Proc. of the 8th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Jinsong Huang, D.V. Griffiths, Shui-Hua Jiang, Anna Giacomini and Richard Kelly
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doi: 10.3850/978-981-18-5182-7_10-006-cd

Mine Subsidence Characterization and Susceptibility Mapping to Guide Risk Mitigation

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Abstract: Subsidence above abandoned coal mine workings presents hazards to people and animals. Open cracks, potholes and sinkholes around abandoned shallow mines are common. Records of subsidence related features can be assembled into spatial databases and multi-criteria analysis techniques utilized to develop susceptibility maps.In the assessment of mine subsidence risk, these maps can be used and updated to quantify the likelihood of hazard occurrence spatially. However, consideration of the probability of interaction with the hazard, as well as the vulnerability of those affected is needed to assess consequence and hence risk.A case study of mine subsidence hazard identification and development of a susceptibility map is used to demonstrate an appropriate procedure and highlight the necessity and challenges of incorporating human behavior and vulnerability into quantitative risk assessment with respect to loss-of-life and mobile elements at risk.

Keywords: Mine Subsidence; Susceptibility Mapping; Quantitative Risk

1 Introduction

Our society deems it appropriate to mine metalliferous coal to produce carbon steel. One of the legacies of underground coal mining is subsidence of the ground surface. Subsidence features may take the form of troughs, cracks, potholes and sinkholes of varying geometries, frequency of occurrence and distribution. While fatalities have occurred due to subsidence hazards, it is a rare occurrence despite the existence of numerous hazards in and around populated areas (Mackenzie 2022).

The re-purposing of mining land to other uses, such as residential development or grazing for example, changes how subsidence prone land is accessed and managed. That is, the exposed population is no longer controlled, as far as is reasonably practicable, by the mining company and the treatment of subsidence hazards may be less diligently undertaken. Furthermore, the post-mining exposed population may have less awareness of hazards yet encounter them in circumstances where they are more vulnerable.

In New South Wales, relinquishment of a mining lease requires approval from the Department of Planning and Environment. A common condition has been for the land to be ‘safe’ and ‘stable’ – both terms being absolute and enduring, and hence incapable of being strictly complied with legally. A quantified level of acceptable risk is not specified nor a duration for which the conditions are to remain.A risk-based approach is needed whereby the methodology of assessment and criteria for acceptance is more consistently applied.The landslide risk management approach (AGS 2007) is recommended as are the concepts of the individual most-at-risk and societal risk (Golder 2020) as applied to mobile elements at risk for landslides.

With an appropriate procedure in place, the challenge becomes estimating the likelihood that an individual will encounter a hazardous feature, not avoid it, and be harmed. As demonstrated by the presented case study, the use of geospatial information systems (GIS) and multi-criteria analysis (MCA) is useful for generating susceptibility maps. The usefulness of such maps relies on the quality of input data as well as the experience of practitioners to identify causal mechanisms, assign weightings to contributing factors and review the outputs.

Finally, and perhaps most challenging, is communicating the assessment assumptions, uncertainties, and findings to different audiences. Afterall, an individual’s willingness to knowingly accept risk or subject others to risk, can only be based on that individual’s appreciation of risk and uncertainty in familiar terms that allow comparison to other risk sources and evaluation of the benefits of risk taking versus the counter. In other words, being able to make an informed and educated decision.

2 Examples of Mine Subsidence Hazards

Subsidence above mine workings occurs in a strain-driven environment and typically takes the form of vertical and horizontal displacement of the ground surface by way of troughs and subsidence bowls. Secondary effects can include creation of sinkholes, potholes, and cracks, which occur somewhat variously with depth of cover.

Potholes occur where the roof above a mining void progressively caves (collapsed and falls) and the void propagates upwards, eventually breaching the ground surface. The caved material increases in volume (bulks) and propagation of the void can be halted where the void becomes full. Propagation can also halt where a strong stratum of rock is met which can span the void, or where overburden arches over a void.

Pothole formation is controlled by the thickness of overburden, rock defects, mining conditions, and bulking. Johnston et al (2017) propose the height of potholing is correlated to the ratio of bord to pillar width. Canbulat et al (2017) looked at 450 'sinkholes'and recommended bulking-controlled failure analysis with probabilistic modelling be used to quantify associated risks.

The term sinkhole is frequently used interchangeably with pothole. Sinkholeis sometimes used to describe a depression formed by transportation of soil (usually with water) into mining voids. As cracks can propagate hundreds of meters above mine workings, such sinkholes are not limited to depth of cover. Other terms such as 'erosion features', 'secondary subsidence' or 'piping' may be used to describe the same or similar phenomenon.

