Investigation Into Abnormal Surface Subsidence Above a Longwall Panel in the Southern Coalfield, Australia

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ABSTRACT

The subsidence over a longwall panel at Tahmoor Mine in the Southern Coalfield of NSW, Australia, was found to be approximately twice the size it had been in previous measurements. An investigation into the potential causes was conducted using computer modeling together with hydrological characterization and detailed geotechnical characterization of the strata.

The abnormal subsidence was found to be consistent with localized weathering of joint and bedding planes above a depressed water table adjacent to an incised gorge. The study showed that other factors such as variation in stress field, joint zones, variation in rock strength and topographic factors did have sufficient impact to induce the abnormal subsidence.

The results have significant implications to subsidence prediction in areas that may be prone to the phenomenon found at Tahmoor. Key indicators of the potential for this form of abnormal subsidence are presented.

INTRODUCTION

The investigation was conducted at Tahmoor Mine, which is located in the Southern Coalfield NSW Australia; it mines the Bulli Seam at approximately a 420 to 480m (1,344 to 1,536 ft) depth. The location of the mine is presented in Figure 1. Panel widths have varied over time and the current panel width is approximately 272 m (870 ft). At the time of the investigation, extraction thickness was approximately 2.4 m (7.7 ft).

Subsidence characteristics of the overburden had been consistent with empirical regional estimates over the history of the mine which included 23 longwall panels. The abnormal subsidence occurred within Longwalls 24a and 25.

The subsidence characteristics and the layout of Longwalls 22 to 25 are presented in Figure 2. In general, the abnormal subsidence is located in the southern area of the panels. Longwalls 22 to 24b and the northern part of Longwall 25 displayed the normal subsidence characteristics.

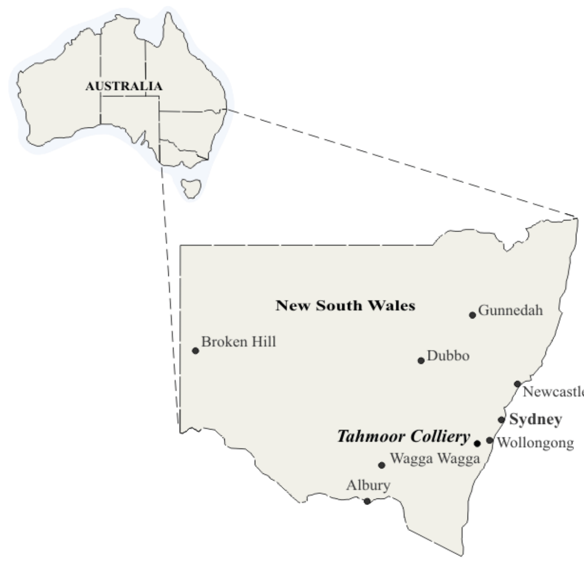


Figure 1. Location of the mine area.

The regional subsidence characteristics are summarized in Figure 3, which presents the subsidence relative to the width to depth ratio of the panels. The subsidence is presented as a proportion of extraction height. The width to depth ratio of Longwall panels is approximately 0.65 and was anticipated to be subcritical in dimension. The predicted range for Longwall panels 24a and b is presented in Figure 3. The subsidence was anticipated to be in the range of 400–600 mm (15.7–23.6 in).

The subsidence measured after Longwall 24a was in the range of 1–1.2 m (3.2–3.8 ft), which was up to double that of the empirical estimates and that of past experience. Though the abnormal subsidence was located in Longwall 24a, further north in Longwall 24b the subsidence returned to be within the regional and previous range for the mine. The abnormal characteristics were also noted in Longwall 25 within the initial 20%–30% of the panel.

The investigative approach to find the cause of the abnormal subsidence involved using a computer model to simulate extraction

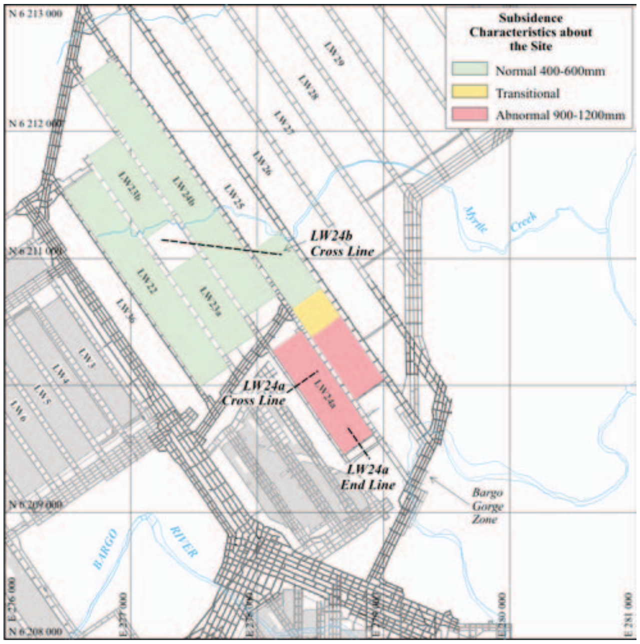


Figure 2. Subsidence measured and location of the longwall panels.

