Resource Operators Conference

Faculty of Engineering and Information Sciences

2023

Defining explosion risk exclusion zones around coal mine openings in emergency situations

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DEFINING EXPLOSION RISK EXCLUSION ZONES AROUND COAL MINE OPENINGS IN EMERGENCY SITUATIONS

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ABSTRACT: The risk of explosions in coal mines is an important subject that requires a comprehensive understanding of explosion dynamics, mining operations, and mining safety. Recent spontaneous combustion events in New South Wales (NSW) and Queensland have resulted in mine evacuations due to a Trigger Action Response Plan (TARP) being activated at the evacuation level. A sound basis is required for defining the high-risk working zones, mine operational exclusion zones for both emergency activities and mine design considerations, and public exclusion zones during emergency situations. This paper presents a methodology for predicting and defining explosion risk around the coal mine portals developed using Computational Fluid Dynamics (CFD) and experimental results from an advanced blast simulator simulating blast waves exiting a portal entry and propagating over an outside mine site terrain. The methodology can be applied to generate exclusion zones that account for the effects of blast waves emanating from the mine openings. A worked example is provided at the end of the paper as a reference to engineers for the development of mine exclusion zones from blast wave effects.

INTRODUCTION

Over the past century, the underground coal mining industry experienced a large number of explosions leading to a considerable loss of life and severe destruction of surface infrastructure. National Institute for Occupation Safety and Health (2019) recorded 503 cases of underground coal mine disasters caused by methane-air and/or coal dust explosions with a total of 12 000 recorded casualties. While technological improvements and stricter safety regulations have reduced coal mining-related fatalities, accidents are still too common. Looking back as close as November 19th 2010, the Pike River coal mine located northeast of Greymouth in New Zealand exploded, trapping miners underground and ultimately claiming twenty-nine miners underground (Mine Accident and Disaster Database, 2021).

Significant research efforts worldwide have been directed at investigating the prevention and minimisation of the effects of explosions in underground coal mines. However, not sufficient attention has been given to the potential risks associated with explosive forces expelled through the mine opening and resulting in injuries and infrastructure damage in proximity to the mine opening on the surface. Although several operation guidelines and regulations are currently put in place to establish a high-risk zone around mine portals and ventilation shafts, there is an inadequate scientific basis to support the zone dimensions suggested in the Queensland Mines Rescue Services document (MIU-931, 2019) which appear to be derived arbitrarily.

A review of studies performed in the military context (of underground ammunition and explosive storage) reveals empirical relationships developed to estimate blast wave characteristics as a function of azimuth angle and distance from the tunnel exit into an open space (Skjeltorp et al., 1977, Helseth, 1985, Kingery, 1989, Swisdak and Ward, 2000). Although the environment and explosion sources can be different, some of the studies could provide insight and a framework for developing new data that could be relevant for underground mine explosions. For example, blast parameters such as peak overpressures, duration and impulses can be characterised into explosion risks by relating them to personnel injury and structural damage thresholds compiled by the NATO manual for safety principles of storage of military ammunition and explosives (AASTP-1, 2010).

This paper proposes a methodology for predicting explosion risk around different types of mine portals to develop scientifically established exclusion zones that consider the effects of blast waves emanating

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from mine entries. A detailed worked example is provided to demonstrate the application of the developed methodology.

DEVELOPMENT OF METHODOLOGY FOR SCIENTIFICALLY PREDICTING HIGH-RISK ZONES AROUND MINE ENTRIES

Physical Simulation of Blast Waves Propagating from Mine Openings

To investigate the propagation of blast waves exiting mine entrances and over an outside mine site terrain, an Advanced Blast Simulator (ABS) with cross-sectional dimensions of 0.3 m x 0.3 m was fabricated (**Figure 1**). The simulator is based on the ABS concept, which is specially designed to generate shock or overpressure waves that replicate the wave dynamics of an actual free-field explosive blast (Gan et al., 2020). The Driver of the ABS has a divergent wedge-shaped profile and operates by the detonation of the oxy-acetylene mixture to generate a propagating shock wave. The characteristic blast wave shape is created by the expansion of the gas out of the divergent Driver and through the initial divergent Transition Section; once formed, the wave is smoothly re-converged into the Test Section before eventually exiting the ABS into the open space as a propagating shock front.

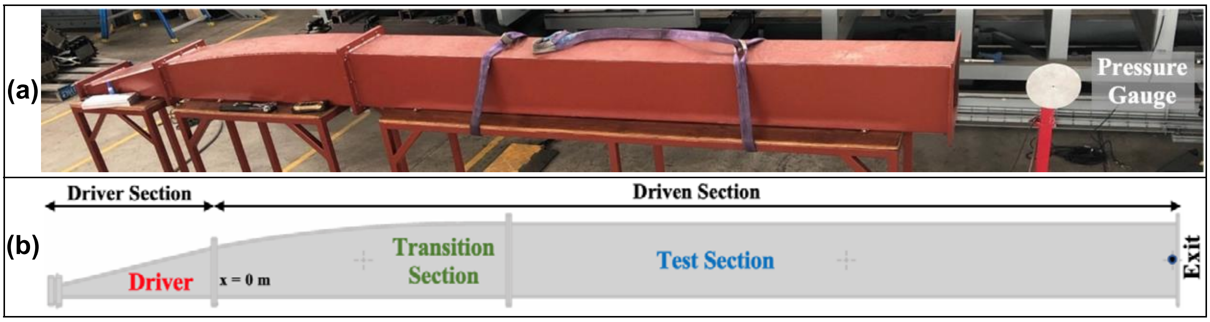


Figure 1: (a) 0.3 m x 0.3 m Advanced Blast Simulator (ABS); (b) main components of the ABS

