On the Deception in Requiring and Providing Singular Accurate Predictions for Surface Subsidence, Tilt and Strain

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Summary

Many, if not most, ground movement predictions for environmental assessments of new or ongoing underground coal mines in New South Wales involve the presentation of singular graphs, contour sets, or tables of vertical movements, tilts and strains. This is in part the result of the various regulators requiring 'accurate' predictions of deformations. These singular predictions may be accompanied by generalised statements expressing uncertainties, but the impression given to other parties is one of substantial confidence in the accuracy of the numbers.

The writers consider that this typical approach is intellectually dishonest and can be misleading in the assessments made of impacts on the environment. The logical flaw is that risk assessment techniques are used to evaluate impacts. These require determination of the probability of occurrence, and this cannot properly be done without reasonable expression of the likelihood of the range of ground movements that could, or will, cause impacts. The writers argue that there are inherently variable geological and geotechnical conditions that may determine critical subsidence deformations.

Usually the prediction methods adopted in NSW give, on average, reasonable predictions of vertical movements, tilts and strains. But problems are, typically, not with average values, they are with the unexpected, the extremes: what Nassim Taleb brilliantly named the 'Black Swans'. And, as described in his later book, most present-day subsidence prediction assessments are part of a Fragile System, these being systems that are sensitive to the unexpected. The problem is that something unusual happens – usually. This paper summarises situations in NSW associated with mine subsidence where the unusual happened, some with quite serious consequences, and others with benefits to both the mining companies and the environment, and seeks to take a small step towards a more honest treatment of subsidence engineering.

This paper does not deal with sub-surface movements and groundwater impacts.

1. Introduction

This paper arises out of three dilemmas that we set out below.

1.1 The First Dilemma – Accurate Subsidence Predictions

Subsidence effects are reasonably defined as:
'. . . the deformation of the ground mass surrounding a mine due to the mining activity. The term is a broad one, and includes all mining-induced ground movements, including both vertical and horizontal displacement, tilt, strain and curvature.' (NSW Department of Planning, 2008).

There are, in essence, four parties to the subsidence approval process in New South Wales – the government regulators, mining companies, consultants, and community groups. They all have different interests and knowledge bases but rely on one process to present the necessary information about subsidence. The approval process is managed by the Department of Planning and Infrastructure and the scope for the required environmental impact study is set by the Director General Requirements (DGRs), from numerous government agencies. Recent DGRs have required 'accurate' predictions of the potential subsidence effects and, by the way, accurate estimates of vegetation clearing: there are, to our knowledge, no other specified requirements for accuracy.

The accurate predictions are required for vertical and horizontal movement, tilt, and strain for an unspecified number of locations. Since survey measurements are typically made at 20m intervals, and the locations of the survey lines are not known, or set, in advance of the predictions, it follows that a typical longwall panel may require, in effect, about a million accurate predictions, represented by contours and section profiles. NSW regulators have in the past confirmed the requirement for accurate predictions over the entire area of interest[1]. Other regulators have required the use of specific prediction methods – implying that only those methods are 'accurate'.

In the fields of science and engineering, an accurate[2] value implies that value reflects the actual (true) measurement. The term is not typically used by engineers for predictions, as the true value is not and cannot be known before the event. More appropriate terms are 'reliable' or 'probable'. Subsidence predictions are inherently subject to geological unknowns and geotechnical uncertainty, in what is a chaotic system.

1.2 The Second Dilemma - Subsidence Criteria

Mining companies seek to maximise extraction consistent with acceptable subsidence outcomes. With the current process, the companies have to set acceptability limits because no one else will – the regulators do not, and too many of the environmental consultants are reluctant to do so even though they claim to be capable to judge suitability if they are provided with accurate subsidence deformations.

Community groups are usually not interested in the detailed engineering of the mine – in the most they are concerned about environmental impacts, and at the extreme some are against coal mining as an economic activity.

The net result is that there are few accepted criteria for assessing acceptable subsidence impacts – the new NSW Aquifer Interference Policy probably being an exception.

1.3 The Third Dilemma – Our Inability to Deal with Uncertainty

Daniel Kahneman was awarded his Nobel Prize for, amongst other things, demonstrating the limitations of rational thinking in we humans, and our inability to deal with statistical reality. One of the searing chapters in his recent book is titled *The Illusion of Understanding*, from which the following is extracted:

> 'You cannot help dealing with the limited information you have as if it were all there is to know. You build the best possible story from the information available to you, and if it is a good story you believe it. Paradoxically, it is easier to construct a coherent story when you know little, when there are fewer pieces to fit in the puzzle. Our comforting conviction that the world makes sense rests on a secure foundation; our almost unlimited ability to ignore our ignorance.'

