subsidence incorporates a degree of conservatism, such that trueness aims to achieve ratios of observed to predicted maximum subsidence of less than one, i.e. observed maximum subsidence should be less than predicted maximum subsidence.

This conservatism is incorporated into the original handbooks provided by the, then, NSW Department of Mineral Resources, which state that their predictions curves were *'drawn to enclose most of the observed values under it and therefore it may be suggested that it over estimates S_{max} by up to 10 %'* (Holla, 1985(a)). Similarly the IPM was developed with the intent of over-estimation of maximum predicted subsidence in order to avoid under-prediction (Waddington & Kay, 1995).

5. Review of current accuracy of the empirical methods

The accuracy of the vertical subsidence predictions that are obtained using two empirical methods has been assessed by comparing the maximum predicted vertical subsidence with the maximum observed vertical subsidence along several ground monitoring lines from the Southern Coalfield of NSW. The two empirical prediction methods reviewed are the DMR Handbook method for the Southern Coalfield (Holla & Barclay, 2000) and the IPM (Waddington and Kay, 1995).

Comparisons have been made at the point of maximum observed incremental subsidence measured along a monitoring line, rather than at each individual survey mark over the mined panels, as more complex issues are associated with full monitoring lines, such as profile offset, surface topography, seam dips and localised irregularities. These issues may be the subject of future studies. The statistical analysis of data was also restricted to being carried out on results with an observed maximum subsidence of greater than 200mm to obtain a representative distribution for the assessment of accuracy. At less than 200mm, accuracy of predictions to within ±50mm of predicted subsidence is often quoted as being reasonable.

A significant exceedance over the predicted subsidence value was monitored above a longwall at Tahmoor Colliery, where the observed subsidence was far greater than predicted. This was considered an unusual and unique event for the Southern Coalfield of NSW and has not been included in the data set analysed for assessment of accuracy for the following two reasons:

- the area is very small (less than 1%) in comparison to the Southern Coalfield collieries represented in the data; and
- given the intensive monitoring undertaken in this area, the sample size is large in proportion to the total data set and its inclusion would skew the statistical analysis.

The greatest increase in observed subsidence over predicted subsidence was a measured subsidence value of 1169mm at a location where 600mm was predicted. The cause for this increased subsidence was investigated by Strata Control Technologies on behalf of Tahmoor Colliery (Gale and Sheppard, 2011). The investigations concluded that the increased subsidence was consistent with localised weathering of joint and bedding planes above a depressed water table adjacent to the incised gorge of the Bargo River.

6. Assessment of accuracy

The comparison of the maximum observed and maximum predicted vertical subsidence was first carried out using the published DMR method provided in the revised handbook produced for the Southern Coalfield (Holla and Barclay, 2000) and is provided in Figure 5.

There are a number of methods available that can be used to review the trueness of predicted maxi-

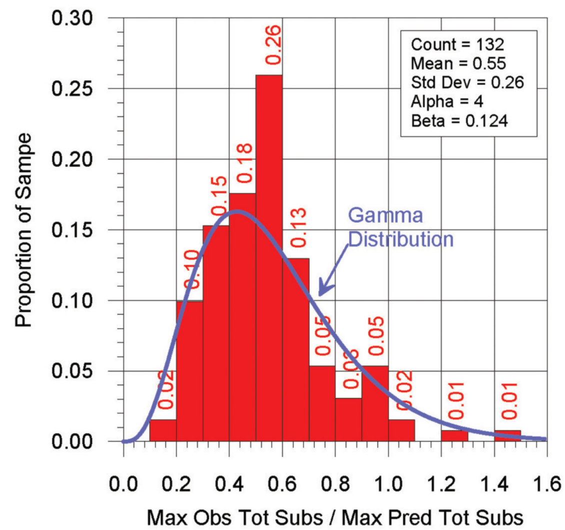

Figure 6 **Histogram of maximum observed/maximum predicted total vertical subsidence with gamma distribution**