3 Case Study: Northern (Rhondda) Colliery

3.1 Background

Rhondda Collieryisnear Wakefield NSW, about 20 km west of Newcastle. Mining dates to 1899 with extraction of the Great Northern Seam (GNS) and Fassifern Seam until 1971 when the shallower GNS caught fire.

A 3 to 4 m thickness of GNS was mined by bord and pillar methods with up to 6 m mined in places. The overburden is comprised of Permian aged sandstone and conglomerate known as the Teralba Conglomerate Member with stratigraphic dip up to about 7°. The thickness of the overburden (cover) varies from about 5 to 70 m and is generally naturally less along ephemeral watercourses which traverse the site in small valleys.

The fire burnt for about 36 years and resulted in widespread subsidence and cracking of the ground surface. Extensive mine filling and rehabilitation activities were undertaken by Rio Tinto Coal Australia (RTCA), who owned the land and held the mining lease until it was sold to Yancoal Australia Ltd in 2017.Neither RTCAnor Yancoal ever mined coal from the site.

Yancoal is now working towards relinquishing the lease with a land use of bushland/grassland the objective.The ongoing appearance of small holes and cracks is of concern with respect to the relinquishment criteria of safe and stable. An appreciation of the risk associated with such features in a bushland/grassland was sought.

3.2 Initial database development and analysis

3.2.1Data collation and characterization of features

A 2016 GHD geotechnical assessment collated data on features such as cracks and holes. This comprised basic descriptions and coordinates for155 features which occurred over the few years prior and had since been rehabilitated. The coordinates of features had been recorded with a handheld GPS, akin to what a hiker might use. A three-day mapping exercise by GHD in September 2016 identified 117 features, with these being located using a survey grade differential GPS with position accuracies of less than a meter. The mapped features were limited to holes and cracks that were judged to be hazardous;that is, greater than about 0.1 m diameter / width.

The GHD assessment found that observed cracks and holes were attributed to 'secondary subsidence' whereby surface soils wash or fall-in to existing subsidence cracks in the bedrock overburden. Typical examples are shown in Figure 1. 'Primary subsidence', such as further collapse at mine level leading to trough subsidence, potholing or additional cracking was not recorded or observed.

Figure 1. Examples of exposed bedrock crack and hole at Rhondda in 2016

McNally (2000) referred to features of this nature as ‘piping’ which is possibly apt for situations where dispersive soils are transported into cracks with water. At Rhondda, piping in this manner is expected to occur in some instances during heavy rain. However, soil erosion into cracks and collapse (without groundwater flow present) is expected to be more common as the regolith is generally sandy and often less than 1 m thick.

In areas where the regolith is thicker, such as along watercourses, roughly circular holes rather than cracks were more common. On first assessment, these appeared to be associated with pothole subsidence. However, excavation down to rockhead for rehabilitation purposes revealed these holes to be above cracks in the bedrock, typically up to about 0.1 m in width. Lines of small holes following bedrock cracks were often observed in areas of thinner regolith whereas the occurrence of larger holes seemed to correspond with areas of thicker regolith along watercourses where perched groundwater was likely to be present following heavy rainfall. The largest hole since fire extinguishment occurred in August 2014 following heavy rain and was about8 m in diameter and 3 to 4 m deep. When the water and saturated soil was pumped out and excavated, a crack in the bedrock was observed in the base of the ‘sinkhole’.

3.2.2 Map development and hypotheses on contributing factors

To assess the mechanics for the spatial distribution of cracks and holes (features), a layered map was developed in ArcGIS and the attributes listed in Table 1appraised separately to identify correlations.

Table 1. Appraisal of map attributes to identify possible correlations to feature distribution

Attribute	Appraisal method	Distribution of features
Cover depth	Lidar digital terrain model (DTM) and seam difference	Generally reducing with depth
Overburden character	Review of geology map layer	No trends identified
Chitter emplacement	Overlay of mapped emplacement area	No features present
Regolith thickness	Assumed thinner along ridges than in gullies	Affect on feature shape noted
Proximity to watercourses	All ephemeral watercourses traced into GIS	More common along watercourses
Ground slope (gradient)	lidar DTM analysis	More common in steeper areas
Elevation change	2014 and 2015 lidar DTM difference	Changes were due to other factors
Curvature and roughness	Analysis of gradient raster	No clear trends identified
Coal extracted	Percentage of coal mined from mine plans	No trends identified
Void remaining	Digitized records of mine filling completion estimate	No trends identified
Longwall layout	Overlay of mine plans of longwalls 260 to 310 m below	No trends identified
Fire extent	Digitized fire observation sketch map	No trends identified
Stratigraphic anticline	Digitized seam structure contours	No trends identified
Dykes and faults	Digitized from mine plans	No clear trends identified

Areas of shallower cover to the GNS were identified as having more features, but it was not clear if this was merely because there was a greater area of shallow cover across the site. The GIS map was used to extract the areas of undermining within cover ranges in 5 m increments. The number of features in the database from pre-2016 (past features) and between 2016 and 2018 (mapped by GHD) were then counted for each cover range and the density of features calculated on a per hectare basis and plotted as shown in Figure 2.

