PROBABILISTIC RISK ASSESSMENT OF MINE SUBSIDENCE

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ABSTRACT

Instability of coal pillars within disused underground mines is an important cause of mine subsidence affecting surface developments. Uncertainty and variability of materials, dimensions and loads affects our ability to assess the stability of these coal pillars. Traditionally, these parameters have been quantified using a deterministic approach. Variables affecting coal pillar stability were probabilistically analysed to determine the factor of safety and probability of failure. Two case studies in the Newcastle region were undertaken in order to simulate real situations. There are two types of uncertainty that need to be modelled: aleatory and epistemic. Aleatory uncertainty is ‘random’ uncertainty or natural variability. Epistemic uncertainty is uncertainty due to the lack of information. The probabilistic risk assessment method used in the case studies provided an assessment of aleatory and epistemic uncertainties. In the assessment of the stability of pillars in old abandoned workings, both types of uncertainty are encountered. Hence, the UNSW Pillar Design Method under-estimates the probability of failure as it ignores epistemic uncertainties of old pillars in abandoned mines. It was also found that there is no direct relationship between factor of safety and probability of failure. It was revealed that the level of uncertainty can have a significant impact on the probability of failure of a section of workings. The results of this study may lead to a requirement that developers use probabilistic methods to verify that proposed developments are subject to an acceptably low risk of subsidence damage.

1 INTRODUCTION

Much of Newcastle and the Lower Hunter region have been undermined by underground bord and pillar coal mining. The stability of the remaining pillars is an important issue affecting surface development. Economic development in the region is leading to a demand for larger buildings putting increased loads on the remaining pillars in the abandoned mines. Consequently, Newcastle City is a particular area of focus for the Mine Subsidence Board of NSW, who need to ensure that these 19th and 20th century workings will remain stable under 21st century developments.

A coal pillar will fail if the load it is supporting is greater than its strength. A range of factors affect the strength and loading of coal pillars. These include: pillar width, mining height, coal strength, roof and floor strata conditions, the gap between pillars, density and depth of the overlying materials. In many cases, precise values of these factors cannot be obtained due to inaccurate and insufficient records. In these cases, a range of possible and probable values exist. To be able to effectively assess the stability of coal pillars where exact values are not known, probabilistic methods should be employed (e.g., Christian and Baecher (2001). Hence, Duncan (2000) suggests that both the factor of safety and the probability of failure should be taken into account when undertaking a geotechnical analysis as both provide insight into the level of safety of a system. The principles of probabilistic risk analysis are well documented and are applicable to a wide range of engineering systems (e.g., Stewart and Melchers, 1997). Stewart and Love (2005) have shown the importance of including uncertainty in mine workings dimensional uncertainties when conducting a risk assessment of the level of stability of the existing pillars of mine workings beneath a high-rise development in the Newcastle area. This paper will present a more detailed probabilistic risk assessment that will enable the probability of failure (instability of existing coal pillars) to be calculated.

There are two types of uncertainty that need to be modelled: aleatory and epistemic. Aleatory uncertainty is ‘random’ uncertainty or natural variability associated mainly with the high spatial variability of geologic material properties. Epistemic uncertainty is uncertainty due model accuracy and lack of information about parameter estimation. The level of epistemic uncertainty can be reduced by obtaining more information, such as drilling extra boreholes or undertaking additional laboratory testing. The level of epistemic uncertainty resulting from a lack of knowledge of what is under the surface will vary from site to site. There is a need to include both types of uncertainty in a probabilistic risk assessment of mine subsidence. The empirically derived UNSW relationship between factor of safety and probability of failure (Galvin et al. 1998) provides for some assessment of aleatory uncertainty only. However, in the assessment of the stability of pillars in...
old abandoned workings, both aleatory and epistemic uncertainties are encountered. Hence, the UNSW relationship underestimates the probability of failure as it ignores epistemic uncertainties.