In an earlier chapter titled *The Law of Small Numbers* Kahneman also points out our severe limitations in dealing with statistical reality and shows that:

> '. . . even sophisticated researchers have poor intuitions and a wobbly understanding of sampling effects'.

Taleb (2013), of Black Swan fame, introduces the concept of 'Anti-Fragile', being systems that gain from disorder[3], and he expounds on the difficulties arising from Fragile systems, which cannot cope with outliers.

Using his idea we think that the present situation can be categorised as follows:

(i) A regulatory system that is Fragile because of the requirement for accurate predictions, so that any exceedance may lead to an attack on the credibility of the predictor and, possibly, reconsideration of the approval for a mine.

(ii) Perceived robustness through inappropriate use of 'accurate' predictions, be they upper bound or something else; in inherently flawed risk evaluations.

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[1] One suggested a new concept: 'accurate worst case' – which is a contradiction in terms.

[2] Accurate, 'in exact conformity to truth; free from error or defect' – The Macquarie Dictionary

[3]AntiFragile systems are more than just robust, they can benefit from uncertainty.

There appears to be reluctance to move to an alternative, hopefully, Antifragile system that acknowledges geological reality, incorporates the limitations and capabilities of geotechnical engineering in a collapsing environment[4], accepts uncertainty, and determines how to benefit from such uncertainty.

2. Predicting Subsidence Using Applied Mechanics

The prediction of subsidence deformations using geotechnical applied mechanics is substantially limited by the knowledge of, and parameters for[5], prediction of deformations in a three-dimensional blocky rock mass.

This does not mean that analytical geotechnical modelling is of no value. Substantial value is gained from elastic theory, Voissoir beam analyses, and jointed finite element or discrete element analyses (Seedsman, 2010, Keilich, 2009). These are a means for engineering understanding and intelligent design of longwall layouts. It is just that they cannot predict accurately.

For the present we have to rely on our limited analytical tools and, heavily, on the use of heuristics[6]:

> *'Heuristics are simplified rules of thumb that make things simple and easy to implement. Their main advantage is that the user knows that they are not perfect, just expedient and is therefore less fooled by their powers. They become dangerous when we forget that.'* (Taleb, 2012)

3. Ordered, or Systematic, Surface Subsidence

The term Ordered Subsidence is defined as that part of the deformation field that can be reasonably expressed by a continuous function.

The state of the art in subsidence prediction is to propose the general shape of distribution of vertical movement by way of a continuous function, and then tilts and curvature are the first and second derivatives of the vertical function. Arbitrary assumptions are needed to predict inflection points, maximum tilt, profiles and surfaces (some assume a Gaussian curve; Mine Subsidence Engineering Consultants adopt a multivariate curve with 11 parameters). Strain is then empirically related to curvature. Cracking is interpreted from the predicted strains.

Whether there truly is Ordered Subsidence is debateable, but it is a useful concept as long as one keeps in mind variability, which for convenience is placed in the category of Disordered Subsidence, as discussed below.

4 Sources of Variability – Disordered Subsidence

4.1 Geology

It is obvious that the geological strata between the level of mining and the surface have substantial impact on the amount and pattern of surface subsidence. It is well known in the relevantly simple horizontally bedded strata of the Sydney Basin that, for a given longwall geometry and depth, the maximum settlement in the southern coalfields is different from the Central Coast to Newcastle area, which is different again from the western coalfields through to Ulan. These differences represent changes in the stiffness and strengths of the conglomerates, sandstones and shales that form the Permian strata above the coal seams.

However, in addition to the broad differences in the horizontal strata, the magnitude and patterns of subsidence are impacted by the presence of faults and joints swarms, both at depths and particularly

[4] Most geotechnical engineering is directed to creating a factor of safety against collapse, because failure is normally unacceptable, and failure mechanics is chaotic. Subsidence engineering exists in this difficult environment.

[5] Geology in three dimensions; joint and fault locations; mass moduli; in-situ stresses; joint, bedding and fault normal and shear stiffnesses; joint, bedding and fault shear strengths; groundwater pressures; and then the big one – the chaotic development of fractures in a brittle material.

[6] What is sometimes loosely referred to as 'engineering judgement' is actually an ill-defined heuristic.

near the surface. Faults are not perfectly planar and are not laterally continuous surfaces. This means that faults at seam level cannot simply be projected to the surface or vice-versa. Furthermore, faults that may impact of surface subsidence if mined through by the longwall face will only be detected during the mining operation and certainly not by the initial resource drilling. The location of joint swarms are basically impossible to predict.

The very nature of these geological influences means that there is variation in even ordered subsidence across the Sydney Basin, and the impacts of faults and joint systems even raise the question as to whether there is such a thing as ordered subsidence.

