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The Effect of Roof Rock Mass Properties on Wind Blast: Laboratory Modelling and Field Investigations in Australian Underground Coal Mines

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Summary In some collieries where the roof comprises strong and massive rock, the roof strata do not cave regularly as extraction progresses but 'hang up'. These areas can collapse, suddenly and often without warning, compressing the air beneath and forcing it out of the void through surrounding openings giving rise to *wind blast*. Field investigations and physical modelling in the laboratory have revealed some aspects of the dynamics of the interaction between falling roof elements and the air. The 'permeability' of the roof elements and bed separation prior to the fall have both been shown to play a significant role. Caving is influenced by both geological features and the layout of the longwall panel. Fall area, location, failure sequence and obstructions in airflow paths all influence the velocities and overpressures measured in mine openings. The present study will help in establishing safe layout and design norms for mining under massive conglomerate roof and in risk assessment for operational and safety considerations.

1. INTRODUCTION

Wind blast is a mass movement of air displaced by a goaf fall and caused to flow through adjacent roadways. The event is experienced as a pressure pulse combined with a flow of high velocity air sometimes reaching 'hurricane' force. The celerity or rate at which the wind blast event propagates through the mine workings has shown to be approximately equal to the theoretical value of the speed of sound at standard temperature and pressure. Longwall mining under massive conglomerate roof in the Newcastle Coalfield of New South Wales has resulted in wind blasts of sufficient intensity to raise serious concerns regarding the safety of mine personnel, disruption to the ventilation system and potential expulsion of methane from the goaf. Coal mines in the Newcastle Coalfield which have experienced significant wind blasts include Wallarah, Myuna, and Cooranbong Collieries (Fowler, 1997), Endeavour Colliery (where, in 1995, a significant wind blast associated with a major goaf fall preceded an explosion), and, more recently, Newstan and Moonee Collieries.

1.1 Newcastle Coal Measures Conglomerates

While most of the major coalfields within the Sydney Basin contain coal mines which have been subject to significant wind blasts, the incidence of the wind blast phenomenon in the Newcastle Coalfield is higher than in any other coalfield in Australia and, probably, in the world. The reason for this is believed to lie in the particular geology of the coalfield, a dominant feature of which is the presence of massive conglomerates whose basal sections often lie in close proximity to the coal seams. The conglomerates, in common with the other clastic sediments, show considerable variation in both their lateral and vertical extents throughout the coalfield. They have been proven to extend over areas in excess of 200 square kilometres in irregular lenticular sheets, several discontinuous lenses often occurring on the one stratigraphic horizon.

The Newcastle Coal Measures attain a maximum proven thickness of 450 metres. The relative abundance of conglomerates exhibits an upwardly increasing trend and averages 29 per cent of the sequence while the recorded thickness of single conglomerate beds ranges up to a proven maximum of 86 metres. Of the twelve seams which have been recorded as having been worked, no fewer than eight have conglomerate members within ten metres of the seam roof over all or part of their area of exploitation.

For example, the Great Northern Coal, located near the top of the Newcastle Coal Measures, is overlain by the Teralba/Marks Point Conglomerate Member which is up to 60 metres in thickness and is composed of conglomerate, sandstone and some mudstone. Conglomerates, however, predominate in the form of massive sheets and lenses up to 50 metres thick. From a mining point of view, such massive conglomerate is often difficult to cave in total extraction panels and gives rise to dynamic phenomena such as periodic weighting, 'bounces' and wind blast. Although over part of its worked extent the Great Northern Coal is directly overlain by the Booragul Tuff Member, comprising up to three metres of tuff and tuffaceous sediments which cave readily, the thickness of the latter is insufficient to significantly modify the caving characteristics of the overlying conglomerate.

By contrast, the West Borehole Coal, situated at the base of the Newcastle Coal Measures and formed by the merging of the Borehole, Yard, Dudley and Nobbys Coals in the west of the coalfield, is generally directly overlain by the Shepherds Hill Formation, the basal member of which is the Nobbys Tuff. The Nobby's Tuff Member, together with the overlying unnamed sandstones and shales which constitute the remainder of the Shepherds Hill Formation, cave readily in total extraction panels. However, over part of its extent, the West Borehole Coal is overlain by a massive conglomerate unit which has been proven to be up to 50 metres in thickness and to approach the coal seam. Where the thickness of interburden between the working horizon and the overlying conglomerate is less than about seven metres (twice the extracted seam height), wind blasts have been occasioned in narrow longwall panels. However, a greater thickness of interburden significantly modifies the caving characteristics of the conglomerate unit, obviating wind blast.