The present paper will use probabilistic risk assessment methods to predict the probability of failure of old, abandoned bord and pillar workings considering aleatory and epistemic uncertainties. Two case studies in the Newcastle region were undertaken in order to simulate real situations: (i) Borehole Seam under Newcastle West and (ii) Victoria Tunnel Seam under Charlestown. Mining maps, results from previous geotechnical investigations, historical documents and expert opinions were used to develop probability distributions for each parameter. The probability distributions generated were used in a Monte-Carlo simulation analysis to predict the probability of failure or instability of the existing coal pillars. A sensitivity analysis was conducted, analysing the impacts of the probability distributions of each individual parameter on the overall stability of the coal pillar. Probabilities of failure were compared with the UNSW relationship. Finally, the utility of the predicted risks for consent authority decision-making to ensure that proposed developments are subject to an acceptably low risk of subsidence damage are discussed.

2 EXISTING PRACTICE: UNSW PILLAR DESIGN METHOD

At the present time, the most common method used for the design of new coal pillars, or the assessment of existing pillars, is the UNSW Pillar Design Method developed by Galvin, et al. (1998). The method covers the assessment of strength of rectangular and diamond shaped pillars. This is now described.

\[
R = 8.60 \left( \frac{w \Theta}{h} \right)^{0.51} \frac{1}{h^{0.84}} \quad \text{for } R \leq 5
\]

\[
R = 27.63 \Theta^{0.51} \left[ \frac{w}{0.22h^{0.11}} \right]^{2.5} \left( \frac{w}{5h} \right)^{-1.1} 1.1 \quad \text{for } R > 5
\]

where \( \Theta = 1 \) for \( w/h < 3 \)

\[
\Theta = \frac{2w_2}{(w_1 + w_2)} \quad \text{for } 3 \leq w/h \leq 6
\]

\[
\Theta = \frac{w_2}{(w_1 + w_2)} \quad \text{for } w/h > 6
\]

The load acting on the coal pillar is determined by using the tributary area method:

\[
S = \rho H \left( \frac{w_1 \sin \theta + b_1)(w_2 + (b_2 / \sin \theta))}{w_1 w_2 \sin \theta} \right)
\]

where \( w_1 = \) minimum pillar width,

\( w_2 = \) maximum pillar width (or pillar length),

\( \theta = \) angle between adjacent sides (\( \leq 0 \) for this paper),

\( w = w_1 \sin \theta, \)

\( h = \) pillar height,

\( \Theta = \) a dimensionless factor,

\( b_1 = \) roadway width (with respect to pillar width),

\( b_2 = \) roadway length (with respect to pillar length),

\( \rho = \) density of overburden, and

\( H = \) depth of overburden.

The strength and load are both given in terms of stresses. The factor of safety (FOS) is thus strength divided by load which equates to \( R/S \).

There are a number of assumptions and limitations of this method: (i) 'punching' failure is not considered, (ii) tributary area for loading is only a good approximation if the pillars are uniformly loaded by the overburden and are not subject to abutment or other loadings and are of similar geometry. Coal pillars with significantly different dimensions, have different stiffnesses, with the larger pillars attracting more load. This leads to a sharing of load between pillars (Hawkins, 2005), (iii) it ignores the effect of geology of the roof and floor yet this plays a part in the strength of coal pillars - strong rock roof and floor materials will result in significantly higher pillar strengths than pillars with the same geometry and weaker surrounding strata (Gale, 1999), and (iv) it assumes good floor and roof conditions.

The probability of failure (\( p_f \)) can be calculated from FOS by the empirical expression developed by Galvin et al. (1998):
\[ p_f = 1 - \Phi \left( \frac{\ln \text{FOS}}{\sigma} \right) \quad \text{FOS} \leq 2.1 \]  

where \( \Phi() \) is the standard normal distribution function and \( \sigma \) is the standard deviation. The standard deviation is based on the power model of pillar strength using the University of New South Wales (UNSW) Australian database, thus \( \sigma = 0.157 \). The relation between \( p_f \) and FOS is shown in Figure 1.