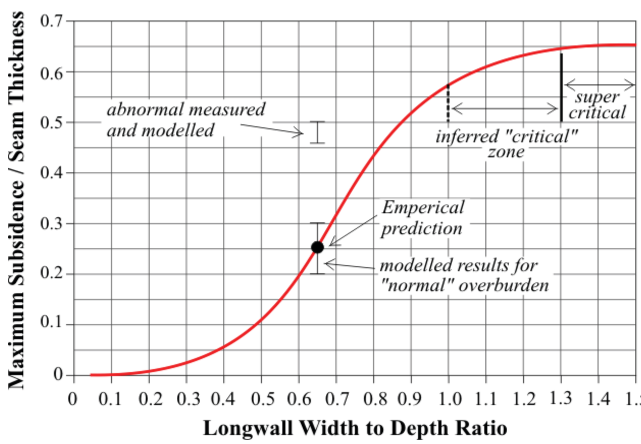


Figure 3. Regional subsidence characteristics for longwall panels.

of Longwall 24a and the surrounding panels within the strata section over the mining area. Computer modeling of longwall caving has been undertaken by SCT Operations for a number of years and has been found to reliably simulate the rock failure and caving mechanics of the overburden in coal measure strata. It was seen as the best method to assess the potential causes of the abnormal subsidence at this site.

The potential causes investigated were

- variations in horizontal stress
- higher joint density associated with faulting
- weathering effects
- topographic effects
- variations in overburden strength

GEOTECHNICAL INFORMATION

The overall site and major features are presented in Figure 4. The areas of abnormal subsidence are located north of the Bargo Gorge. There are also major fault structures in the area. The Bargo Gorge has incised the surface approximately 100 m (320 ft) and has caused a reduction in the water table in the surrounding area. The water table in the southern and eastern areas of the blocks is level with the base of the gorge, whereas further north it increases to approximately 30–40 m (96–128 ft) below surface. The fault structures are also known to be water conduits within the overburden.

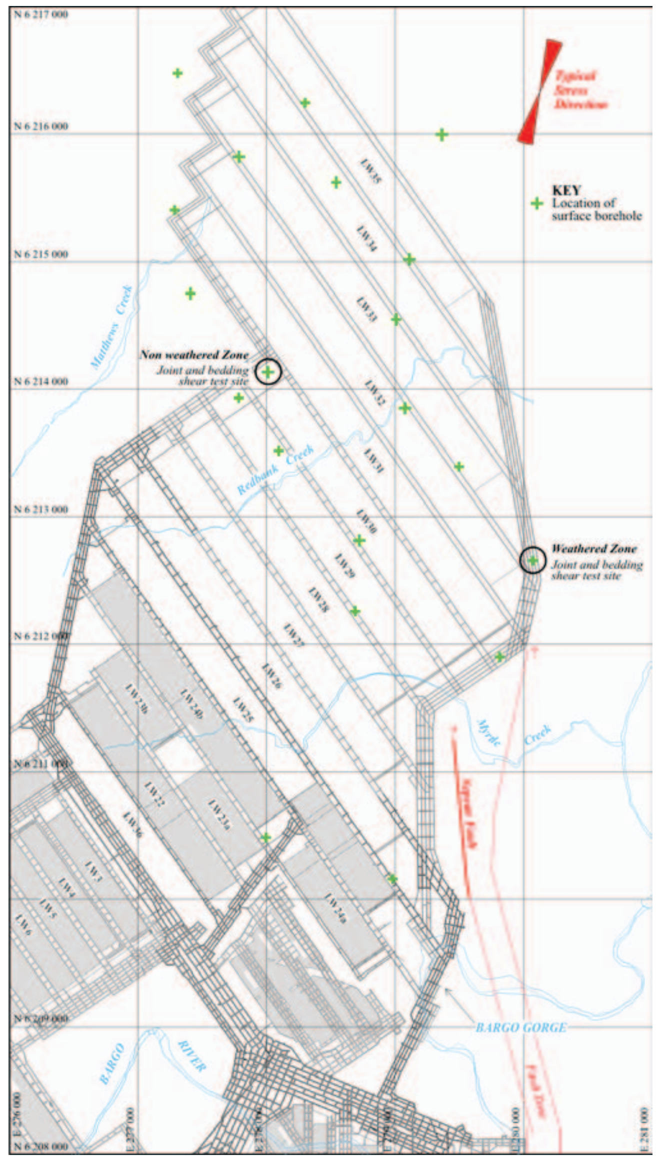


Figure 4. Mine plan and general features.

The overburden is composed of interbedded siltstone, sandstone and minor claystone units. The unconfined strength (UCS) of the strata section is presented in Figure 5 for a range of boreholes in the area. The borehole locations are presented in Figure 4. The UCS was determined on the basis of sonic velocity and core testing. In general, the strata strength varies throughout the section and there is a range within the key units over the area. During this study, a number of strength sections were analysed, including those from neighboring mines. On the basis of the variation, two end members have been used to assess the effect of any strength variation in the overburden on the abnormal subsidence. The end member strength profiles are presented in Figure 5 as the "weak" and "strong" geology range.