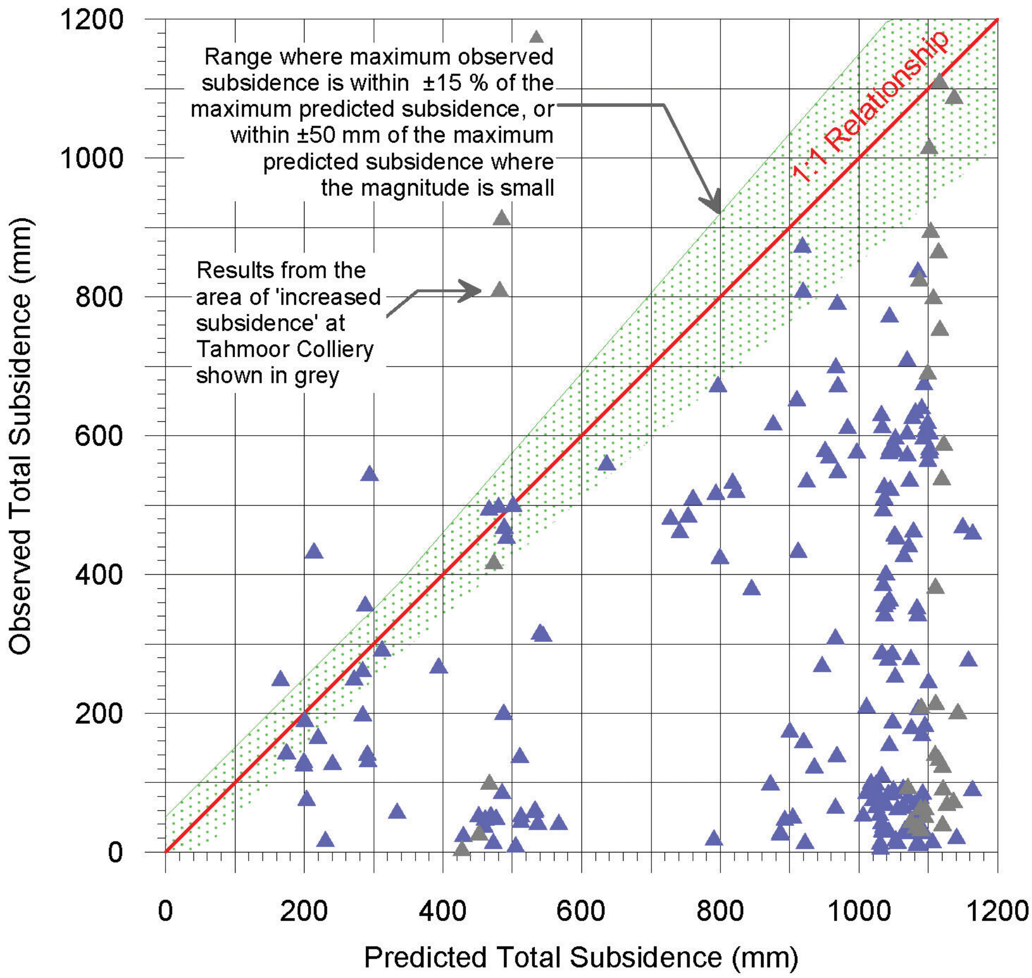

Figure 5 **Comparison between the maximum observed and maximum predicted subsidence for the available ground monitoring data in the Southern Coalfield of NSW based on the DMR Method**

mum vertical subsidence. The probability of exceedance is considered by the authors to be the most appropriate method for this task, i.e., how often do the observed movements exceed those predicted?

A histogram of the maximum observed subsidence divided by the maximum predicted vertical subsidence (DMR) is shown in Figure 6 for the available Southern Coalfield data that is presented in Figure 5. The mean and standard deviations of the raw data are also provided in Figure 6. Gamma probability distribution functions have been fitted to each of the histograms. Gamma probability distributions are generally used by the authors for statistical analysis of subsidence monitoring data as they offer skewed and asymmetric fits to the data.

The probabilities of exceedance for maximum vertical subsidence have been obtained using the fitted gamma probability functions and these are shown in Figure 7.