4.2 Wrinkles in flat terrain

Holla and Barclay (2000) discuss the 'Tahmoor Wrinkle' which formed in shales and fine grained sandstones of the Wianamatta Group, which overly the more thickly bedded Hawkesbury Sandstone. Considering how a subsidence profile and bedded units may interact (Figure 1), it is easy to understand how such 'wrinkles' are common.

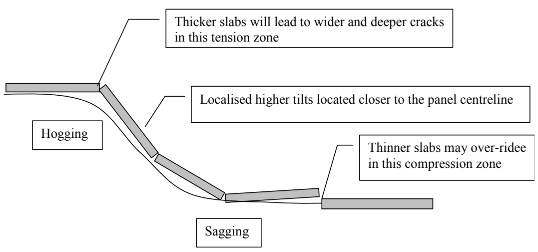

Figure 1 **Disordered subsidence in flat terrain**
Agioutantis Z and Karmis M 2013 SDPS - Surface Deformation Prediction System for Windows, Version 6.1M.

A similar 'wrinkle' occurred in 2010 across Appin Road and through a chicken farm above a Westcliff longwall. This may, or may not, have been associated with a near surface fault.

A more substantial fault caused disordered subsidence along the Cataract tunnel, above Appin Colliery longwalls (Swarbrick et al, 2007).

Similarly, in 2010, excellent monitoring by David Christie recorded shear displacements across a near surface fault transgressing the main southern rail line above the 700 series longwalls of Appin colliery.

4.3 Topography

4.3.1 Valley closure and valley floor cracking

The kinematics of a bedded/jointed rock mass indicates that in the vicinity of topographic depressions there will be translation along bedding surfaces.

Keilich (2009) modelled the mechanism proposed by Seedsman and Dawkins (2006) to confirm that rotation of joint-bounded blocks in a convex deflecting layer can cause lateral translation and 'upsidence' away from the centre (Figure 2). This combines with concentration of high horizontal stresses in the floors of gorges exacerbate natural processes of buckling and cracking of near horizontal beds.

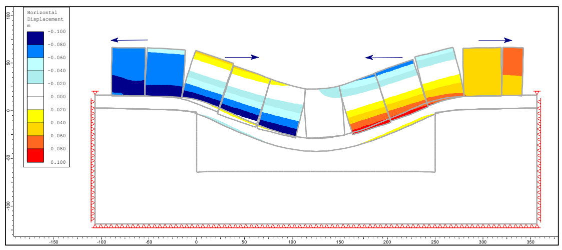

Figure 2 **Movements associated with sagging in orthogonally jointed rock**

In 1995 and 1996 the authors were experts, on opposing sides, to the Mine Warden's Inquiry into the cracking that occurred in the bed of the Cataract River, near Wilton, NSW. Ten longwall mines from Tower Colliery went underneath this stretch of river bed in the 1990s, at a depth of about 430m. During that period the rocky bed was badly cracked in very many places. Water flowing through the freshly broken Hawkesbury Sandstone precipitated iron oxide as it re-entered the water course. Locally a significant portion of baseflow was lost down cracks to reappear further downstream. Methane gas erupted in some places along the river, at one point measured at 20 litres per second. The second author was present when a 40m stretch of the river was set alight and remained burning for several minutes. Ten years later some vents were still active, and the river quality in periods of low flow had not recovered to pre-mining high flow conditions.

Cataract River was not unique. At about the same time there was cracking in the Bargo River above

Tahmoor Colliery longwalls, and since then there has been cracking in the Georges River and the Woronora Rivulet.

Nowadays it is accepted that subsidence impacts from longwall mining under river systems are substantially unpredictable, and may be severe. Unpredictability which may have costly financial or public relations impacts should be avoided and, appropriately, Illawarra Coal now plans its longwall layouts so as not to pass under, or close to, the significant gorges in the Southern Coalfields. There remains the challenge of defining 'close' and 'significant'.

4.3.2 Cliff lines

As shown in Figure 3, in November 1930 a massive crack appeared for a length of 200m behind the cliff line at what was known as Dogface Rock at Katoomba. This became a great tourist attraction; lights were set up and tourist coaches came from Sydney hoping to see a collapse. Nothing happened for months and interest fell away. At 4am on 28 January 1931 residents of Katoomba were woken by rumblings and earth tremors; the front slab of the cliff had fallen, depositing about 40,000 cubic metres of rock in the valley below.