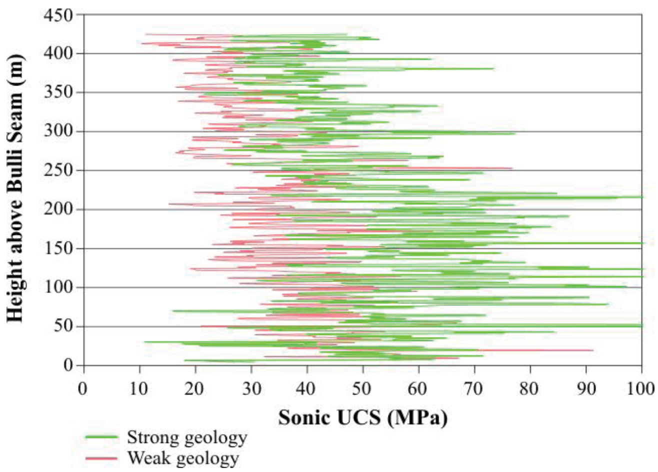


Figure 5. UCS range for boreholes over the area.

MODELING APPROACH

FLAC was the computer program chosen for the investigation, and fish routines were developed by SCT Operations to simulate the rock failure and ground caving characteristics. The background of this has been reported previously (Gale et al., 2004; Gale, 2004; Gale, 2008). The models used for this site ranged up to 1.3km wide and 900 m (2,880 ft) deep. The element size was typically 1 m (3.2 ft) square for simulations of this scale, and the model simulates the elastic and post failure strength properties of the rock units.

Joints and bedding plane partings are included in the overburden on the basis of a normal distribution of the average spacing randomly distributed within the model.

The models are two dimensional to allow for the appropriate level of detail required to map the rock failure modes and stress path.

The generalized strength characteristics for the rock material are presented in Figure 6. Bedding planes have similar intact and post failure characteristics.

The strength of each layer within the model varies about the mean value as a normal distribution. This is an attempt to account for the natural variation of strength within sedimentary strata.

A section of the model with the UCS layers is presented in Figure 7. The mottled appearance of the layers is the variation about the mean for each layer. The sandstone units are fluvial with numerous bedding surfaces.

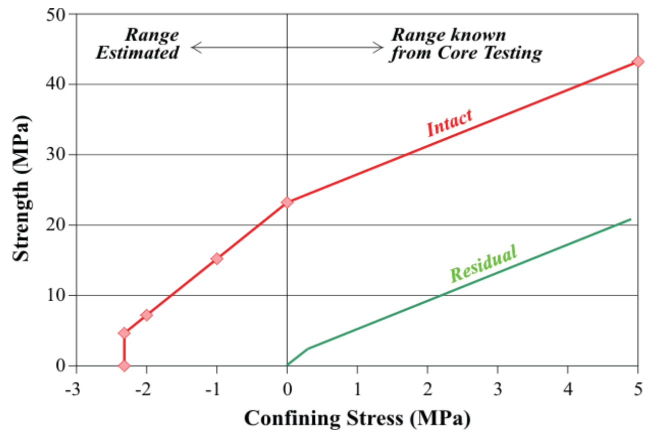


Figure 6. Generic strength characteristics of the rock material.

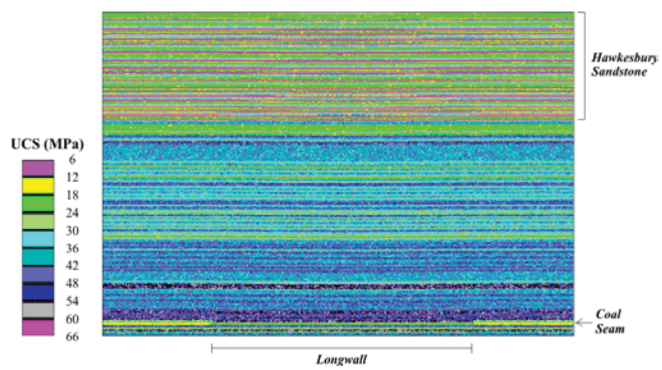


Figure 7. Model section about the longwall area.

The stress conditions for the region and this site are well known from past stress measurements within the mines. The horizontal stress direction for the site is presented in Figure 4. The major stress magnitude is horizontal and relates to a tectonic stress factor of 0.7. This factor is related to the tectonic strain within the rock units. Therefore, the horizontal stress in each layer will vary and is related to the tectonic strain, Young's Modulus and the depth. The vertical stress is based on lithostatic load, with an average gradient of 2.5 MPa per 100 m (362 psi per 320 ft) in depth. A discussion of the stress field and the tectonic stress factor is presented by Nemcik et al. (2005).

This modeling approach has been used extensively in Australia by SCT Operations to simulate caving and overburden fracture characteristics in coal measure strata. The approach has been found to simulate the key aspects of subsidence in terms of the overall subsidence relative to width to depth ratio, and also the subsidence profile.

An example from the Hunter Valley region, NSW, is presented in Figure 8, which shows the evolution of caving and the amount of subsidence as the width to depth ratio of the panel is increased. The model results and the regional empirical data are presented. The model shows a very good correlation and depicts the subsidence relative to the spanning mechanics of the overburden. Examples of the subsidence profile match are presented as part of this study.