For this study, the ABS was set up with three configurations to represent different types of mine entries: a portal into highwall and a standalone portal (**Figure 2**). In addition to measurements of blast pressures at the ABS exit, pressure transducers were mounted outside on baffle plates (for measuring static overpressures) and pitot-static probes (to determine dynamic pressures) as an array along the centreline and on the vertical flange (surrounding the ABS exit) at 1 m intervals from the ABS exit. The ABS was rotated (i.e., 0˚, 30˚, and 60˚) to characterise the outside blast environment at different azimuths. A high-speed data acquisition system (Synergy P Portable; Hi-Techniques, Inc.) was used to record data at a sampling rate of 500 kHz.

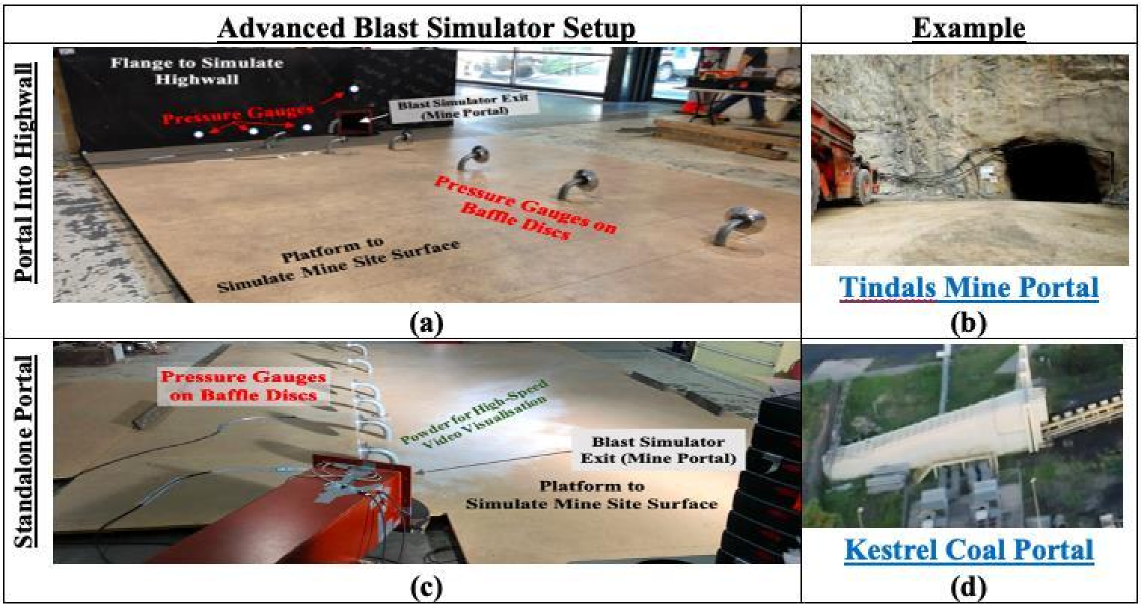
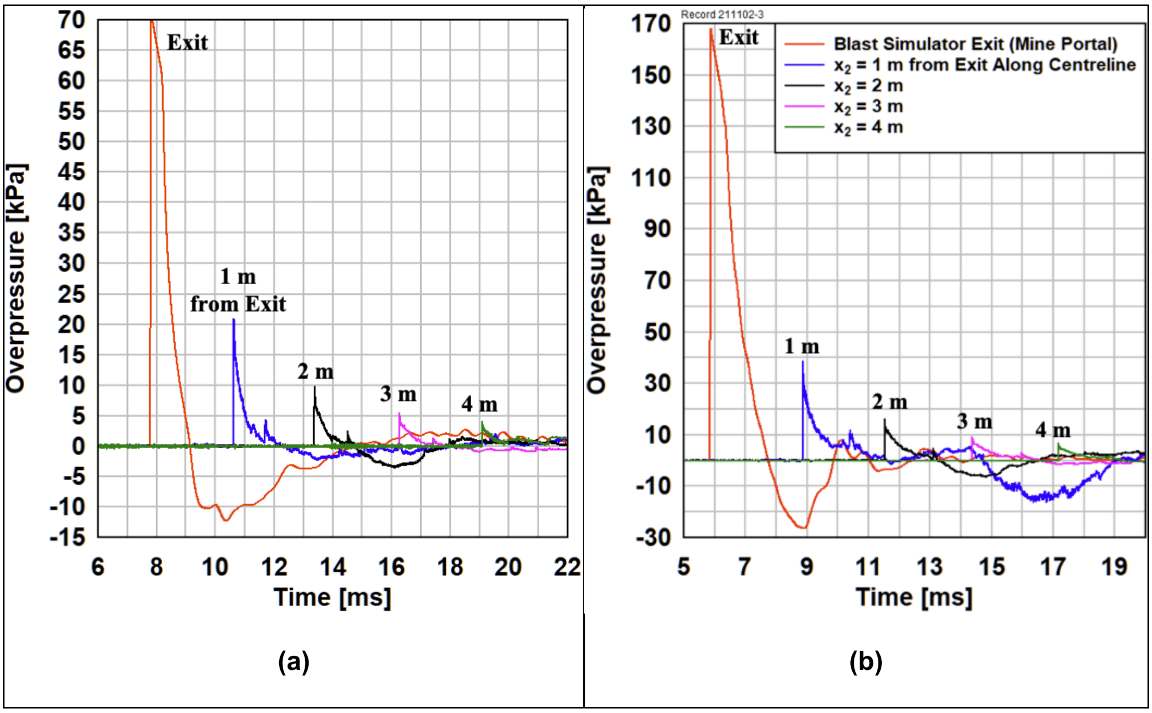