Figure 3 **Tension crack at Dogface Rock, Katoomba, January 1931**

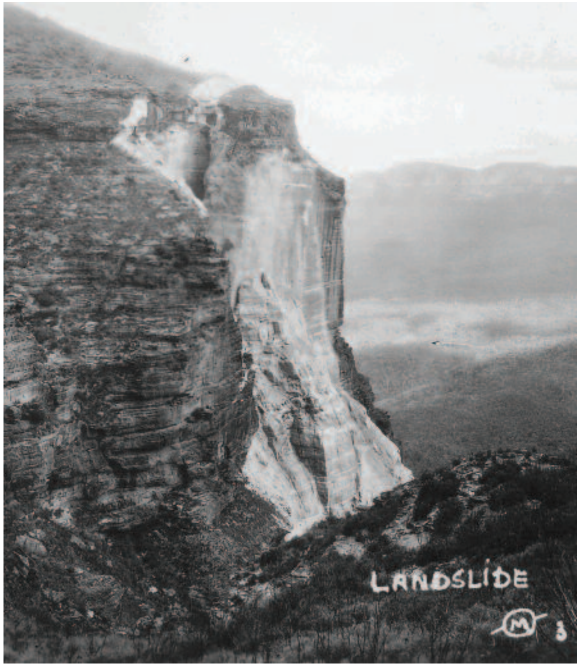

Figure 4 **The first Katoomba collapse, 28 January 1931**

At the time, and for the best part of 50 years after this collapse, it was taken by most to be a natural event. A few in the mining fraternity thought otherwise, but kept very quiet as this would not have been good press. The truth was that the collapse was triggered by pillar recovery in the Katoomba Colliery in the area of workings reopened in 1925 (Figure 5 - see over).

In 1965 an even more spectacular cliff collapse, of about 30 million tonne, occurred at Nattai North. Collapses continue to this present day, with falling rock just reaching the water's edge of Warragamba Dam (Figure 6 - see over). The authors do not know what all was said in the media at the time, but note that a search of the Sydney Morning Herald archives reveals no mention of this event. It seems that only with the publication by Pells, Braybrooke, Mong and Kotze (1987) that it became acknowledged that this and many other cliff collapses were subsidence impacts. Thereafter consideration of such facets became incorporated in Environmental Assessments of proposed underground coal mining activities.

The 'Black Swan' here was the extreme impacts of steep terrain on the predicted tilts and strains