SIMULATION OF LONGWALL 24A

Longwall 24a was simulated as a two dimensional cross-section at a depth of 430 m (1,376 ft). The rock fracture mode for the overburden and stress field anticipated in this area of the mine is presented in Figure 9. This figure shows the main deformation modes are rock fracture around the panel edges and a significant amount of bedding plane slip higher into the overburden.

The subsidence caving zone is presented on the figure and tends to extend to or slightly into the base of the Hawkesbury sandstone depending on the strength of the sandstone unit. In general, the height of the subsidence caving zone extends approximately 1–1.2 times the panel width for this case. Above this, the strata tend to bridge across the panel. This is termed the bridging zone in the figure. Mobilization of pre-existing bedding partings and joints occurs in this bridging zone.

It is typical for the caving subsidence zone to extend 1–1.5 times the width of the panel (Gale, 2006; Mills and O'Grady, 1998).

The subsidence measurements conducted over the site were determined by accessibility and were typically along streets and key infrastructure over the mine area. Therefore complete sections were not necessarily available; however, a number of lines were appropriate for correlation with the model results.

The measured subsidence along a subsidence cross line and one at the start line during Longwall 24a were available to characterize the abnormal subsidence developed in this area. A subsidence cross line oblique across Longwall 24b provides a good example of the normal and regional subsidence characteristics. The subsidence lines are shown in Figure 2.

The subsidence from the model was consistent with that measured in areas not affected by the abnormal subsidence. A comparison with subsidence across Longwall 24b is presented in Figure 10. This longwall is adjacent to Longwall 23 and in order to compare the data with a single panel (as per Longwall 24a), the subsidence from the measurement line is resolved relative to distance from the eastern panel rib to reduce potential effects from Longwall 23. The subsidence profile is therefore resolved normal to the eastern panel edge.

The results compare very well in terms of magnitude and shape, and provide confidence that the model is simulating the caving and subsidence mechanics of the site under normal geotechnical conditions. The magnitude of subsidence is 0.6 m (2 ft) and has a subsidence to seam thickness ratio of 0.25, as per the empirical prediction presented in Figure 3.

These results validate the method used at the site and are a basis to evaluate a range of variations in material properties, stress and topographic features that may have an impact on the subsidence characteristics.

A comparison of the subsidence profiles for the normal and abnormal subsidence is presented in Figure 11. It is clear that the abnormal subsidence has a very different characteristic than that of the typical or normal subsidence over the site.

EFFECT OF VARIATION IN GEOTECHNICAL PARAMETERS

The variation in strata strength profile (UCS as per Figure 5) was modeled and the mode of strata failure was similar across the variation. The subsidence profiles obtained from the models of the end members (weak geology and strong geology) are presented in Figure 10 and show no significant variation. The modeled subsidence is as per the normal subsidence behavior. Modeled data is presented from the left hand ribside and compared to the resolved subsidence from LW 24b cross line.

It is clear from Figure 10 and 11 that there is no correlation with the abnormal subsidence, and as such, the normal variation in overburden strength is not a major influence on the abnormal subsidence.

The effect of modifying the horizontal stress was also simulated and the resulting subsidence is presented in Figure 12 together with the abnormal subsidence data. The horizontal tectonic stress factor varied from 0.7 to 1.2. The effect of reducing the horizontal stress to lithostatic in the weathered zone was also simulated. Again, these variations had no significant impact and did not induce the abnormal subsidence. All modeled subsidence data is relative to the left hand ribside of the panel.

The effect of the topographic relief of the gorge was also modeled. It was thought that this might vary the horizontal stress field and the caving mechanics above the initial part of the panel. However, this had no significant impact.

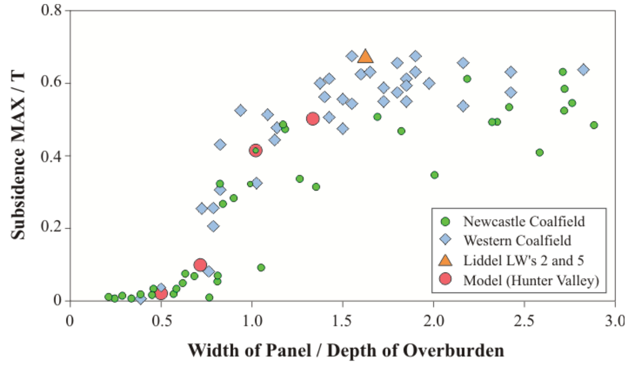
The conclusion reached was that variation in the overburden strength, topographic relief of the gorge, and in the stress field could not account for the abnormal subsidence.

The effect of an increased joint and bedding parting density (up to double) was also simulated. The joints were simulated on the basis of an inclusion within the rock mass with cohesion and friction properties typical of joints within the rock units. The subsidence results are presented in Figure 13; however, it did not show any significant impact to the subsidence in terms of matching the measured data.