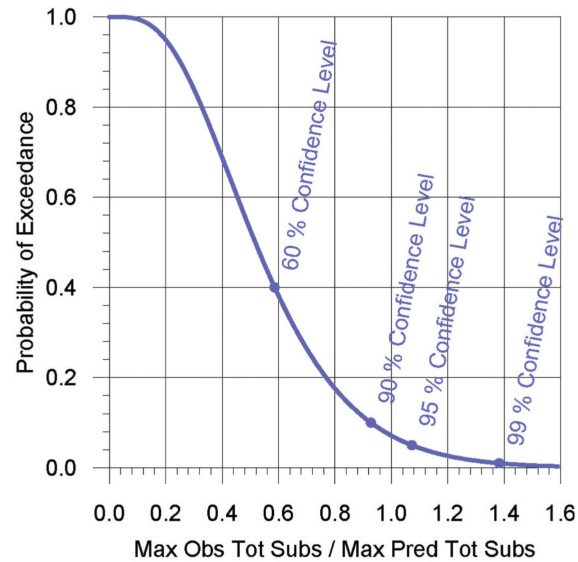

Figure 7 **Probability of exceedance for maximum observed/maximum predicted total vertical subsidence**

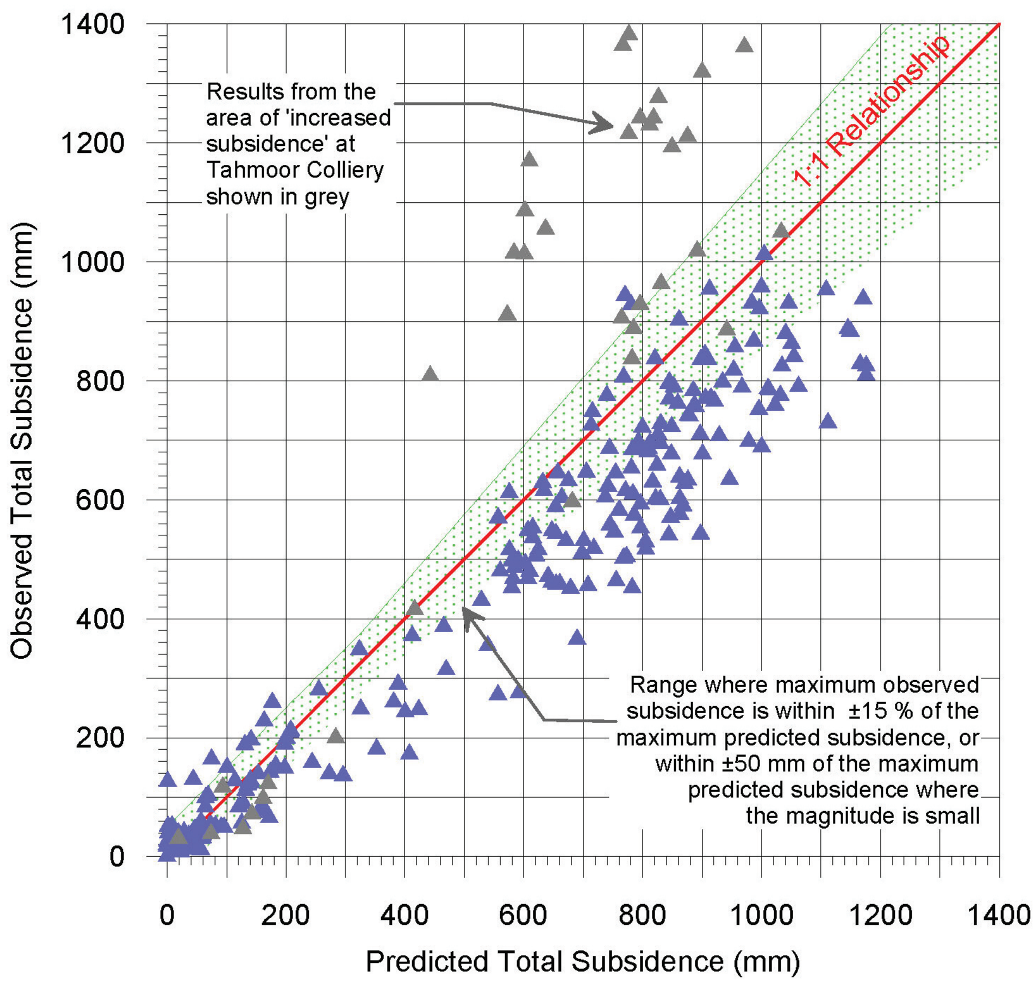

Figure 8 **Comparison between the maximum observed and maximum predicted subsidence for the available ground monitoring data in the Southern Coalfield of NSW based on the IPM Method**

The mean of the observed maximum subsidence divided by the maximum predicted vertical subsidence (DMR) shown in Figure 6 for the available Southern Coalfield data is 0.55 indicating that, on average, observed vertical subsidence is approximately 45% less than predicted, or conversely, predicted maximum vertical subsidence is on average approximately 82% higher than observed.

The ratios of the maximum observed subsidence to maximum predicted vertical subsidence (DMR) based on 90%, 95% and 99% confidence levels as shown in Figure 7 are 0.93, 1.07, and 1.38 respectively. These results indicate that based on the 95% confidence level (or probability of exceedance of 5%), the maximum observed vertical subsidence for the Southern Coalfield is within +7% of the maximum predicted vertical subsidence (DMR).

A similar comparison of the maximum observed and maximum predicted vertical subsidence made using the IPM (Waddington and Kay 1995) for the Southern Coalfield is provided in Figure 8.