2. WIND BLAST DYNAMICS

A wind blast comprises three distinct phases as determined by physical modelling (Fowler & Torabi, 1997).

1) A primary phase characterised by a high velocity flow of air which exhibits a peak and corresponds to the period during which the roof element is accelerating.

2) A secondary phase characterised by a residual air flow of lesser velocity than in the primary phase and corresponding to the period during which the roof element is falling at its terminal velocity.

3) A tertiary phase characterised by a flow of air towards the fall (suck back).

Evidence of the secondary phase has yet to be clearly observed in the mine situation and it may be that the conditions of a real roof fall in the coal mine are such that the primary phase is always prematurely terminated by the falling roof element hitting the floor with the result that the secondary phase (corresponding to the roof element achieving its terminal velocity) does not develop.

3. LABORATORY WIND BLAST MODEL

In order to investigate the phenomenon, a physical laboratory model was constructed. The model, at a scale of 1:125, comprises representations of solid coal, 12.5 m square pillars, and 4.75 m wide by 2.5 m high headings together with cut-throughs and goaf areas "sandwiched' between an aluminium base plate and a perspex lid. The goaf fall is represented by a group of four square pistons contained within a piston box representing an area 56.5 metres square. The head of each piston is a hollow aluminium box which is provided with a valve incorporating an occlusion disk containing three pressure relief holes. The holes can be partially or totally occluded from outside the piston box by means of a special tool. The pistons are capable of being loaded internally with lead inserts and lead shot ballast and externally with steel weights such that they are capable of exerting a maximum pressure of 10 kPa. The base plate which forms the underside of the box is equipped with four ports which function as pressure tappings and four others through which extension rods can pass in order to transfer the vertical motion of the pistons to displacement transducers or accelerometers. The abutting pistons are suspended electromagnetically and released in computer controlled time sequences. The model is instrumented with Hewlett Packard displacement transducers (LVDTs) and Environmental Equipments piezoelectric accelerometers, which respond to changes in relative vertical position and acceleration of the pistons respectively, with Honeywell Micro Switch pressure transducers, which detect changes in pressure above and below the pistons, and with Airflow Developments miniature pitot tubes and associated differential pressure transducers which respond to the flow of air in the model openings.

3.1 Control and Data Acquisition

Control of the model and acquisition of data is afforded by an Apple Macintosh computer equipped with a National Instruments NB-MIO-16XL-18 input/output board. The data acquisition and control program, written in National Instruments LabView, controls the release of the pistons, which simulate the goaf fall, in controlled time sequences and acquires the subsequent output from the LVDTs, accelerometers, gauge pressure transducers and differential pressure transducers.

4. EFFECT OF ROCK MASS PROPERTIES

A comprehensive series of experiments using the physical model provided insight into the dynamics of the interaction between the falling roof strata and the air (Fowler, Torabi and Daly, 1995). During the fall of a roof element, a zone of reduced air pressure formed above the element while pressure below increased. These pressure changes were shown to moderate the acceleration and terminal velocity of the roof element and, consequently, to influence the peak and residual velocities of the ensuing wind blast.

4.1 Flow Paths through Roof Element

The effect of flow paths through the falling roof was examined. Such flow paths allowed a supply of air into the zone of reduced air pressure above the element, permitting the later to attain a higher terminal velocity. Despite the consequent reduction in the total quantity of air expelled from the goaf into the surrounding mine workings, the higher "piston" velocity resulted in an increase in residual wind blast velocity. In the real mine situation, such air paths may take the form of open joints, bedding planes, cracks and fissures. Such discontinuities may already have opened before the fall commenced or their opening may be occasioned by the fall itself.

4.2 Voids above the Roof Element

The influence of a pre-existing void above the roof element was also investigated. The presence of such a void led to a reduction in the peak vacuum gauge pressure and, consequently, to an increase in the acceleration of the roof element. The resulting higher peak rate of air displacement resulted in an increase in peak wind blast velocity. In the real mine situation, such a void may form due to bed separation prior to the goaf fall.

A particularly hazardous situation was shown to occur in the case of a roof failure which extends to the ground surface, i.e. a 'plug type' collapse. In this circumstance, the zone of reduced air pressure which would moderate its fall does not form. Such a collapse will potentially generate the highest peak velocities during wind blasts.