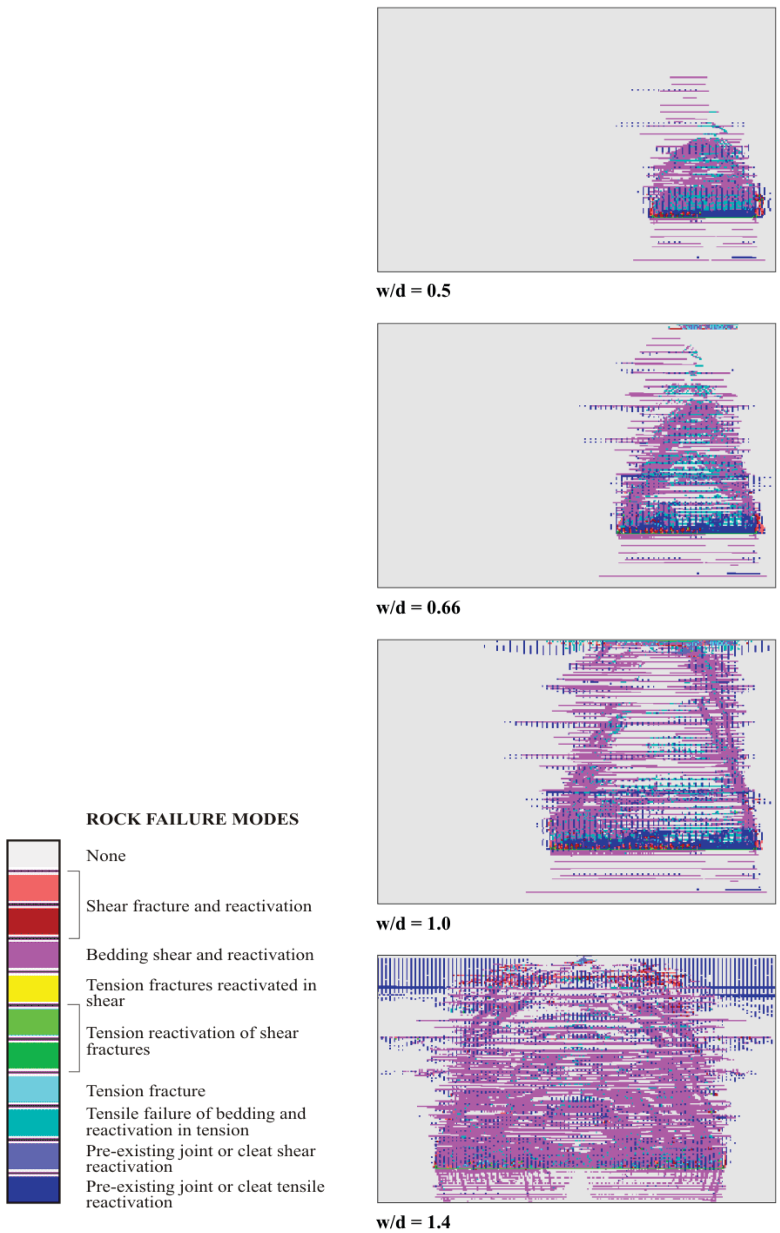
The simulation of these factors showed that they were not sufficient to cause the abnormal subsidence phenomenon.

A review of the subsidence data indicated that the abnormal subsidence was more akin to that related to panels of critical to super critical dimension. Therefore, overburden above the caving subsidence zone was not bridging across the panel at this site, as was the case at other sites. It was concluded that the nature of the strata must be different to allow the non-bridging behavior. However, it was known that the material strength of the strata was not significantly different from other sites, and as such the rock material had not significantly changed.

It was noted in the exploration work that the water table was significantly lowered toward the gorge. It was also noted that water loss during drilling occurred in these zones. Hydrological testing of the overburden indicated that the conductivity of the strata above the gorge floor was two to three orders of magnitude greater than the conductivity of the strata below the gorge and that of holes



a) General Relationship.



b) Modelled Strata Fracture.

Figure 8. Example of validation for the method using Hunter Valley data.

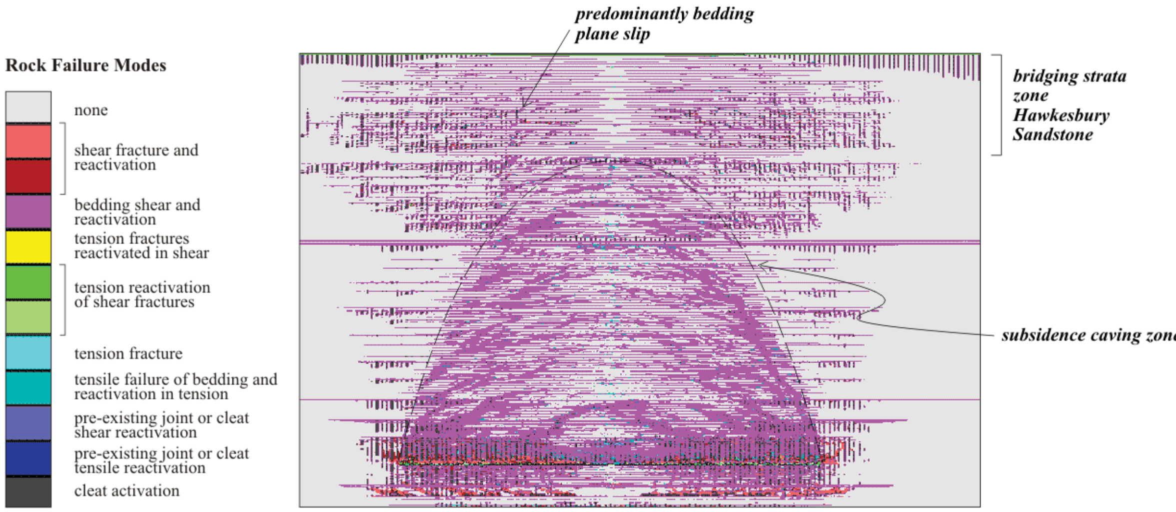


Figure 9. Rock failure mode for the "normal" overburden.