Figure 1: UNSW Relationship between Probability of Failure and Factor of Safety.

There are two issues that need to be considered when using Eqn. (4):

1. It should be noted that the expression for \( p_f \) is based on an Australian database of failed pillars, with a highest recorded FOS of approximately 1.3 (\( p_f = 0.047 \)). The method used by Galvin et al. (1998) to extrapolate probabilities of failure for values of FOS higher than 1.3 is dependent on the upper tail of the fitted probability distribution (in this case lognormal). As such, probabilities of failure below 0.047 are highly sensitive to the fitted probability distribution and so are subject to considerable uncertainty.

2. There appears to be no definition as to the reference period associated with the factor of safety or probability of failure. The term ‘probability of failure’ should always specify over what time period it refers to – e.g., annual \( p_f \), 50-year \( p_f \), etc. For an engineering component with statistically independent failure events and low annual probability of failure, a 50-year \( p_f \) is not significant. The factor of safety as defined by Galvin et al. (1998) is time-invariant (constant with time). It is much more likely, however, that the factor of safety is a time-dependent variable which might decrease as mine works age increases (if there is deterioration), but might possibly increase if there is no deterioration. Assuming no deterioration, a longer survival age indicates that the pillars have survived ‘proof loading’ and so are less likely to fail at some future date. Computational models to include the effects of survival age and deterioration on the time-dependent reliability of structural systems have been developed (Stewart and Rosowsky, 1998; Stewart, 2001), and in principle, similar computational techniques could be developed for other load-capacity systems such as mine workings.

Although Galvin et al. (1998) has derived an empirical relationship between factor of safety and probability of failure, there is often a lack of invariance with such relationships. For this reason, no such relationship exists or has been proposed for any structural system. The standard approach is to calculate the probability of failure considering aleatory and epistemic uncertainties. For example, failure of a load-capacity element occurs when the load effect (S) exceeds the resistance (R). The probability of failure is then the probability that a load exceeds a resistance (see Figure 2):

\[ p_f = \Pr(R \leq S) = \Pr(R - S \leq 0) = \Pr[G(X) \leq 0] \]  

where \( G() \) is the limit state function (e.g., \( G = R - S \)) and \( G() = 0 \) defines the boundary between the ‘unsafe’ and ‘safe’ domains. In general, the resistance and load effect are dependent on the vector of variables \( X \) and the limit state equation(s) is derived from predictive models of loading and capacity. More general formulations including system and time-dependent effects are described elsewhere (e.g. Stewart and Melchers, 1997).
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In the present case, the limit state is

\[ G(X) = ME \times FOS \]  \hspace{1cm} (6)

where ME is the model error to represent uncertainty in resistance and load analysis and FOS = \( R/S \). As discussed above, there are a number of assumptions and limitations associated with the calculation of FOS. For structural resistance and analysis predictions this is to be expected. For example, the Danish Road Directorate guidelines for reliability assessment of existing structures (DRD 2004) recommends that a structural analysis model with 'low uncertainty' (lowest model error) has accuracy of \( \pm 15\% \) which leads to mean(ME)=1.0 and COV(ME)=0.10 (coefficient of variation COV = standard deviation divided by the mean). The statistics assume that there is no bias (systematic variation) in the modelling techniques used. It is reasonable to assume that the model used to predict factor of safety has low uncertainty. If the model is deemed less accurate then COV(ME) may increase to 0.20 or higher.

![Load Effects (S) vs Resistance (R)](image)

Figure 2: Variability of Load and Resistance.

In the present case, there is uncertainty and variability associated with: pillar dimensions, roadway dimensions, and density and depth of overburden. Other uncertainties such as coal strength, changes in geologic conditions, loading, water level, etc. are not considered. Factors of safety and probabilities of failure are calculated for two sites in the Newcastle region. These are now described.