Figure 2: Experimental setups for physical simulation of blast propagation from different mine openings: (a) portal into highwall; (b) standalone portal

Figure 3 presents examples of blast wave records for the laboratory ABS exit pressures of 70 kPa (**Figure 3a**) and 170 kPa (**Figure 3b**) at varying distances from the ABS exit along the centreline. The records illustrate that peak static overpressure reduces considerably as the blast wave propagates away from the ABS exit.



(a)

(b)

Figure 3: Experimental records recorded at the ABS exit and several locations away from the exit along the centreline: (a) 1.75 L Driver; 70 kPa portal; (b) 7 L Driver; 170 kPa portal

Figure 4 compares the blast wave records taken at various angles with respect to the ABS centreline 1 m from the ABS exit. The 90˚ record is taken from a pressure transducer mounted on the vertical flange which represents a highwall. The plots indicate that the most severe conditions are generated along the centreline axis (i.e., 0˚) with peak overpressure reducing according to the azimuth angle. Interestingly, while the least severe conditions were generated at the 90˚ angle, the blast or explosion overpressure wave appears to arrive soonest at the 90˚ and latest along the centreline (i.e., 0˚).

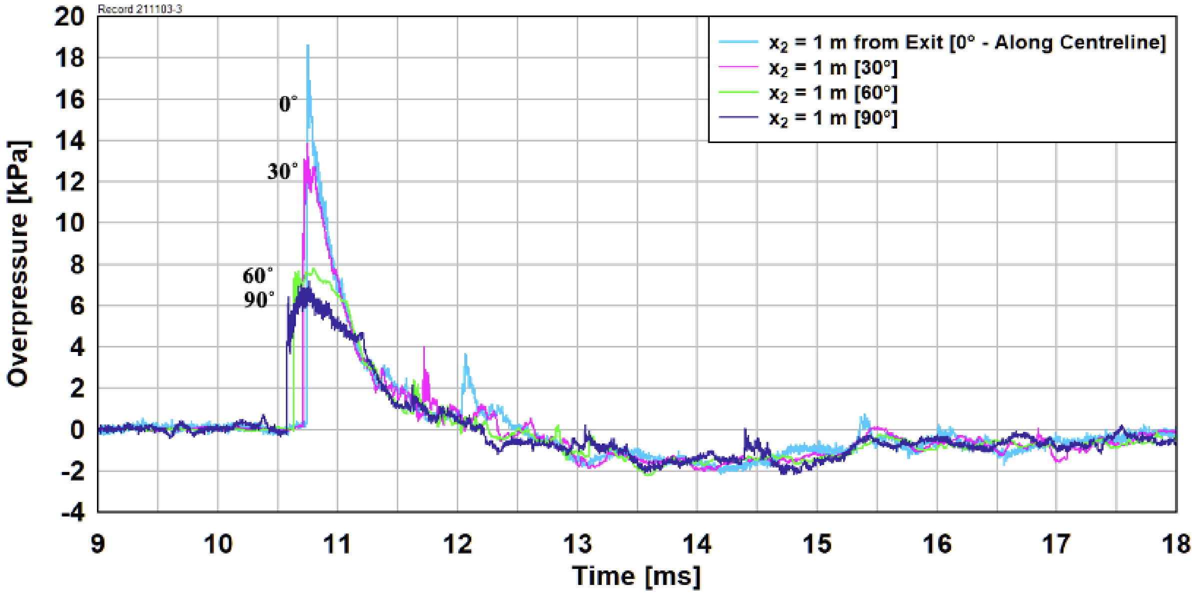


Figure 4: Comparison of blast wave records generated with a 1.75 L Driver and measured at different azimuth angles from the ABS centreline. All angles are at 1 m from the exit

The preliminary experimental results presented in this section provide a framework for developing relationships (represented with pressure contours) describing the blast environment beyond different variants of mine openings.

Non-Dimensional Parameters of the Portal

Figure 5 provides a sample of eight experimental tests performed with the ABS with either 1.75 L or 7 L of oxy-acetylene filled in the Driver of the ABS to vary the blast wave strength. These examples were based on the ABS set-up representing blast waves propagating out of a portal with a surrounding highwall surface (**Figure 2a**). When the results were divided with the ABS exit (portal) pressure and ABS diameter, a consistent trend of pressure ratio P/P_{portal} vs. distance ratio R/D_{portal} is observed for all results regardless of differences with the blast wave strengths (see **Figure 5**). P is peak overpressure determined, P_{portal} is the peak overpressure at the portal, R is the outside distance from the ABS exit, D_{portal} is the diameter of the ABS exit.