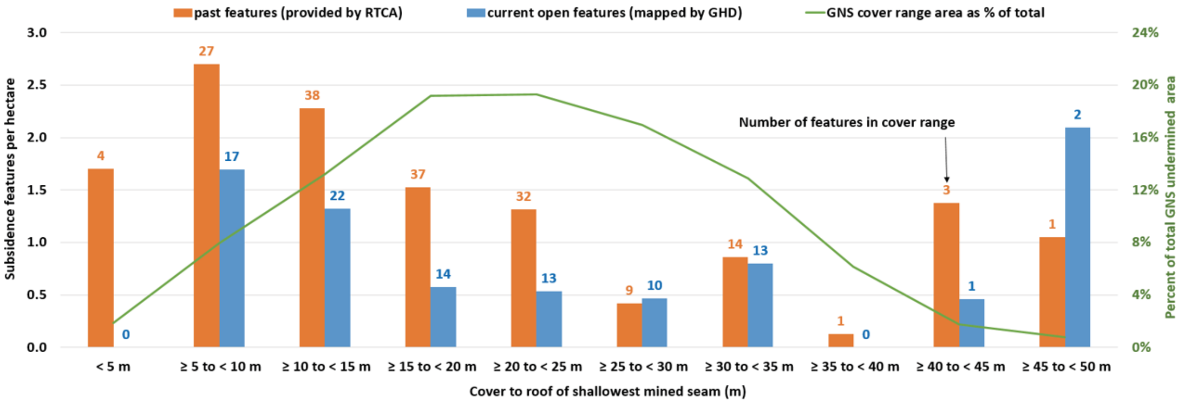

Figure 2. pre-2016 (orange) and 2016 to 2018 (blue) feature density per hectare in relation to cover depth to top of GNS

The blue and orange column heights in Figure 2 correspond to the left axis. The number above each column is the number of features in that cover range. The green line corresponds to the right (secondary) axis.

The 5 to 10 m cover range had the highest density of features with this reducing with greater cover. However, the very shallow cover range of less than 5 m had a markedly lower density. A possible explanation is that the cracks along watercourses have filled with sediment and hence there is less opportunity for formation of features.In contrast, feature density in areas of greater than 40 m cover showed a marked increase even though the number of features was low. The increase in density was thought to be due to the cracks in these elevated areas being more open and less infilled, in contrast to those along watercourses.

3.2.3 Multi-criteria analysis (MCA) and preliminary susceptibility map development

To develop a preliminary susceptibility map that represented observations and could be used for prediction of future feature distribution, a MCA was undertaken using ArcGIS software.

The variables judged to correlate most strongly with observed features were selected as criteria in the MCA. Attributes of each criterion were then grouped into classes;for example, a cover depth criterion could be split into classes of say <10 m, 10 to 20 m, 20 to 30 m, and so on. Each class was assigned a non-linear score ranging from 0 for 'highly likely to coincide with increased subsidence', to 100 for 'unlikely to coincide with increased subsidence'. The subjective importance of each criterion was then ranked against the other criteria to generate a score and weighting for each. Next, raster images were generated for each criterion by classifying each image pixel. Finally, the raster images were combined, and criterion weightings applied to each raster and a combined score calculated for that pixel. The lower the combined score, the more likely a feature is to occur.

Three MCA runs were completed with various rankings and weightings trialed to explore the sensitivity of output to changes in parameters. In each case, the observed feature locations were used to 'calibrate' the MCA. The final rankings and weightings adopted are presented in Table 2.