A histogram of the maximum observed divided by the maximum predicted vertical subsidence (IPM) is shown in Figure 9 for the Southern Coalfield data presented in Figure 8. The mean and standard deviations of the raw data are also provided in Figure 9.

The probabilities of exceedance for maximum vertical subsidence (IPM) have been obtained using the fitted gamma probability functions and shown in Figure 10.

The mean of the maximum observed divided by the maximum predicted vertical subsidence (IPM) shown in Figure 9 for the Southern Coalfield data is 0.81, indicating that, on average, observed vertical subsidence is approximately 20% less than predicted, or conversely, predicted maximum vertical subsidence is on average approximately 23% higher than observed.

The ratios of maximum observed to maximum predicted vertical subsidence (IPM) based on 90%, 95% and 99% confidence levels in Figure 10 are 0.99, 1.05, and 1.17 respectively. These results indicate that based on the 95% confidence level (or probability of exceedance of 5%), the maximum observed vertical subsidence for the Southern Coalfield is within +5% of the maximum predicted vertical subsidence obtained using the IPM.

This comparison indicated that the probability of exceedance of the published DMR method is similar to that of the IPM, however there is a significant difference in precision between the two methods.

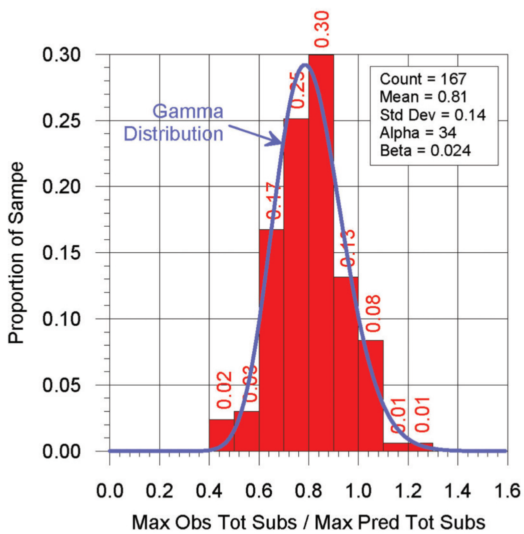

Figure 9 **Histogram of maximum observed/maximum predicted total vertical subsidence with gamma distribution**