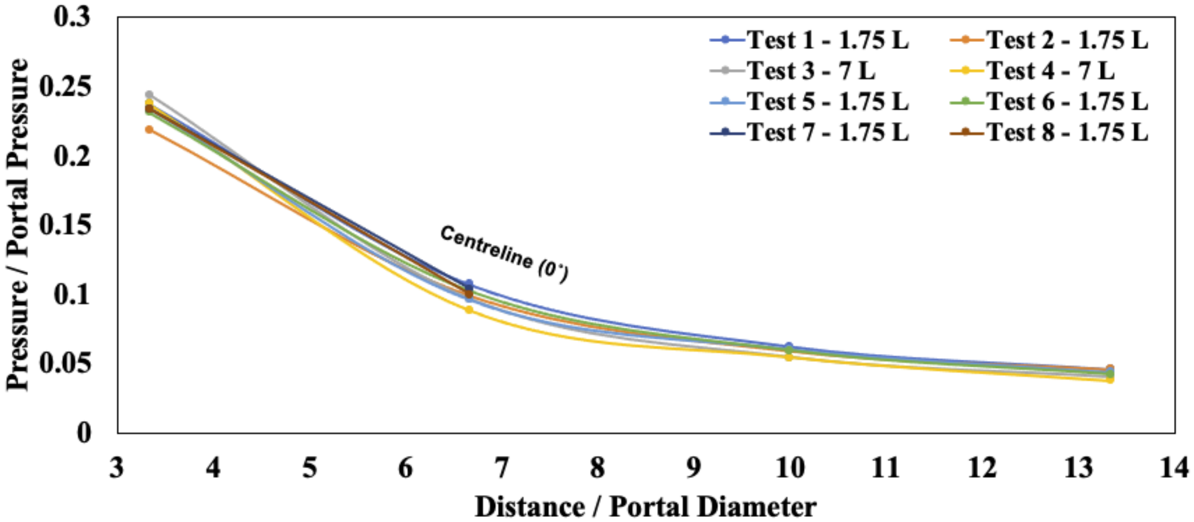


Figure 5: Several experimental tests superimposed. Consistent trend along the ABS centreline (i.e., 0˚) generated regardless of the volume of gas mixtures in the Driver of the ABS (i.e., detonation chamber)

Numerical Simulation of Blast Waves Emanating from Mine Openings

Numerical models based on Computational Fluid Dynamics (CFD) were developed with the Viper::Blast software (Stirling Simulation Services Limited, 2020) (**Figure 6**). The models were based on the laboratory ABS described in the previous section and were employed to correlate the experimental results, validate the scalability of the results to full-scale dimensions of coal mine infrastructure, and supplement the collected experimental data to increase the resolution of the data points for developing visualisations of blast pressure contour maps outside the mine portals.

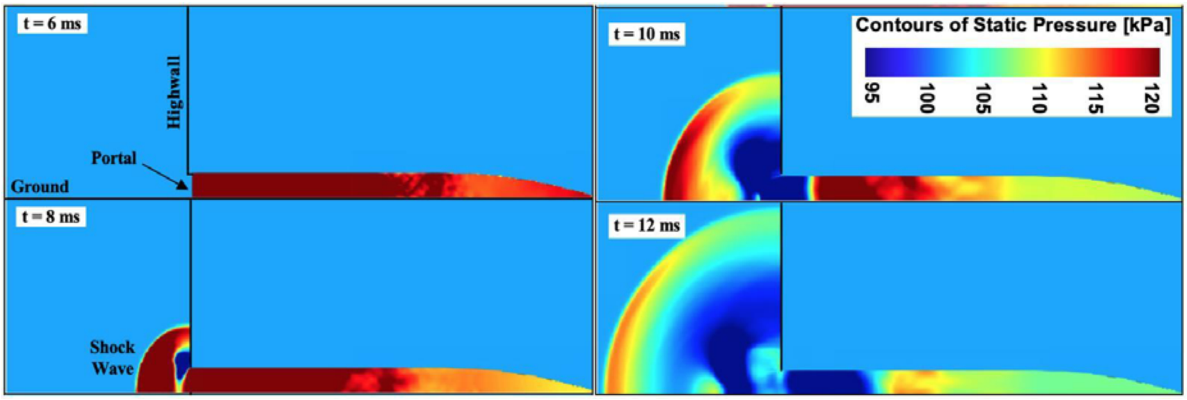


Figure 6: Pressure contours from CFD model showing blast wave propagation from ABS exit (representing mine portal) at snapshots up to 12 ms after detonation

The CFD results were validated with small-scale laboratory experimental testing and existing empirical relationships of blast wave parameters given as a function of azimuth angle and distance from the tunnel exit taken from previous research on underground munition storage explosions from the open literature and military documents. **Figure 7** compares results for pressure ratio P/P_{portal} vs. distance ratio R/D_{portal} generated with the CFD model for standalone square portal with existing empirical equations (Skjeltorp et al., 1977, Helseth, 1985, Kingery, 1989, Swisdak and Ward, 2000) along the centreline of the tunnel (0˚). This figure demonstrates that the CFD model correlates well with other existing equations and the experimental results in this paper.