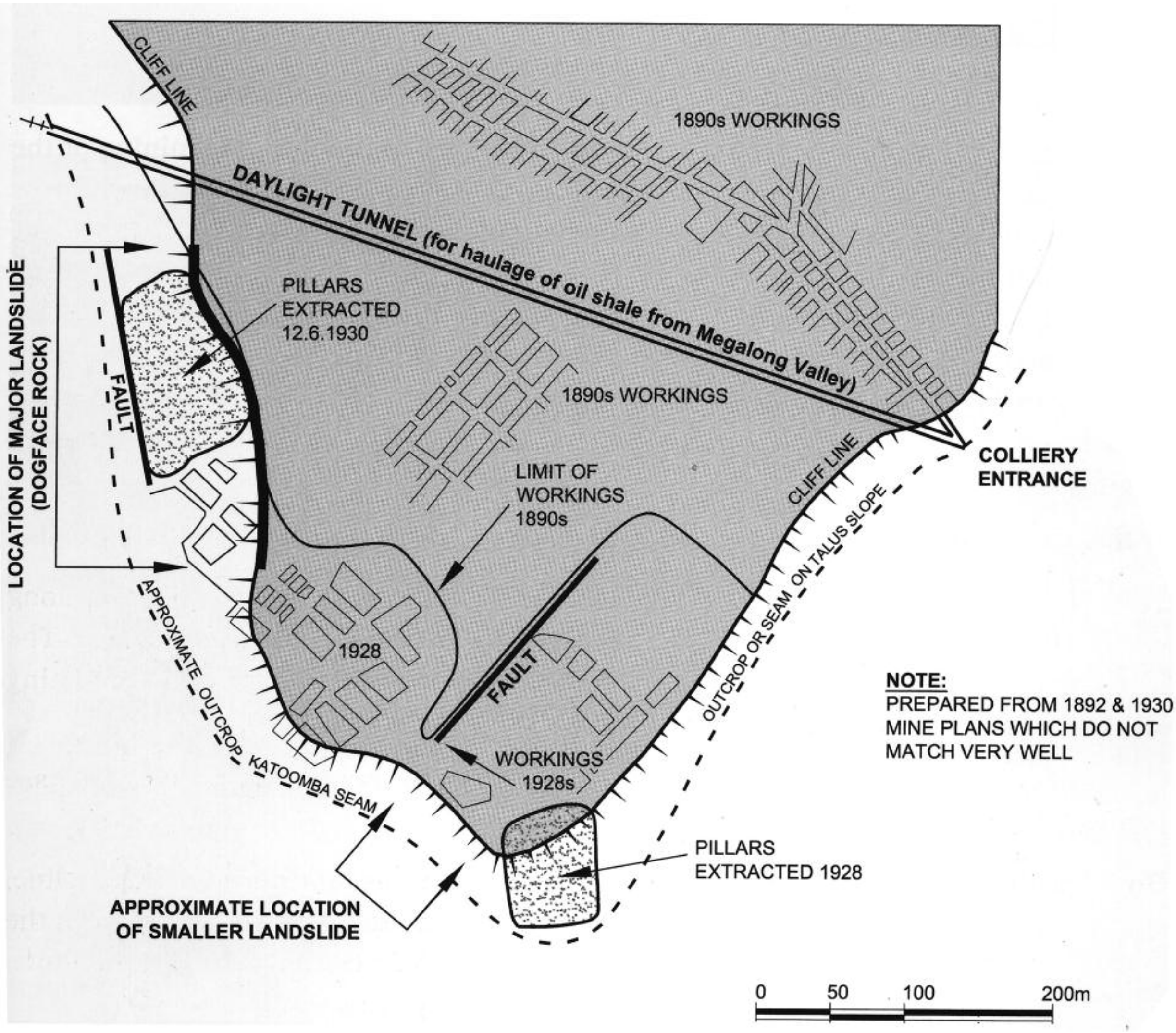

Figure 5 **Areas of pillar recovery in 1930 within the Katoomba colliery**

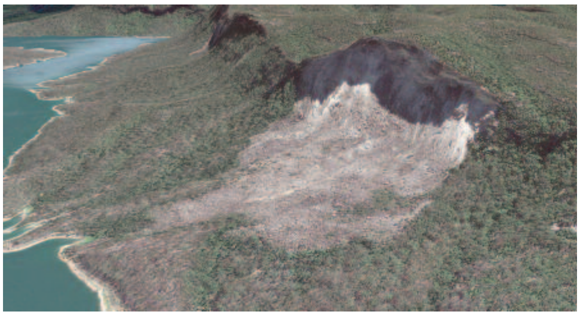

Figure 6 **Collapse at Nattai North**

Figure 7 **Slope failure in Sugarloaf State Conservation Area, late 2013**

arising from underground coal mining, particularly longwall mining. This is a matter still not being properly recognised as evidenced by the 2013 cracking and land sliding in the Sugarloaf State Conservation Area above the West Wallsend longwalls, where the extent of damage was a surprise (Figure 7).

4.4 Chain pillars

Where longwall extraction is conducted at depth (or with narrow panels such that there will be spanning units higher in the overburden sequence) the sag deflections directly above the extraction panels are small and the significant surface subsidence develops above the chain pillars. This pattern has been referred to as trough subsidence, as illustrated in Figure 8.

A close inspection of subsidence cross lines in this case reveals that there are higher tilts and strains over the solid coal side of the first panel and of the last extracted panel (Figure 8). A simple geometric analysis suggests that the higher tilts may be due to the block rotation of the overburden from the solid coal onto the adjacent chain pillar. For example, the case in Figure 8 involved 150m wide panels and the subsidence on the chain pillar was about 0.8 m – this implies a tilt of 5mm/m, which would be superimposed on the 2 mm/m – 3 mm/m maximum tilt for the individual panels. From this it follows that predicting the deformation above the chain pillars is critical to understanding tilt and curvature.

Modern longwall mine design seeks to minimise the width of chain pillars so that resource recovery is increased and the amount of roadway development is reduced. In practice the result is often a chain pillar close to its yield condition at the tailgate end of the retreating longwall face. Pillar stresses subsequently increase as the face retreats with the result that the chain pillar is well into its yield zone. From a geotechnical perspective, the modulus of deformation of a yielded pillar is substantially less than the elastic modulus and there will be a step increase in the deformation of the pillar (Seedsman 2004). Quantification of this behaviour warrants further research.