4.3 Thickness, Plan Area and Weight

During the fall of a roof element which may be classified as 'thick', i.e. one which exerts a force per unit area which is significantly more than standard atmospheric pressure (1013 hPa), the comparative influence of the partial vacuum above the element is much reduced and it is the increased air pressure generated below the element which significantly influences its acceleration and terminal velocity. This pressure, together with the resistance to air flow in the openings, controls the rate at which air is expelled from the goaf and, consequently, determines roadway air velocity.

Peak air velocity in the roadways was found to be directly proportional to the mass per unit area of the roof element while the effect of the latter on the residual velocity was less marked. Extrapolating laboratory results to the field, it is to be expected that failures of thicker, denser strata will generate potentially higher peak velocities during wind blasts.

The plan area of the falling goaf exerted little influence upon its acceleration and terminal velocity. However, failures of larger areas of standing goaf resulted in larger quantities of air being expelled in unit time and, hence, increased roadway velocities. This was shown to apply both to the case of total collapse of the standing goaf area and to that of partial collapse.

4.4 Mining Height

'Critical distance' is the potential distance through which the roof element would need to fall in order to achieve its terminal velocity. If the height of the standing goaf and, hence, the distance through which the roof element falls is equal to the critical distance, the primary phase of the wind blast will be fully developed and the potential peak air velocity generated. Heights greater than critical will permit development of the secondary phase, characterised by lower velocity residual flow, leading to an increased duration for the overall event. Conversely, fall height which is less than critical distance will cause the primary phase to be truncated and peak air velocity to be reduced.

5. FIELD INVESTIGATIONS

Field investigations have been carried out at several wind blast prone coal mines with significant wind blasts being recorded at both Newstan and Moonee collieries.

5.1 Wind Blast Monitoring

Wind blast monitoring undertaken by The University of New South Wales School of Mining Engineering utilises a monitoring system specially developed to record air overpressures and velocities during wind blasts occasioned by massive roof falls. The equipment comprises a wind blast data logger, four sensor pods and a hand held interface. The equipment is certified and approved for use in hazardous locations in underground coal mines. The wind blast data logger is an intrinsically safe apparatus built into a flameproof enclosure. Four sensor pods are deployed to monitor absolute pressure, differential pressure and wind velocity in the ranges 0 to 200 kPa, ± 14 kPa and ± 150 m/s respectively. The hand held interface is an intrinsically safe module used to program the wind blast data logger and to transfer data from the latter to a personal computer. The data acquisition unit is the 'heart' of the system and continuously monitors the current loop circuits at a sampling frequency of 1000 scans per second, recording an event only when the preset trigger levels are exceeded (Fowler, Torabi & Daly, 1996).

5.2 Newstan Colliery

Newstan Colliery is located approximately 20 km south west of Newcastle, New South Wales, within the Lake Macquaire district of the Newcastle Coalfield. It currently works the West Borehole Coal at the base of the Newcastle Coal Measures by the longwall method. During 1994, Longwall 5 experienced strata control problems, severe periodic weightings and a dozen midface roof falls. The panel was 226 m in width and located at a depth of approximately 200 m. The overburden included a massive sandstone/ conglomerate channel up to 50 m in thickness and located within 5 to 25 m of the working horizon.

In order to obviate the strata control difficulties, the subsequent panel, which had already been developed, was split longitudinally into two blocks each 95 m wide between gateroad centrelines. The expectation that the massive strata would bridge the goaf or fail well behind the face was borne out in practice. Unfortunately, however, wind blast presented a hazard over parts of Longwalls 6 & 7 when the main roof 'hung up' and the immediate roof strata, comprising coal, shale and mudstone, was less than about twice the extraction height of 3.3 m. Although the friable immediate roof caved readily behind the longwall chock supports, it provided insufficient bulked material to fill the goaf void. These conditions created significant gaps above and behind the chocks and exposed the face to air displacements following any major roof fall. However, provided that the base of the channel was sufficiently distant (vertically separated) from the seam horizon, then the immediate roof strata 'bulked up' sufficiently to fill the goaf void and cushioned any failure of the overlying channel strata, thereby obviating wind blast. Face lengths for subsequent panels were increased to 127 m between gateroad centrelines. However, for part of the extraction of Longwall 8 and 9, during which the geological conditions described above persisted, wind blast remained a hazard.