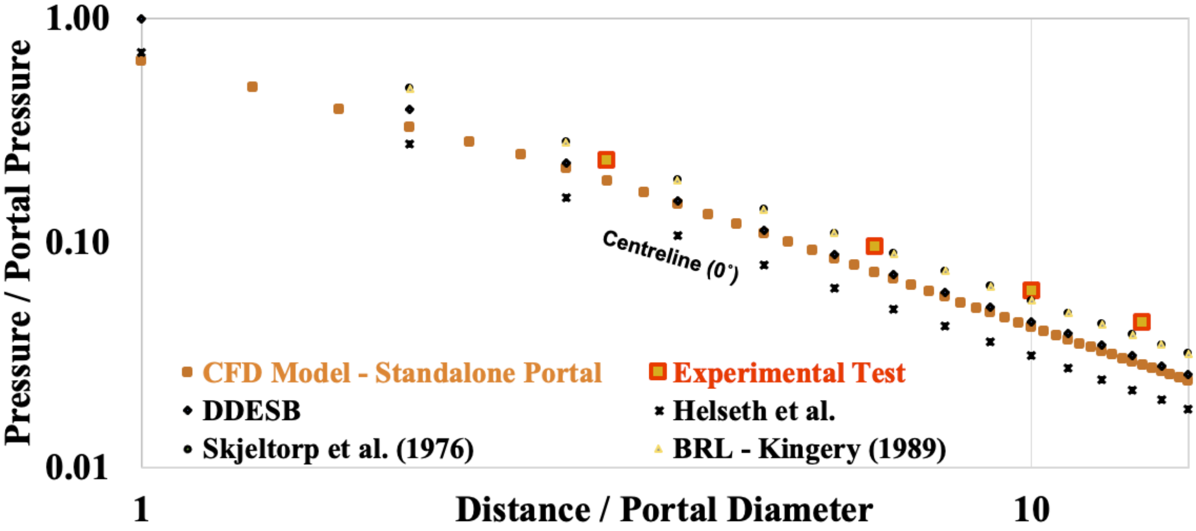


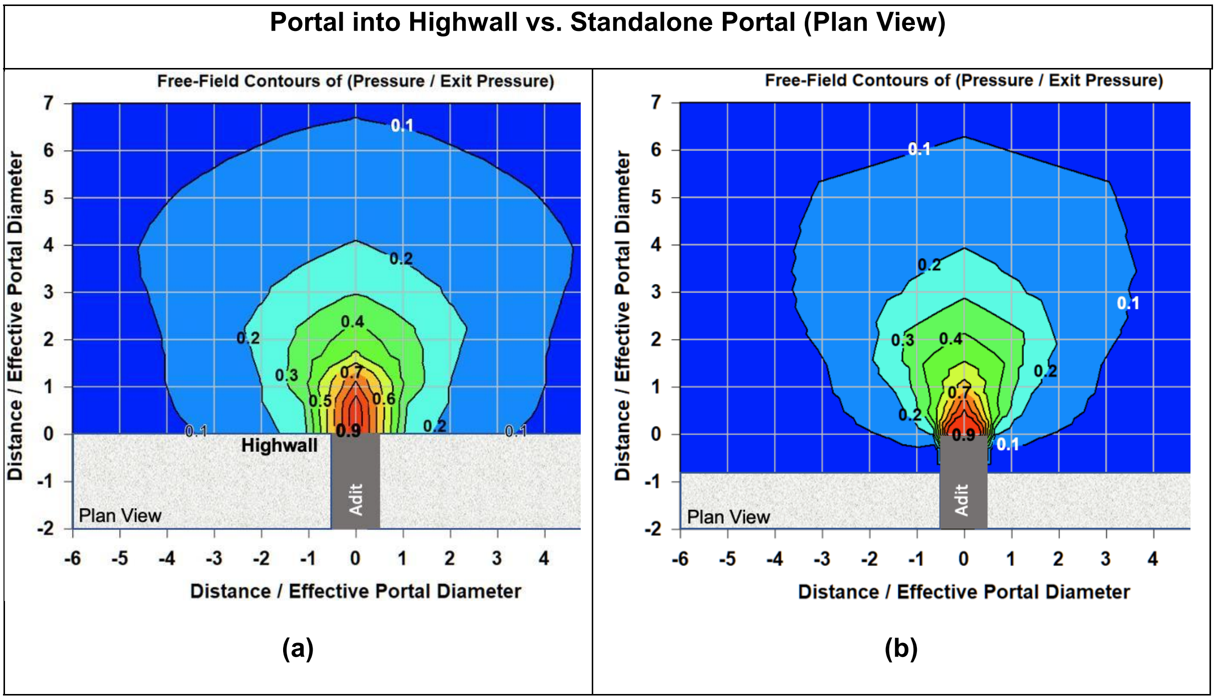
Figure 7: Comparison of CFD model and experimental results in this study with empirical equations from previous studies of blast propagation from ammunition storage tunnels

Using the CFD model, the scalability of the results generated by the 0.3 m x 0.3 m ABS was also confirmed and validated. CFD models with an adit cross-section of 0.3 m x 0.3 m and 3 m x 3 m to represent small-scale and full-scale dimensions of mines, respectively were used to generate contours of peak static overpressure. When the results were divided with the portal exit pressure and effective portal diameters, all differences resulting from the length scales become cancelled out and identical contours are generated. This confirms that the results generated from the 0.3 m x 0.3 m ABS model are valid and applicable for characterising the blast environment of full-scale mine openings. Additionally, it was found that relationships presented as ratios of portal pressure and effective portal diameters are applicable for different portal shapes.