Table 2. Multi-criteria analysis criterion and weightings

Criterion	rank	weighting	Classes				
			Highly likely	Very likely	Slightly likely	Neutral	Not likely
Cover Depth (m)	1	40%	5 to 15	15 to 20	20 to 50	>50 or <5	Not used
Chitter	2	30%	Not used	Not used	Not used	Not present	present
Proximity to watercourse	3	20%	< 5	5 to 10	10 to 20	>20	Not used
Slope (gradient)	4	10%	> 60%	25 to 60%	15 to 25%	<15%	Not used

'Cover' was assigned the highest weighting based on the density of features. The second highest weighted criterion 'chitter' reflects the observation that no features had been observed within the chitter (coarse washery reject) emplacement area. As such, future cracks and holes in this area were classified as only 'slightly likely' and elsewhere had no affect and so was neutral.The proximity to watercourses was included to reflect the experience that cracks and holes are more likely along watercourses, although this frequency was appearing to lessen in 2018, possibly due to sediment filling cracks in these areas as previously discussed.The slope of the ground surface also appeared to correspond with a greater likelihood of cracks and holes with many of the open features observed on the sides of gullies (small valleys). This was attributed to lateral spreading during subsidence that resulted in wider and more voluminous subsidence cracks.

3.3 2022 review of susceptibility map

Since 2017, Yancoal continued with inspections to map and fill holes and cracks under their management plan for the site. This data provided an opportunity to appraise the 2016 susceptibility map as a prediction tool and make adjustments.

In total, 35 new features were recorded (excluding those in a new venting/oxidation area). The mechanism of formation was consistent with the 2016 GHD report and the number occurring each yearwas asshown in Table 3. With no features occurring in the 'Low' hazard zone, 5 in the 'Moderate' hazard zone and 30 in the 'High' hazard zone; the 2016 susceptibility mapping was considered a general success and a revision of the MCA was not warranted.Minor adjustments were made to hazard zone boundaries.

Table 3. 2018 to March 2022 feature locations compared to 2016 hazard zones

Year	Total count	Number of features in 2016 hazard zones			
		Nil	Low	Moderate	High
2018	6	0	0	2	4
2019	12	0	0	0	12
2020	7	0	0	0	7
2021	6	0	0	1	5
To March 2022	4	0	0	2	2

3.4 Preliminary risk assessment for bushland/grassland

3.4.1Methodology

A quantitative assessment was undertaken by GHD with reference to Australian Geomechanics Society Landslide Risk Management guidelines (AGS 2007b) forthe likelihood of a fatality forthe individual most-at-risk. The assessment was then extended to consider societal risk for assumed site visitors and trespassers.Whilst this approach was developed for slope instability, it was adapted for subsidence hazards and consideration of loss-of-life as described in Mackenzie (2022).

To allow consideration of societal risk, where more than 10 people per annum are exposed to the hazard/s, the methodology for mobile elements (people on foot) and F-N pairs was used as described in Golder (2020). This first requires consideration of the individual most-at-risk and then extension to an average societal risk to loss-of-life as a function of the exposed population. For societal risk, different risk acceptance criteria apply dependent upon the number of people (N) affected by a single incident. For this assessment, N remains assumed to be 1 (i.e., the societal risk assessment considered a single fatality per incident rather than one incident resulting in multiple fatalities) in the context of the assumed usage by single individuals in jeopardy. For both the individual most-at-risk and societal risk assessment, the combined risk from each hazard was calculated and this compared to risk acceptance criteria.

3.4.2 Assumptions to estimate annual likelihoods

In the absence of actual data, the assessment required estimatesto be made for thenumber of hazardous features existing, as well as consideration of aspects such as: how people would use the site, in what vehicles or on foot, at what speeds and conditions, for how long per visit, with what degree of hazard awareness, visibility and responsibility and in what hazard zones. With these considerations in mind, as well as consideration of the likely severity of an interaction (i.e., the probability of a fatality), an estimate was made of the annual probability of fatality of the person most-at-risk.In this case, assumed to be the person undertaking site maintenance inspections. While the numerous assumptions required may not prove to be valid in the long-term, they are necessary due to lack of actual data and do allow a preliminary risk assessment and indication of the sensitive of assessed risk to the assumptions. That is, a better appreciation for what is important.

For the scenario that at any one time, 4 hazardous features are open along tracks preferentially used by people, and in all other areas 15 hazardous features are open, the annual probability that the individual most-at-risk (visiting the site 12 times per annum)would encounter a hazardous feature along a track was judged to be 1 (certain) and in all other areas 0.02(1 in 50).

Along tracks, the likelihood that the individual most-at-risk will not see and avoid afeaturewas adopted as 1 in 500. Within other areas, this likelihood was increased to 1 in 50 to account forground surface obscuring vegetation, making detection, and hence warning less likely.For incidents (e.g., once the individual most-at-risk has tripped), the vulnerability to loss-of-life was adopted as: 1 in 5,000 along tracks (where cracks are assumed to be up to 0.3 m wide) and 1 in 1,000 in all other areas (where holes are assumed to be up to 1 m diameter).