5.2.1 Instrumentally Recorded Events

A total of 23 wind blast events were recorded instrumentally at Newstan Colliery during the mining of Longwalls 7, 8 and 9 between 1995 and 1997. Of these 8 were significant i.e. of sufficient intensity to pose a risk of personal injury or of damage to the mine ventilation system (Simson, Hebblewhite & Fowler, 1997). Maximum values of the various recorded parameters are shown in Table 1.

Table 1. Wind blast parameters at Newstan Colliery.

Parameter	Maximum value
Peak air velocity	40 m/s
Rate of rise of velocity	50 m/s/s
Peak overpressure	10 kPa
Rate of rise of pressure	5 kPa/s
Impulse	20 kPa.s

5.3 Moonee Colliery

Moonee Colliery is located on the New South Wales coast at Catherine Hill Bay, approximately 30 km south of Newcastle. Like Newstan Colliery, it is situated within the Lake Macquire district of the Newcastle Coalfield. However, it mines one of the uppermost seams of the Newcastle Coal Measures, the Great Northern Coal. The mine reopened in 1995 as a longwall operation and, in order to minimise surface subsidence, the longwall panels are only 100 m wide between riblines. The depth of cover for Longwall 1 panel is approximately 160 m and the longwall extraction height is approximately 3.5 m. The Booragul Tuff, the so called 'claystone roof' (Olsen, 1984) overlies the coal and is itself overlain by the Teralba conglomerate member which is up to 35 m in thickness and comprises conglomerate, sandstone and some mudstone.

5.3.1 Instrumentally Recorded Events

During the mining of Longwall 1 at Moonee Colliery in 1998, a total of 24 wind blast events were recorded instrumentally. Of these 15 were significant. Table 2 gives the maximum values of the various recorded parameters.

Table 2. Wind blast parameters at Moonee Colliery.

Parameter	Maximum value
Peak air velocity	80 m/s
Rate of rise of velocity	100 m/s/s
Peak overpressure	26 kPa
Rate of rise of pressure	25 kPa/s
Impulse	42 kPa.s

Figures 1 and 2 show the wind peak velocity and overpressure time histories for two typical events recorded during the mining of Longwall 1 at Moonee Colliery. Figure 3 indicates the relationship between peak wind blast velocity and peak overpressure for a measuring location near to the coal face, while figure 4 gives the attenuation of peak overpressure with distance from the face. In contrast to the monitoring at Newstan Colliery, it was possible at Moonee Colliery to identify the roof falls which gave rise to the wind blasts and to assess their plan areas. The relationship between roof fall area and wind blast intensity is given in Figure 5. It is expected that as more data becomes available, the relationship will become better defined.

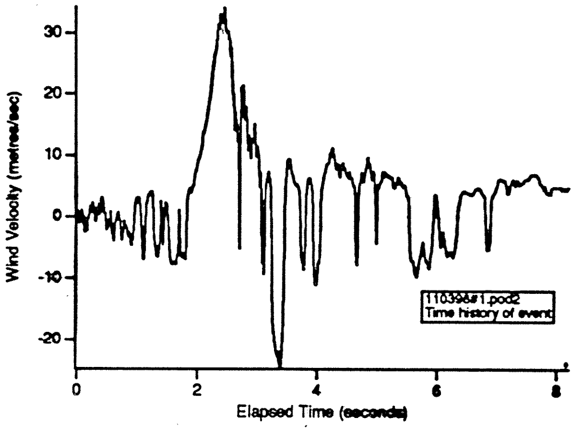

Figure 1. Velocity time history for a typical wind blast event.

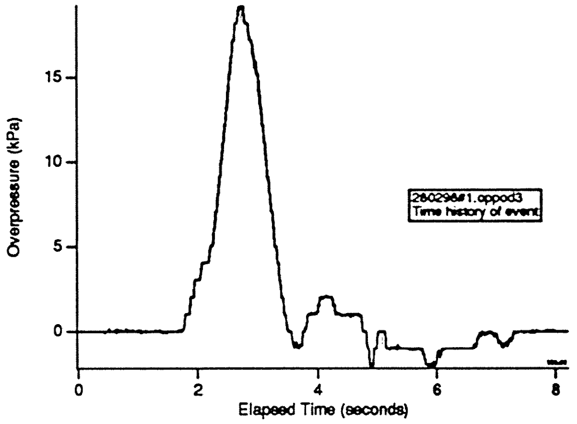

Figure 2. Overpressure time history for a typical wind blast event.