GENERATION OF EXTERNAL BLAST ENVIRONMENTS IN PROXIMITY TO DIFFERENT MINE OPENINGS

This section investigates the external blast environment in proximity to different types of common mine openings generated with the CFD models. Where applicable, the results in this paper are provided as ratios of effective portal diameters (R/D_{portal}) and ratios of portal pressures (P/P_{portal}). This enables external blast environments to be characterised by a wide range of mine openings of different diameters, shapes, and portal conditions. Results can be calculated and read in meters and kPa (pressure) by multiplying lengths with effective portal diameters and portal pressures. The use of the effective diameter of portal openings as a single parameter to characterise other portal shapes has been verified in the present study. The effective diameter for a rectangular portal of 6 m x 4 m cross-section would be 5.5 m.

Figure 8 presents contours of blast overpressures that characterise the blast environment outside of different mine opening types and scenarios. In these figures, it can be observed that blast pressures dissipate with distance away from the mine opening. The contours visualise the effect of directionality with the most severe blast environment occurring along the centreline of the opening and decreasing in severity with azimuth angle at the same distance.



(a)

(b)

Figure 8: Comparison of non-dimensional contours of blast overpressure for (a) portal into highwall and (b) standalone portal

A portal could be a standalone structure or surrounded by a surface (**Figure 8a** vs. **Figure 8b**). The surrounding surface appears to influence only the distribution of pressures in the direction perpendicular to the portal and in close proximity to the portal. The results generated along the centreline of the portal are only minimally influenced by the surrounding surface. The most severe blast conditions occur along the centreline of the portal opening with about 6-7 portal diameters required to dissipate blast waves to 10% of portal conditions.

The Blast Wind

In addition to a blast pressure wave that propagates out of a mine entrance or tunnel resulting from an underground explosion event as characterised in the previous section, a venting of a powerful jet or blast wind originating from within the drift also occurs. The blast wind possesses a much larger destructive energy than a blast wave exiting out of a tunnel. From the present study, it was ascertained that the blast wind only manifest most significantly along the centreline and become very weak or insignificant at larger azimuth angles. It should be noted that the hazard posed by blast winds extends far beyond that when only considering blast waves. Further study is needed to quantify and properly account for the hazards from blast winds for the development of all-hazard exclusion zones.

WORKED EXAMPLE OF DEVELOPING EXCLUSION ZONES

Develop blast pressure exclusion zones for coal mine portal with dimensions 6 m x 4 m. Portal type: Portal into highwall.

1) Select/copy the non-dimensional contour map for the required type of portal shown in **Figure 8**. For this example, select **Figure 8(a)**.
2) Find the effective diameter of the portal, D_{eff}, which is defined as a circular opening.
    a. Portal dimensions are 6 m x 4 m.
    b. The area of the portal is 6 m x 4 m = 24 m^2.
    c. The effective diameter of the portal is $2\sqrt{24/\pi} \approx 5.5$ m.
3) Estimate from blast wave propagation analysis the exit peak pressure at the portal, P_{portal}.
    a. For this example, the exit peak pressure $P_{portal} = 70$ kPa is used. Generally, an assumption needs to be made about a likely starting overpressure event (e.g., ignition of gas on an active longwall face) then the reduction of the overpressure wave as it travels towards the mine openings needs to be calculated.
    b. Multiply the distances on the scaled contours (i.e., the X and Y axes) by D_{eff}.

c. Multiple the blast contours by P_{portal}.

d. Update the contour map view to show the actual values of distances and blast overpressures outside the mine opening (**Figure 10**).