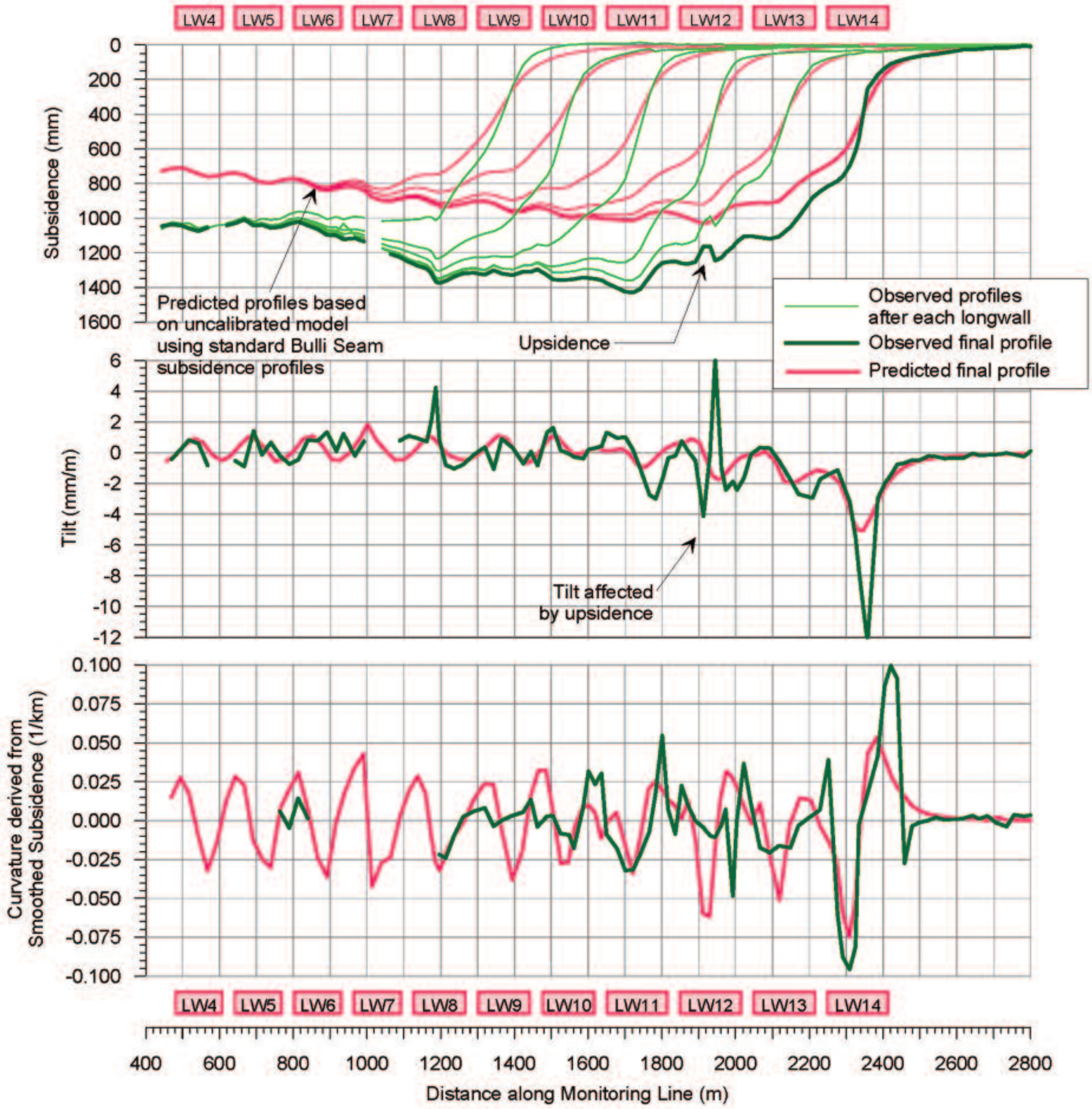

Figure 8 **Subsidence at Metropolitan colliery (MSEC, 2009)**

5. Resulting Scatter in Databases

5.1 Ordered Subsidence

The standard approach is to fit a smooth curve to cross-line and centre-line data and to use this for predictions for a new mine layout. A 20mm threshold is adopted based on perceptions of survey accuracy, shrink/swell of clay rich soils, and the recognition that associated impacts are small.

The key parameters for the smooth ordered subsidence curve using the Holla (1985) methods and influence function methods such as SDPS (2014) are the maximum vertical subsidence, the maximum tilt, the location of the maximum tilt with respect to the edge of the extraction panel, parameters to estimate the maximum tensile and compressive strains, and the angle of draw from the edge of the extraction to the point of 20 mm of vertical movement. The details of the MSEC (2007) system are unpublished except to note the use of 11 coefficients in 5th order polynomial.

All the key parameters mentioned in the previous paragraph are site specific. There are different compilations of the parameters for different coal fields and Figure 9 summarises data presented by Holla (1987, 1991) and Holla and Barclay (2000) for the New South Wales coal fields. The data indicate that there is approximately a 30% variability when selecting values for any of the key subsidence parameters. This highlights the futility of expecting accurate predictions. It should be noted that plus-minus 30% accuracy in the prediction of deformations compares well with other geotechnical ventures (Morgenstern 2000).