3 CASE STUDY 1: NEWCASTLE WEST

3.1 SITE CHARACTERISTICS

The site chosen for the case study is a panel of workings in the Borehole seam, underlying Newcastle West. At the present time, Newcastle City (including Newcastle West) is of great interest to developers. Development plans are allowing for the construction of taller and larger buildings. These new developments are placing additional loads on underlying coal pillars. The case study area encompasses a section of the No. 2/Hamilton Pit mined by the Australian Agricultural company in the second half of the 19th century. The No.2/Hamilton Pit was mined between 1861 and 1901, with the case study area taking in an area mined between 1890 and 1892. It is known that the pillars in the case study area are still standing. The Borehole seam is bounded by competent roof and floor materials, hence pillar failure is the most likely failure mechanism and it is most likely that the pillar will generate enough confinement for the UNSW method for the determination of pillar strength to be valid.

Records from the time of mining provide a limited picture of the geometry of the workings. Record tracings were made on large pieces of linen showing information including plan dimensions, time of extraction and a typical working section. The accuracy of the record tracings is a significant issue in assessing the stability of the pillars. For each site, three different maps were produced; working plans, a royalty map and an abandonment map. It has been found that there are often contradictions between maps. Additional uncertainties come from the stretching of the linen records which have been stored hanging for many years. Correction of record tracing copies used by the Mine Subsidence Board and geotechnical engineers has been attempted however the accuracy of these corrections may be questionable.
3.2 PARAMETER STATISTICS

A map of the pillar layout is shown in Figure 3. The panel analysed is circled. The hatched area in the South-West corner of the map identifies areas where second workings have been undertaken. The white area in the North of the map shows an area that hasn’t been mined. The black lines indicate contours of the depth of the coal seam below the surface.

Figure 3. Newcastle West Case Study Pillar Layout

As can be seen by Figure 3, three different types of pillars have been used;

i. Large long pillars (Long pillars);
ii. Long pillars which have been cut in two (Half pillars) and
iii. Little pillars separating the rows of long and half pillars (Little Pillars).

For the case study, these have been treated separately. Failure of one pillar may lead to the failure of many pillars, or a ‘pillar run’. As a result, which may be conservative in cases where ‘pillar run’ will not occur, it is assumed that the panel is only as safe as its weakest pillar, with the probability of failure being the probability that any pillar will fail and the factor of safety being the factor of safety of the weakest pillar. A variety of sources were utilised in estimating the dimensional data for the coal pillars.

Frequency histograms were compiled from the data. While it would be preferable to fit probability distributions to the data, the data was often scattered and multi-modal and so standard probability distributions could not closely approximate the measured data. Hence, the reliability analysis to follow was based on the probability histograms. As dimensional measurements were taken from tracing records, there is likely to be some uncertainty and error in these measurements. If it is assumed that measurement uncertainty and error is ±5% then it follows that this measurement error is modelled as a normal distribution with mean of unity and a COV of 0.05.

3.2.1 Pillar and Roadway Dimensions and Overburden Depth

Pillar width and length and roadway width and length were determined by taking measurements from mining maps held by the Mine Subsidence Board. These maps were derived from the original record tracings. The overburden depth was obtained from the Mine Subsidence Board’s mapping system. Additional information obtained from boreholes drilled by Coffey Geosciences (Coffey, 2004) suggested that the Mine Subsidence Board’s overburden depth data has an accuracy of approximately plus or minus one metre (approximately ±5%). The number of measurements was 24, 70 and 46 for long, half and little pillars, respectively. The probability histograms of measured dimensions are shown in Figures 4, 5 and 6 for
long, half and little pillars, respectively. For each probability histogram the left-side y-axis refers to count and the right-side y-axis refers to probability density.

Figure 4: Probability Histograms - Long Pillars.