With respect to societal risk, the likelihood of encountering a feature was decreased to 1 in 10 for tracks and 1 in 500 elsewhere on account that these peopleare not expected to be travelling as far.

3.4.3 Tolerable and acceptable risk criteria

AGS (2007b)suggeststypical likelihoods considered tolerable or acceptable as presented in Table 4. Likelihoods for annual loss-of-life to an individual were adopted for ‘existing developments’ rather than ‘new developments’ – this being considered appropriate for a closed mine. Also presented in Table 4is guidance from Golder (2020) on societal risk acceptance where the number of people killed by a single incident is 1 (N=1). These have been adapted from the ANCOLD (2003) societal risk criteria.

Table 4. Quantitative risk acceptance definitions for loss-of-life – existing developments (AGS 2007b; Golder 2020)

Risk category	Indicative annual likelihood for individual most-at-risk [A]	Combined probability for societal risk where N=1 [B]
Unacceptable without treatment.	> 1:10,000 pa	> 1:1,000 pa
Tolerablewith treatment to as low as reasonably practicable.	1:10,000 to 1:100,000 pa	1:1,000 to 1:100,000 pa
Usually **Acceptable**. Ongoing maintenance is required.	<1:100,000 pa	< 1:100,000 pa

A: Combined risk (R_{LOLC}) for all hazards

B: Average risk (A_vR_{LOLC}) for each hazard and exposed population (e) combined to give an annual loss-of-life probability for multiple hazards (F_c) and considering a single fatality per incident (N=1)

3.4.4 Quantitative risk assessed for bushland/grassland

With reference to the risk categories of Unacceptable, Tolerable (ALARP) and Acceptable as described in Table 4, and assumptions described in Section 3.4.2, the annual risk of subsidence related cracks and holes resulting in a single person fatality was assessed to be as presented in Table 5 for various annual exposed populations.

Table 5. Preliminary quantitative risks –person on-foot – annual risk-to-life

Element at risk	Annual combined risk-to-life (R_{LOLC}/A_vR_{LOLC})	Exposed population/visits per year (n)	Combined loss-of-life probability for societal risk (F_c)	Risk category
Individual most-at-risk	8 x 10^{-6} p.a.	12	Not applicable	Acceptable
Societal risk (N=1)	8 x 10^{-7} p.a.	500	4 x 10^{-4} p.a.	Tolerable ALARP
		1350	1 x 10^{-3} p.a.	Unacceptable

4 Conclusions

Advances in Global Positioning Systems and Global Information Systems have facilitated processing and analysis of spatial data. Tools such as multi-criteria analysis are useful for exploring correlations and testing hypotheses on causal factors for mine subsidence hazards. Where sufficiently accurate and reliable records are available over several years, such analysis techniques can be checked and refined. These efforts are expected to lead to a deeper understanding of on-going post mining subsidence and related phenomenon such as secondary crack and hole formation that would be particularly useful for situations where data availability is poor.

In contrast to many other geohazards, such as rockfall for example, a subsidence hazard is more likely to be present (i.e.: have been realized) when the element-at-risk (the person) comes across it. Whilst the spatial distribution and frequency of the hazard occurring is important, predicting the human interaction with a stationary hazard is equally important in such situations. In the context of incorporating human behavior and vulnerability into quantitative risk assessment in the example provided:How likely is it that a person will see and avoid a hazard? How dependent is this on what they are doing and in what context? If they do interact with the hazard, how likely are they to be permanently injured, and how dependent is that on the availability and effectiveness of medical assistance?

These aspects of risk assessment are appreciated conceptually, but quantifying them with meaningful reliability is, in the author's experience, presently challenging yet critically important. The behavior and responses of people, whilst not relevant to geotechnical practice traditionally, becomes of utmost importance when assessing risks associated with geohazards, yet is an aspect that we as a profession are not generally familiar.

Collaboration with researchers in fields such as behavioral psychology and emergency medical services is expected to provide new insights that would improve quantitative risk assessment of geohazards. Further publication of data on incidents, includingtheir causes and consequences, would provide valuable references for comparison. For site specific assessments, data on how an exposed population moves through an area could be collected through GPS tracking applications as 'heat-maps' with data on likelihood of encountering and avoiding hazards ('near hit' in Workplace Health and Safety terms) collected over time or through field experiments.

Acknowledgments

The author would like to thank Yancoal for their permission to prepare this paper and support in undertaking the assessment.

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