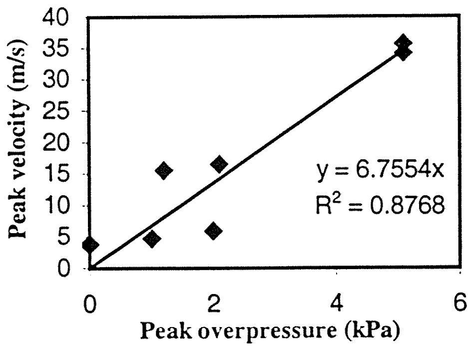

Figure 3. Peak wind blast velocity versus peak overpressure.

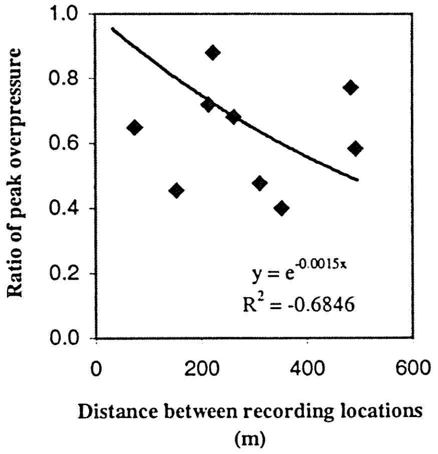

Figure 4. Attenuation of peak overpressure with distance.

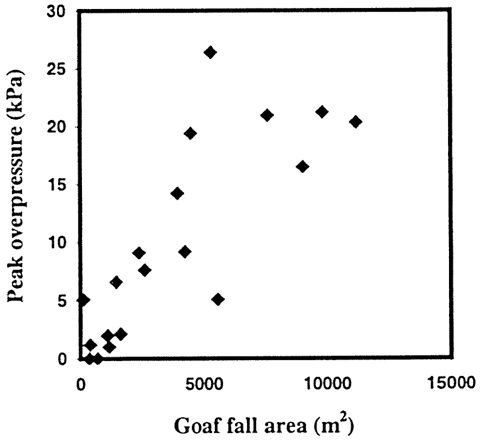

Figure 5. Peak overpressure versus goaf fall area.

6. ANALYSIS OF RESULTS

Roof caving is influenced both by geological features and by the layout of the longwall panel while roof fall area, location of the fall with respect to the measuring locations, failure sequence and obstructions in airflow paths all influence peak air velocities and overpressures measured in adjacent openings.

7. SIGNIFICANCE OF RESULTS

Wind blast monitoring in conjunction of physical modelling has facilitated the following:

- The quantification of wind blast intensity and of the attenuation of intensity with distance from the face for the following purposes:
  - Defining the extent of areas within which full 'wind blast working conditions' must be implemented for the protection of mine personnel.

  - Determining safety distances or exclusion zones for periods of high wind blast risk.
  - Providing guidance regarding 'safe havens'.
  - Providing guidance for overall panel design.
- The quantification of the results of wind blast reduction measures which may include the following:
  - Providing wind blast safety shields to close potential pathways by which wind blast may directly impinge on mine personnel at the coal face.
  - Erecting wind blast proof stoppings or regulators in mine openings in order to isolate the wind blast prone panel from other workings.
  - Creating preferred wind blast 'pathways' by modifying panel layout.
- The determination of the relationship between the area of roof fall and the magnitude and intensity of the associated wind blast with implications for operational hazard management and risk assessment based on the extent of roof overhang.
- Correlation of measured wind blast intensity with physical damage. The extent of damage to elements of the mine such as water barriers and stoppings has been shown to be related to the intensity of the event as determined by measured overpressures and wind velocities. This has proven valuable for design purposes.
- The assessment of potential injury to mine personnel. High wind velocities can result in mine personnel being blown over and injured or being hit by air entrained objects. Measured or inferred velocities have substantially exceeded the value of 20 m/s which has been tentatively adopted as the threshold for toppling of persons in an upright stance (Fowler & Torabi, 1997). Measured overpressures have approached, but not exceeded, the threshold for ear drum damage.

8. CONCLUSIONS

Laboratory physical model testing has shown that the 'permeability' of the roof elements and the existence of bed separation prior to a roof fall both play a significant role in modifying the intensity of a wind blast event. The roof caving sequence is influenced both by geological features and by the layout of the longwall panel while roof fall area, location of the fall with respect to the measuring locations, failure sequence and obstructions in airflow paths all influence the peak air velocities and overpressures measured in adjacent openings. The present study is continuing and will help in establishing safe layout and design norms for mining under massive conglomerate roof and in risk assessment for operational and safety considerations.

9. ACKNOWLEDGEMENTS

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