Figure 5: Probability Histograms - Half Pillars
3.2.2 Pillar Height

Very little information about the height of the coal pillars was available. The Borehole seam is made up of several layers. The thickness of these layers, and indeed the entire seam, varies across the region. There may be significant variations over small distances, with the seam thickness generally reducing towards the West. From historical records, the Top Band Coal was not mined, so based on borehole sections described by Hawkins (2005) the working height would be 13'11”, or 4.24 m. However, this section is not located in the case study area, and neither is any other section obtained from record tracings. Several logs were available from boreholes undertaken by Coffey Geosciences at the Southern end of the site. In many places the roof of the seam has collapsed to varying extents. Rubble (which will have bulked), and areas of roof falls make it difficult to determine the mined height. In order to overcome these problems, borehole data was used in conjunction with the working heights from record tracings and other sources. As different sources are thought to have different degrees of reliability, working heights obtained from each source was weighted according to a judgement of their reliability – see O’Rourke (2007) for further details. The probability histogram of pillar height is shown in Figure 7.
### 3.2.3 Overburden Density

The density of the overburden was determined from the results of geophysics testing of five boreholes undertaken by Coffey Geosciences (Coffey, 2004) at the Southern end of the site. It is thought that the density distributions would remain relatively consistent across the site. The overburden density was modelled by assuming a normal distribution with the same mean and standard deviation as the borehole data. That is, a mean of 25.32 kN/m$^3$ and a standard deviation of 0.41 kN/m$^3$.

### 4 CASE STUDY 2: CHARLESTOWN

#### 4.1 SITE CHARACTERISTICS

This case study examined an area of workings in the Victoria Tunnel Seam, under Charlestown. As with the previous case study, the workings are over 100 years old and are known to be standing. This case study builds on the work undertaken by Stewart and Love (2005). The case study area is shown in Figure 8.

![Figure 8. Charlestown Case Study Pillar Layout](image)

Similarly to the Borehole Seam, the Victoria Tunnel Seam has competent roof and floor strata, justifying the use of the UNSW Method for pillar strength. However, unlike the previous case study, the coal pillars are all of similar shape and size, hence the tributary area method provides a reasonable estimate of pillar load.

#### 4.2 PARAMETER STATISTICS

The pillar dimensions were quantified using values measured from mining maps held by the Mine Subsidence Board in conjunction with the values used by Stewart and Love (2005) in their analysis. The Charlestown case study was not as rigorous as the Newcastle West case study as not every pillar was measured. A representative sample was taken to obtain estimates of pillar dimensions. The pillars were all reasonably similar in size, suggesting a single design value. Measurements taken from the mining maps gave standard deviations of roughly what may be expected to be variability in mining. As such, measurement error is modelled as a normal distribution with mean of unity and a COV of 0.03. This measurement error is applied to pillar width and length, roadway width and length, and overburden depth. Pillar height was taken from Stewart and Love (2005), who used the expert advice of a senior geotechnical engineer to derive the probability histogram. Statistical parameters are shown in Table 1.
Table 1. Parameter Statistics for Charlestown Case Study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pillar Width (m)</td>
<td>9.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Pillar Length (m)</td>
<td>36.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Pillar Height (m)</td>
<td>50% 1.5 m</td>
<td>30% 1.7 m</td>
</tr>
<tr>
<td></td>
<td>15% 1.9 m</td>
<td>5% 2.1 m</td>
</tr>
<tr>
<td>Roadway Width (m)</td>
<td>7.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Roadway Length (m)</td>
<td>3.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Overburden Depth (m)</td>
<td>154.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Overburden Density (kN/m²)</td>
<td>25.32</td>
<td>0.41</td>
</tr>
</tbody>
</table>

5 RESULTS

Monte-Carlo simulation analysis is used to calculate structural reliabilities. The parameters are randomly generated from the probability histograms given in Figure 4 to 7 and Table 1. Randomly generated dimensional parameters are then multiplied by the measurement error modelled as a normal distribution with mean of unity and a COV of 0.03. The resulting factor of safety is then multiplied by a randomly generated model error (ME) with mean (ME)=1.0 and COV(ME)=0.10. The case studies assessed epistemic uncertainties in two separate locations. The Newcastle West case study reveals a high level of epistemic uncertainty, whilst the Charlestown case study shows a much lower level of uncertainty.