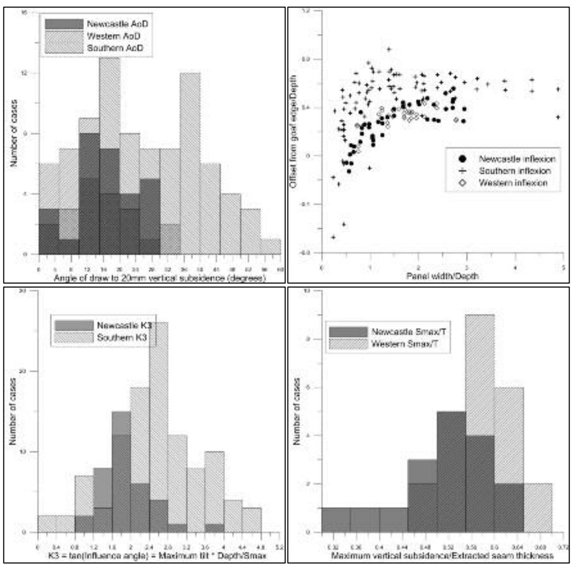

Figure 9 Variability in database for key subsidence parameters

For high width to depth ratios (so called 'supercritical' extraction), Figure 9 indicates that the recorded variability is approximately:

- Smax/T: 0.55 to 0.60
- Goaf offset: 0.1 to 0.3
- tanB: 1.75 to 4.0
- Strain/curvature: 0.08 to 0.15

Keeping Smax/T constant at 0.6, Figure 10 shows the variability that is implicit in predictions for panel cross line. While the individual parameters may be plus-minus 30%, it is clear the possible range of outcomes is substantially greater. Note that in this figure the curves are symmetrical – this is not necessarily the case, as the variation in the database includes data on asymmetric profiles.

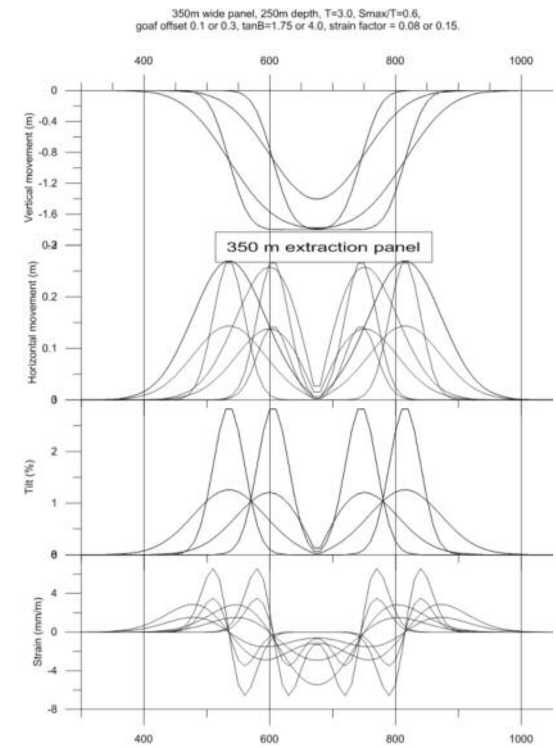

Figure 10 Variation in prediction of subsidence along a cross-line

Another important point is that while the maximum, and range of values, can be predicted with an accuracy of about 30%, the predicted locations (specific Eastings and Northings) do not have even this level of accuracy. It follows that contour and other graphical presentations should only be used to communicate one possible set of possible outcomes. The predictions, be they mean or so'-called 'worst case' for a specific surface location, could equally be the predictions for any other nearby location, possibly up to 100m away.

From a mining company's perspective the use of worst case', region-specific, database-based predictions can be uneconomic.

This is illustrated by data from the Newcastle coalfield as summarised in Figure 11. The figure shows the Holla (1986) compilation of the maximum vertical subsidence, as well as the band of predictions based on an incremental profile method developed specifically for the Cooranbong Extended project (Waddington & Kay 1998). Also shown in the figure are recent data from the nearby mines at Mandalong and Awaba that have been designed using geotechnical considerations of the presence of massive conglomerate units in the overburden. Clearly, the use of the typical worst case approaches – the maximum expected maximum subsidence – could have significant impacts on mine planning.

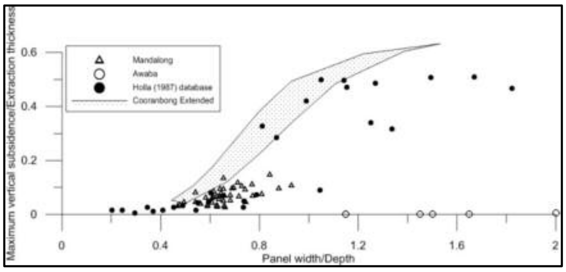

Figure 11 **Impacts of stiff spanning strata used in layout design, Central Coast-Newcastle region**

5.2 Limitations in the construction of the database

The subsidence databases, and typical graphs of subsidence, relate to cross lines, and it is important to note that centrelines usually show variation. As an example, Figure 12 is a centreline settlement for the case of a wide panel at shallow depth. Settlement is irregular, varying between 1.25 m and 1.85 m, or +/- 14% about the mean. In the field, stepped cracks about 100mm – 200mm high were observed. The values included in any cross-line database depend on where the cross line crosses a centreline. Some of the variability in Figure 8 may be readily explained by this simple example.