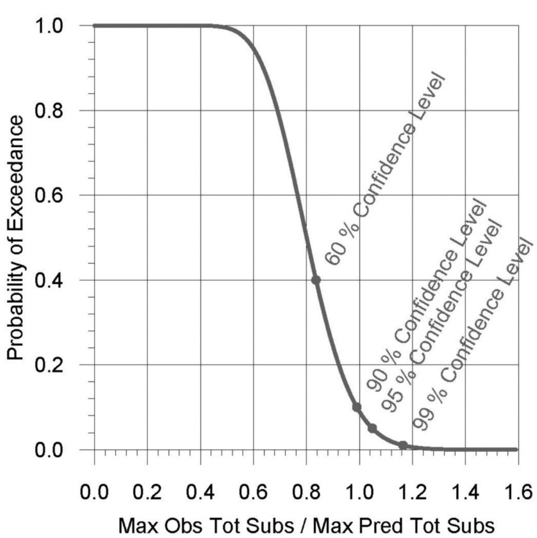

Figure 10 **Probability of exceedance for maximum observed/maximum predicted total vertical subsidence**

7. Precision

The precision of predicted maximum vertical subsidence obtained using the IPM is often quoted as being within ±15 % to ±25 % of the maximum observed subsidence. The results of statistical analysis of the data presented in Figure 8, show a standard deviation of 0.14 (or 14%), which accounts for approximately 68% of the data. Two standard deviations, i.e. 0.28 (or 28%) accounts for approximately 95% of the data.

On this basis, the quoted range of precision of ±15% to ±25% is considered to be reasonable. It should be noted however that observed maximum subsidence is on average approximately 20% less than predicted.

It could be argued that significant improvements in precision have been achieved based on the comparison made above. However, the DMR method provides a quicker mine subsidence prediction method for the Southern Coalfield, based on the more limited data that was available at the time it was developed. By comparison, the IPM method uses a much larger database of monitored data and computerisation allows the processing of more complex digitised information. It is anticipated that similar assessment of subsidence predictions by other prediction methods would also show improvements in precision when compared to the earlier published methods.

8. Management of impacts

The prediction of subsidence provides a tool that has successfully been used for the development of mine layouts and the assessment and management of surface impacts. The processes and decisions made in developing management strategies for the impacts resulting from subsidence effects should be made with a clear understanding of the accuracy of information used in making those decisions.

It can be seen from the assessment of maximum subsidence data in this paper that exceedance of subsidence predictions has occurred in the past, albeit with a relatively low probability of occurrence. Hence it is common practice to include assessments of the likely impacts resulting from mine subsidence based on multiples of the predicted subsidence parameters.

The development of management plans for the ongoing management of natural and built features also includes contingencies for those cases where predictions may be exceeded. It has become standard practice for the ongoing management of natural and built features to conduct detailed and regular monitoring, the result of which is often early identification of locations where exceedances are likely to occur.

9. Conclusion

This review provides information on the history of empirical methods and an assessment of the accuracy of empirical methods of subsidence prediction in terms of trueness, precision and probability of exceedance. Subsidence prediction is but one of the tools in the established decision making process for developing new mining areas and one of the tools used in developing strategies for managing the possible impacts resulting from mining.

An appreciation of the accuracy of the subsidence predictions is important in the decision making process. The review of data in this paper indicates that the precision of predicted maximum vertical subsidence is in the range of ±15 % to ±25 % and probability of exceedance is 5% (or 95% confidence level).

The knowledge base of methods of subsidence prediction and the impacts resulting from subsidence effects continues to develop through ongoing research. Regardless of the level of detailed information and complexity of subsidence prediction models, no subsidence prediction should be regarded as being perfectly accurate, and there will always be a limit to the accuracy of subsidence predictions that can be achieved, given the inherent variability in the many factors that result in subsidence effects.

Similarly, it is inevitable that exceedances of subsidence predictions will still occur but there are many monitoring and management strategies that can be used to minimise subsidence impacts once subsidence monitoring has detected the possibility of subsidence exceedances. A greater understanding of the accuracy and reliability of the subsidence predictions will hopefully lead to more informed decisions in developing management strategies for surface features affected by mining.

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