Figure 9 shows that the variability of factor of safety is high for both case studies. Table 2 shows the mean factor of safety and the probability of failure, as well as the coefficient of variation of resistance and load effects. The probability of failure is compared with the UNSW relationship (and its extrapolation beyond a FOS of 2.1) in Figure 10. In all cases, the probability of failure exceeds the value obtained from the UNSW relationship, in some cases by up to six orders of magnitude. It should be noted that these pillars plot in an area beyond where most of the UNSW relationship data are located and Galvin, et al. (1999) also state "extrapolation with empirical formulas is always fraught with danger." As expected, the probability of failure tends to reduce as factor of safety increases. However, the probability of failure is higher for half pillars (4.8E-8) than it is for the Charlestown case study (2.7E-8) even though the Charlestown case study has a lower mean factor of safety. This occurs because there is more uncertainty about the data needed to calculate factors of safety for the Newcastle West case study and so a higher probability of failure - e.g., Table 2 shows that the COV for loads are higher for the Newcastle West case study. Hence, the probability of failure is dependent on the mean factor of safety and the variability of input parameters and model error. These epistemic uncertainties have a significant influence on probability of failure.

![Figure 9: Variability of Factor of Safety.](image-url)
Table 2. Results of Probabilistic Risk Assessment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean Factor of Safety</th>
<th>Probability of Failure</th>
<th>COV(R)</th>
<th>COV(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Study 1 (Newcastle West)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long Pillars</td>
<td>3.82</td>
<td>2.5E-12</td>
<td>0.138</td>
<td>0.089</td>
</tr>
<tr>
<td>Half Pillars</td>
<td>3.38</td>
<td>4.8E-8</td>
<td>0.098</td>
<td>0.118</td>
</tr>
<tr>
<td>Little Pillars</td>
<td>1.40</td>
<td>0.102</td>
<td>0.109</td>
<td>0.139</td>
</tr>
<tr>
<td>Case Study 2 (Charlestown)</td>
<td>2.92</td>
<td>2.7E-8</td>
<td>0.124</td>
<td>0.052</td>
</tr>
</tbody>
</table>

Figure 10: Comparison of Probabilistic Risk Assessment Results with UNSW Relationship.

A sensitivity analysis revealed that the most influential factors affecting pillar stability are overburden density, depth of cover, pillar height and pillar width. Roadway dimensions were found to have the least impact. The effect of pillar length is dependent on the relative geometry of the pillars. The impact of pillar length on overall pillar stability was found to decrease as the difference between pillar width and pillar length increased. For details see O’Rourke (2007).

6 DISCUSSION

6.1 ACCURACY AND LIMITATIONS OF RESULTS

The difference in pillar size for the Newcastle West case study suggests that the use of the tributary area method may not be particularly accurate. The different geometries of the three types of pillars would result in differential pillar stiffnesses, resulting in a sharing of the load between pillars (Hawkins, 2005). In addition to this, a massive sandstone layer is located above the workings causing beam action to occur in this layer, assisting in the redistribution of the loads towards the larger pillars. The South-Western edge of the first case study area is bound by an area where secondary extraction has taken place and so it is most likely that the pillars in that area have failed. The pillars on the edge of this zone would be supporting additional loads as they are being wedged by the collapsed roof strata (Mackenzie and Clark, 2005). The effects of groundwater were also not considered. Many of these issues could be solved by numerical modelling.