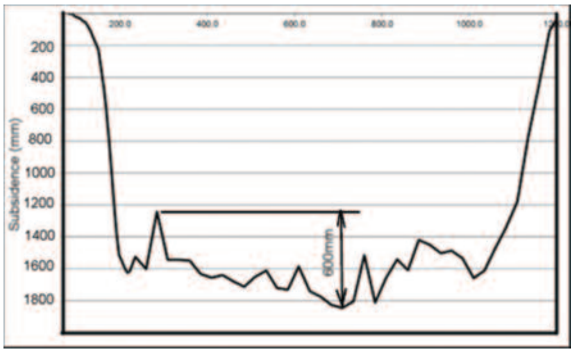

Figure 12 **Variability in subsidence along the centreline of a longwall panel with sparse or no soil cover**

5.3 Vertical deformation above an isolated panel (subcritical)

The relatively low maximum vertical subsidence developed above panels with low width/depth ratios (so called subcritical behaviour) is related to arching within the overburden. Mine designs using subcritical geometries are often adopted in the face of surface subsidence constraints and hence are more exposed to unacceptable outcomes if the design assumptions are faulty.

Figure 13 shows the simple model developed for Mandalong and its application to a geometry similar to that in the NSW Southern coalfield. It clearly demonstrates how the deflection of a beam

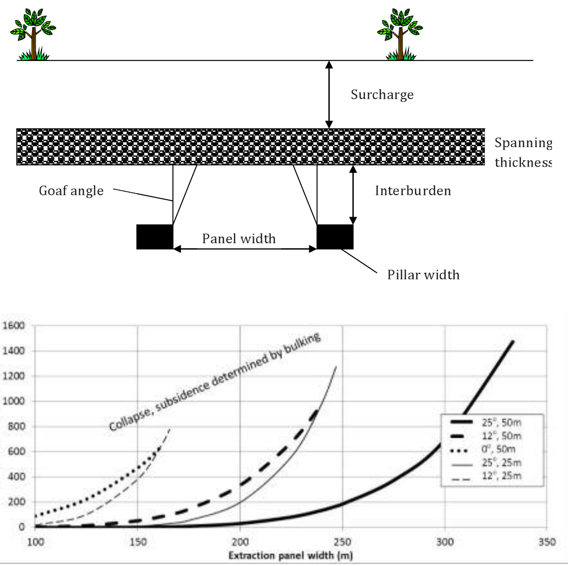

Figure 13 **Changes in predicted deflection with variation in two key input parameters**

(maximum vertical subsidence) depends on the goaf angle (controlled by the joint field) the thickness of the spanning unit, and the extraction width. The strongly non-linear behaviour highlights the uncertainties of increasing panel widths in the subcritical zone.

6. Way forward

Subsidence deformations are the result of an interaction between the geometry of the mine, the engineering geology of the rock mass, and the redistribution of the vertical and horizontal stresses, the spacing of bedding planes, the spacing of joints and the location of the non-flat topography. There is enough geotechnical engineering knowledge to understand the overall deformation patterns, and to know that accurate prediction is futile.

The way forward is suggested as follows:

(i) Adoption of a regulatory system that accepts uncertainty and dispenses with the false idea of accuracy.

(ii) Development of subsidence impact criteria that properly include economic constraints in mining and all environmental considerations, and set project-specific values in a similar way to project-specific noise or dust levels in surface operations. These should be set with no reference to the subsidence predictions.

(iii) With defined criteria, it is then possible to design panels and pillars with cognisance to levels of uncertainty. These uncertainties in settlement, tilt and strain must be expressed in a way that can be combined with uncertainties in consequences, i.e. cliff collapses, valley floor cracking, damage to infrastructure.

(iv) Address risk not in the way currently adopted by the engineering fraternity, but as viewed by The High Court, and as described by Robinson (2014) as 'So Far As Is Reasonably Practicable'.

Mine owners can then manage risk by:

(i) Elimination – based on standoff distances from key surface features;

(ii) Substitution – narrower longwalls and wider pillars;

(iii) Engineering controls – start and end lines, barrier pillars;

(iv) Administrative controls – monitoring.

Anticipating the subsidence prediction problem-faced by specialist subsidence engineers, by about 2300 years, Aristotle is said to have said:

> *'The more you know, the more you know you don't know.'*

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