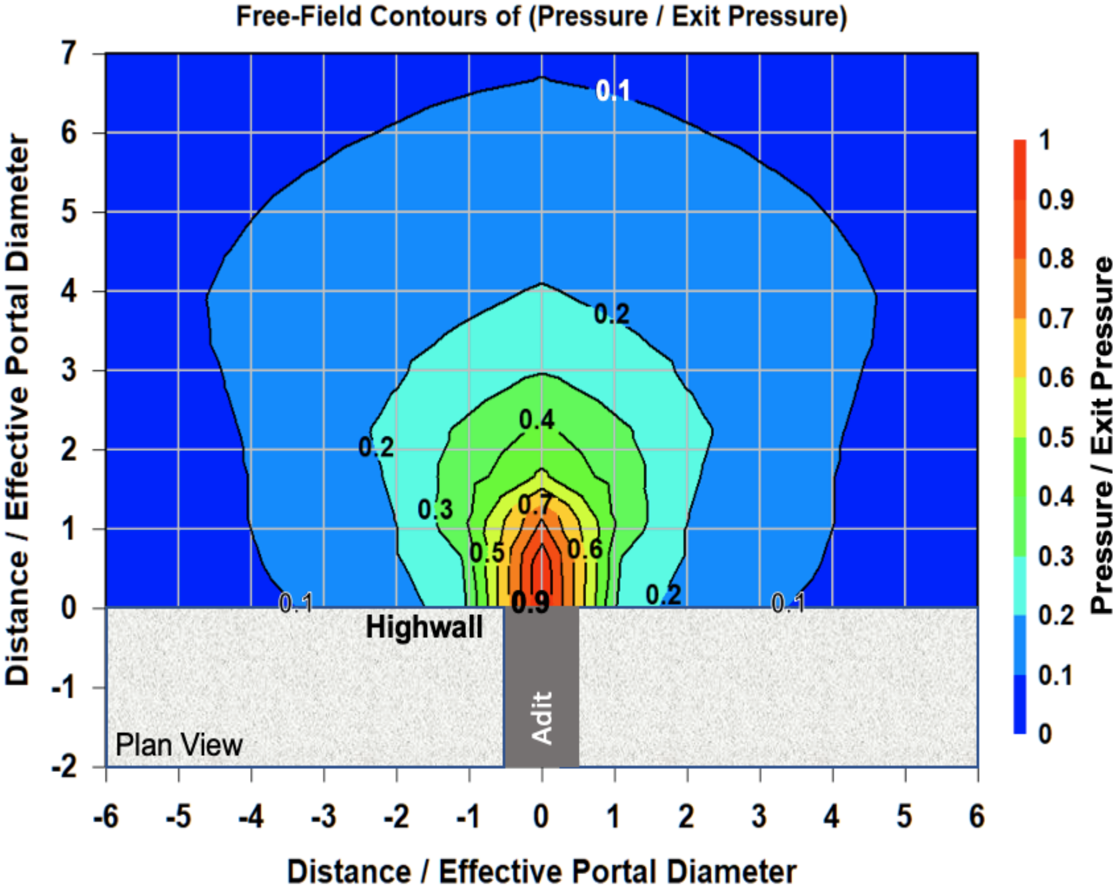


Figure 9: Blast overpressure contours for portal into highwall (non-dimensional)

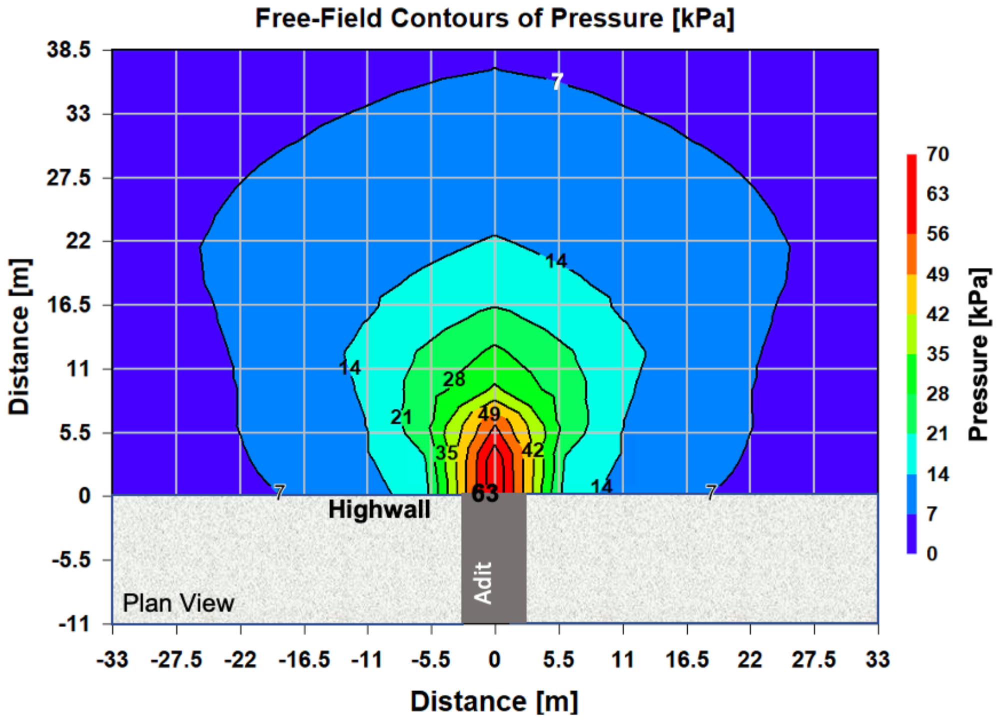


Figure 10: Peak static overpressure contours for portal into highwall (actual dimensions) for 70 kPa portal exit blast pressure

4) Develop an exclusion zone against the effects of blast waves. (Note: this exclusion zone will not account for the effects of strong blast wind or projectiles).
    a. Perform risk assessment or use accepted industry practice to determine critical blast overpressures for personnel or surface infrastructure.
    b. Determine and draw the exclusion zones based on critical blast overpressures to minimise blast risk to personnel, infrastructure facilities and equipment around the coal mine opening.
    c. For example, if it is deemed unacceptable for human injury to occur, critical blast overpressure is 7 kPa from **Table 1**. The exclusion zone line is therefore marked according to that requirement.
    d. The completed exclusion zone is illustrated in **Figure 11**. Note that the worked example is only for determining an exclusion zone based on blast pressure. The effects of blast wind and projectiles are beyond the scope of the current paper and will be investigated in future research projects.