It is recommended that future studies use numerical modelling to determine the loads acting on the pillars in the case study area. The results of the numerical modelling should be compared to the results of this study to determine the accuracy of the tributary area method. Other project specific and published data should also be compared. This comparison would enable the Mine Subsidence Board to make an informed decision of how pillar stability assessments using the tributary area method are interpreted. Notwithstanding the inaccuracy of pillar stability used herein, the paper still illustrates clearly the importance of including aleatory and epistemic uncertainties in a probabilistic risk assessment of pillar stability.
6.2 APPLICATION TO ASSESSMENT OF SURFACE DEVELOPMENTS

The UNSW relationship includes aleatory uncertainty from geological anomalies and some epistemic uncertainty from variability during mining (although this epistemic uncertainty is not properly considered as the database used in its development uses some actual and some design dimensions). For design purposes this provides a reasonable estimate of the likelihood of the success of a design, as the only uncertainties are aleatory uncertainties and construction variability. The UNSW (Australian) database contains 19 failed and 16 unfailed pillars, the combined Australian and South African data bases include 63 failed and 114 unfailed pillars. Although the database is not perfect, the relationship is probably the best available tool for assessing the level of aleatory uncertainty for Australian conditions, conditional on it being applicable for low factors of safety only.

However, in assessing the stability of older workings, there is an additional epistemic uncertainty resulting from an imperfect knowledge of the design dimensions. Hence, the UNSW relationship may need to be modified to provide a reasonable assessment of the probability of failure of old, abandoned workings due to an additional layer of uncertainty. It is thus proposed that future assessments of pillar stability for older workings consider both the aleatory uncertainties and the epistemic uncertainties. The epistemic uncertainty requires assessment on a case by case basis. This is because, as was shown with the two case studies, the level of uncertainty will vary from site to site. The level of epistemic uncertainty can also be reduced by obtaining more information through geotechnical investigation. As a result, assessment of the accuracy of the data should be undertaken using probabilistic methods when assessing the stability of coal pillars. Hence, it is proposed that the probability of failure of a pillar should be assessed based on a probabilistic risk assessment similar to that developed in the present paper. This is the situation for assessing the safety and reliability of buildings, bridges, nuclear power plants, etc. and so there is little reason why mine subsidence risks should not be subjected to a similar type of rigour. Should this method be adopted for the assessment of surface developments, developers would be required to undertake a probabilistic risk assessment to quantify the reliability of their data. The Mine Subsidence Board would assess the results and provide approval based on an acceptably low probability of failure.

The implications of this for developers are that in areas where a high probability of failure is calculated as a result of limited or unreliable data, additional geotechnical investigation may be required to gain a clearer picture of what is under the surface and hence reduce the level of epistemic uncertainty. In some cases it may be cheaper to fill in the abandoned workings and eliminate the risk, rather than to undertake expensive geotechnical investigations that may reveal worse than expected conditions.

The Mine Subsidence Board has approved developments where it can be shown that the factor of safety is significantly greater than 2.1. This is based on the assumption that the probability of failure would be much less than one in a million as described by the UNSW relationship. This research has shown that due to the uncertainty of the available data for old workings the actual probabilities of failure may be higher. A risk-based approach to decision-making requires a definition of risk and risk acceptance criteria. Risk is defined as a combination of the likelihood of an event occurring and the consequences of that event occurring (AS 4360 – 2004). In terms of the economic risk that the Mine Subsidence Board is exposed to from pillar failure, the risk is defined as the product of the probability of the failure of a pillar and the damage done from the resulting subsidence. What constitutes an acceptable risk is a contentious issue and there are differing opinions on the subject. The issue of economic risks and risk acceptance for mine subsidence is discussed in detail by Stewart and Love (2005) and Mackenzie (2006). Stewart and Love (2005) provide a preliminary framework for a risk-based approach to decision making that considers probability of failure, failure consequences, economic risks and risk acceptance criteria.

7 CONCLUSIONS

Probabilities of failure for pillar instability in old abandoned workings were calculated for two sites in the Newcastle region. The probabilistic risk assessment included the variability and uncertainty of model accuracy, pillar and roadway dimensions, cover height and overburden density. There is clearly not 100% certainty about the value of any particular design parameter. The probabilistic risk assessment method used in the case studies provided an assessment of aleatory and epistemic uncertainties. It was found that the UNSW Pillar Design Method under-estimates the probability of failure for old abandoned workings as it ignores some epistemic uncertainties. It was also found that there is no direct relationship between factor of safety and probability of failure.
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