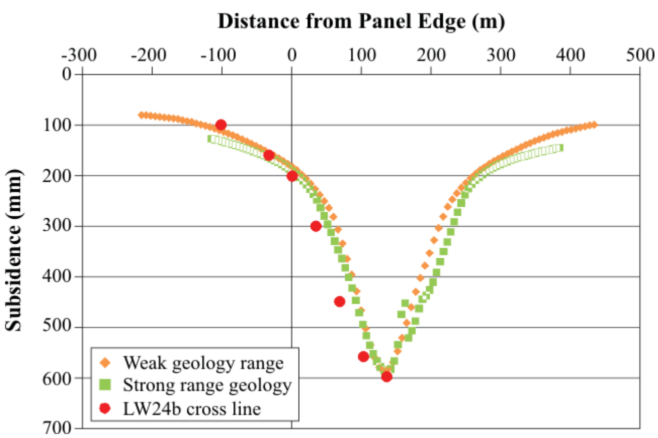


Figure 10. Comparison of the model with normal subsidence characteristics. Note the two end member UCS cases are presented.

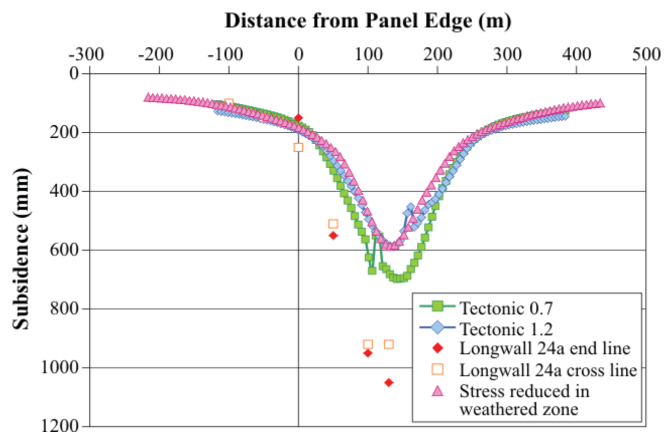


Figure 12. Effect of modifying the horizontal stress through the overburden.

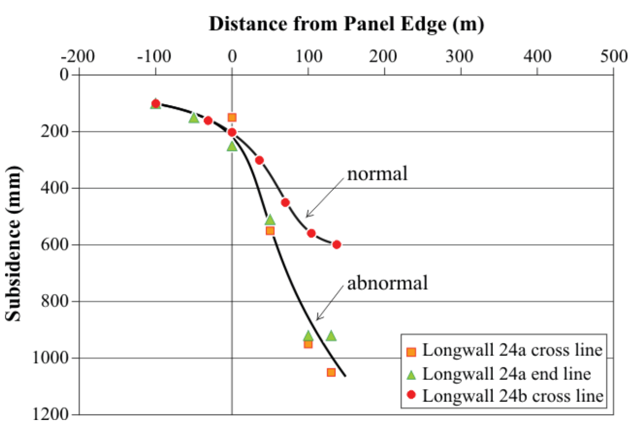


Figure 11. Comparison of subsidence profiles for the normal and abnormal subsidence.

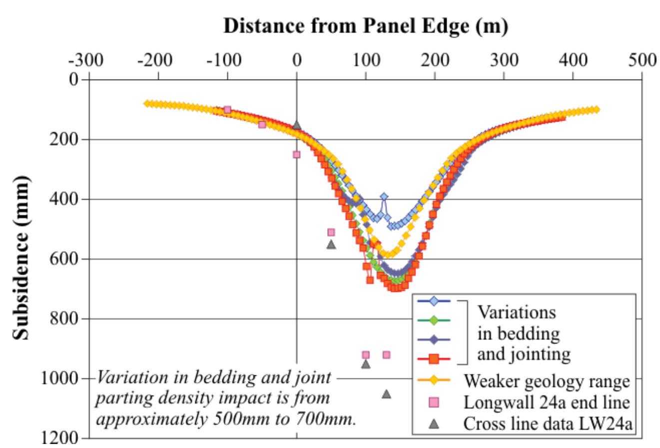


Figure 13. Effect of variation in the density of bedding partings and joints.

where the water table was not so depressed. The conductivity is primarily related to fracture flow and indicated that the joints and bedding planes in this area were open relative to elsewhere.

It was noted that the joints and bedding planes were typically weathered and often coated with clay or clayey sand. It was postulated that the weathering of the joints and bedding planes had occurred due to percolation and flow of water through the overburden down to the level of the gorge. This would have occurred over the time frame of the formation of the gorge. Under these conditions, the shear stiffness and friction angle of the planes would be significantly lower than those unaffected by weathering. The rock material strength (UCS) was not significantly affected, only the joint and bedding margins.

Models were run to assess this assumption by reducing the friction together with the shear and normal stiffness of the joints and bedding in the weathered zone. The results obtained showed a good match of the measured subsidence in terms of magnitude and shape.

As a means to validate the assumption and provide a better range of material properties, additional drilling and sampling was undertaken. Vertical and angled holes were drilled to intersect joints and bedding planes. The planes were tested to determine the shear and normal stiffness together with friction angle and cohesion.

The results are summarized in Figure 14 and show that the joints and bedding planes above the water table were significantly different from those below. The friction angle of the joints and bedding was approximately 17°–27° in the weathered area, but it was approximately 38° elsewhere. The average spacing of high angle joints found in the inclined hole was approximately 4–5 m (12.8–16 ft).

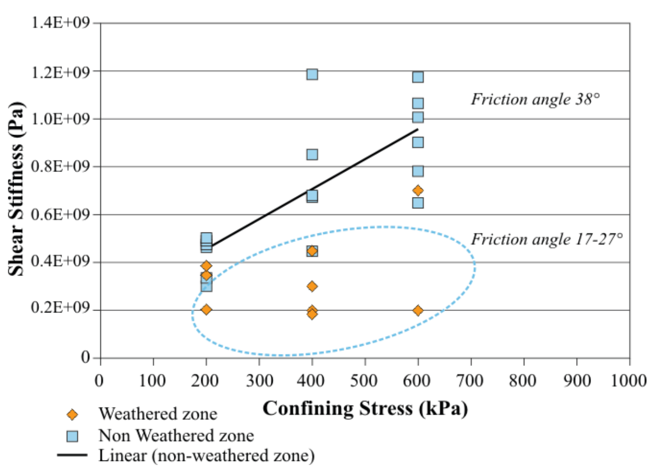


Figure 14. Shear stiffness and friction angle characteristics for the weathered and non-weathered zones.

The updated properties were included into the model, and the resulting subsidence is presented in Figure 15 relative to the measured data. The results are very close in both magnitude and shape, and they demonstrate the impact of localized weathering of joints and bedding above the water table.

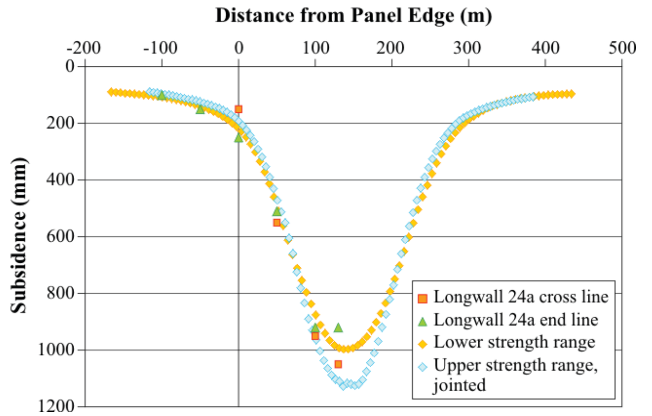


Figure 15. Subsidence characteristics with properties of the weathered zone.

The failure mode of the overburden under these conditions is presented in Figure 16 and shows the dominant role of slip along the bedding and jointing in the weathered zone.

The mechanics of the subsidence process was changed in the weathered zone. In this area, the subsidence caving zone extends up to the base of the weathered zone; however, the strata in the weathered zone have reduced spanning capability due to the low shear stiffness and friction properties of the joints and bedding. The strata in the weathered zone act essentially as a "dead weight" on the caved zone below and cause additional subsidence.

The width of the panel and height of the subsidence caving zone is such that the "non-spanning weight" causes the panel to act more like a critical to super critical panel.

The concept can be related to the empirical subsidence approach by considering that the effective depth of the panel is reduced by the thickness of the weathered zone. Therefore panel width to depth ratio is increased from 0.65 to approximately 0.83. The subsidence relating to these dimensions is presented in Figure 17 and is closer to the measured response. The subsidence in the field and within the model is greater than given by this equivalent empirical approach due to the additional weight of the non-spanning rock within the weathered zone.

Variation in horizontal stress and rock material strength had no significant impact on the results. The key parameter is the stiffness of the joints and, to a lesser extent, the reduced friction angle.

The subsidence decreases along the panels as the thickness of the weathered zone reduces and the depth of the coal seam increases. The subsidence in Longwall 24 and Longwall 25 reduces to the north where the water table is restored to its normal value. The measured subsidence is consistent with the modeling results.

DISCUSSION OF RESULTS

The key outcome of the study is the recognition of the impact of a zone of weathered joints and bedding planes above the water table. Water loss during drilling is commonly noted in dissected topography, meaning that this phenomenon may be more widespread than just this site. Evaluating the potential of this

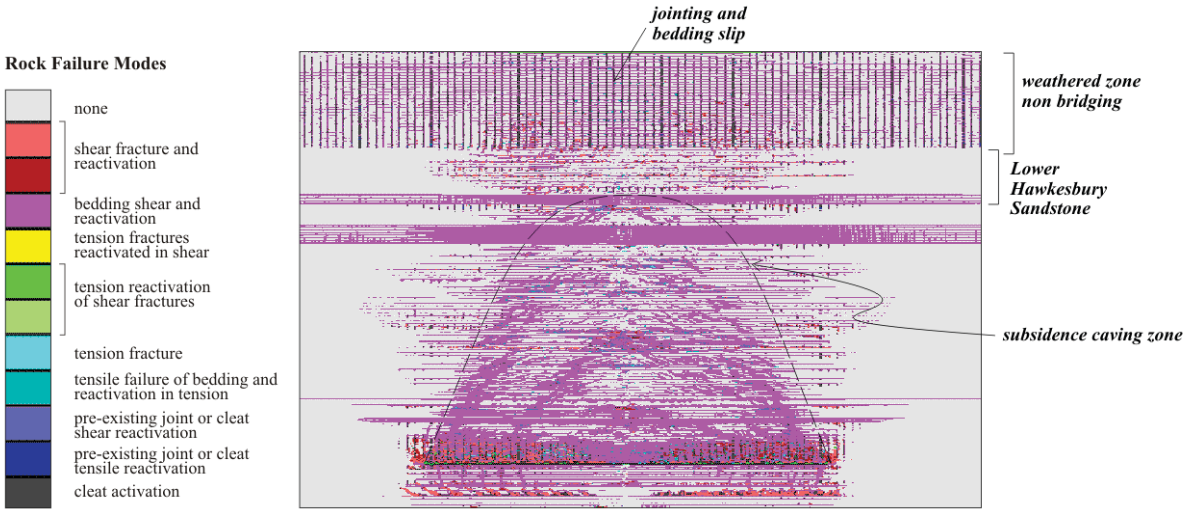


Figure 16. Rock failure mode with updated properties in the weathered zone.

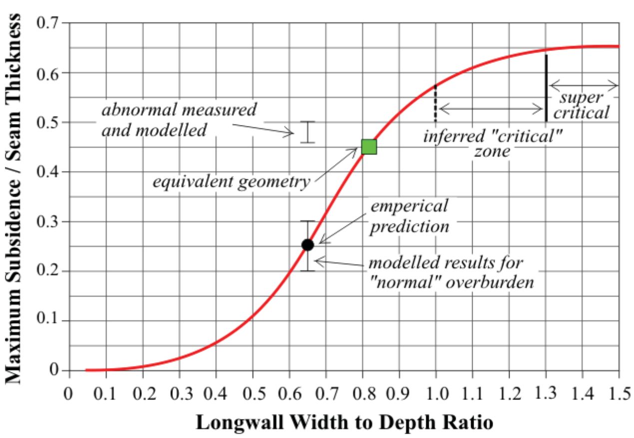


Figure 17. Comparison of equivalent panel dimension with subsidence measured.

phenomenon where the joints and bedding planes are "open" due to weathering associated with water flow is recommended.

The impact of the weathering will also be dependent on the critical to supercritical dimensions of the panels. In this case, it was apparent that the panel was of critical dimension under the weathered zone. The low shear stiffness characteristics of the overburden in the weathered zone caused the panel to act more akin to a supercritical panel, whereas if the seam was mined an additional 100 m (320 ft) deeper, the critical dimensions may not have occurred and the abnormal subsidence may not have developed.

It is possible that at other sites the rock material may be weakened by the weathering process. This phenomenon would also reduce the spanning capability of the weathered section.

It is clear that each case needs to be assessed on the site conditions and mine geometry; however, the phenomenon needs to be considered for subsidence prediction. This is a particular requirement in areas of sensitive infrastructure and residential dwellings where the impact of predictions and remedial measures are a key part of the mine design process.

The key indicators of this phenomenon appear to be a depressed water table and a high hydraulic conductivity of the overburden. Testing of joints, bedding planes, and rock strength are key aspects to confirm the likelihood of this phenomenon occurring at a particular site.

Computer modeling has been an excellent tool to assess this phenomenon and is recommended to assess the potential of this phenomenon at sites that have the key indicators.

CONCLUSIONS

The abnormal subsidence at Tahmoor Mine is consistent with localized weathering of joint and bedding planes above a depressed water table adjacent to an incised gorge. The study has shown that other factors, such as variation in stress field, joint zones, variation in rock strength, and topographic factors did not induce the abnormal subsidence.

The outcome of this work was facilitated by an investigation program that combined normal exploration with hydrological characterization and detailed geotechnical characterization of the joints and bedding planes.

It was found that the low shear stiffness and friction angle of the weathered joints and bedding planes significantly reduced the bridging capacity of the strata. Where the weathered strata formed the bridging zone immediately above the caving subsidence zone, the abnormal subsidence occurred.

The subsidence reduced back to normal as the depth of weathering reduced and the resultant geometry of the weathered zone relative to the caving subsidence zone changed. Normal subsidence occurred where the strata above the caving subsidence zone had higher shear stiffness and friction angle to facilitate bridging across the panel.

The key indicators of abnormal subsidence were found to be

1. depressed water table
2. high hydraulic conductivity of the overburden
3. a panel width for which the caving subsidence zone extends close to the depth of weathered jointing and bedding

Computer modeling has been an excellent tool to assess this phenomenon and is recommended to assess the potential of this phenomenon at sites that have the key indicators

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