Table 1: Injury effects from long-duration blast overpressures summarised by Zipf and Cashdollar (2007)

Blast Overpressure [kPa]	Effect on the Human Body	Effect on the Structures
7	Light injuries from fragments occur	Window glass shatters
14	People injured by flying glass and debris	Moderate damage to houses (windows and doors blown out and severe damage to roofs)
21	Serious injuries are common, fatalities may occur	Residential structures collapse
34	Injuries are universal, fatalities are widespread	Most buildings collapse
69	Most people are killed	Reinforced concrete buildings are severely damaged/demolished
138	Fatalities approach 100%	Heavily built concrete buildings are severely damaged/demolished

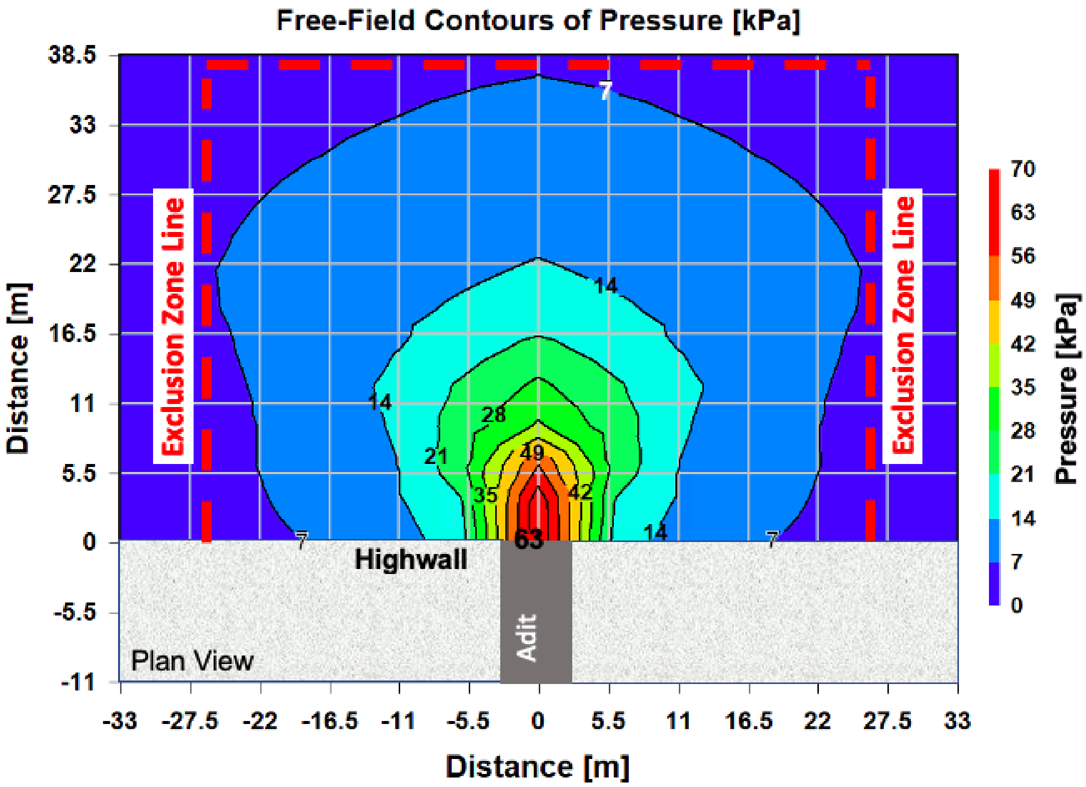


Figure 11: Proposed exclusion zone from effects of blast waves for a 6 m x 4 m portal with surrounding highwall with 70 kPa exit peak pressure

ACKNOWLEDGMENTS

The authors would like to thank the technical staff at the structural laboratory of the University of Wollongong in particular Mr. Alan Grant, Mr. Soon Sien Tan, Mr. Cameron Nielson, Mr. Gavin Bishop, Mr. Alex Gonzales, and Mr. Carl Rindlisbacher for their invaluable support in assisting with the experiments. The developmental work of the Advanced Blast Simulator concept by Mr. David Ritzel of Dyn-FX Consulting Ltd. (Canada) is greatly acknowledged. This work was funded by The Australian Coal Industry's Research Program (ACARP) [Project C29018].

CONCLUSIONS

There exists a significant gap in existing mining safety standards resulting in the usage of highly conservative safety distances/exclusion zones due to a lack of understanding or scientific-driven guidelines. This study aims to address this with the development of a methodology to predict explosion risk and appropriate exclusion zones from mine portals. A 0.3 m x 0.3 m Advanced Blast Simulator was fabricated and employed to conduct experiments on blast waves propagating from different types of mine openings into the open space. The results collected from pressure gauges were used to calibrate Computational Fluid Dynamics models developed for correlating the experimental results, validating that the results could be scaled up to full-scale dimensions of actual coal mine infrastructure, and develop blast contour maps to visualise the outside blast environment beyond the mine openings. It was demonstrated that when the results were given in the form of ratios of effective mine opening diameters and ratios of mine opening pressures, the scaled contours could represent and predict outside blast environments of different opening shapes, dimensions, and pressures at the mine opening. The models indicate that the most severe outside blast environment would be generated from square portals with a surrounding highwall surface while standalone portals generate slightly less severe conditions at the lateral distances from the portal. The findings from the study were consolidated with a detailed worked example provided at the end of the paper as a reference to engineers for the development of mine exclusion zones from blast waves. It should be noted however that hazards arising from the end-jet (strong blast wind) and projectiles are beyond the scope of the current paper and will be investigated in future research projects.

REFERENCES

AASTP-1 2010. Manual of NATO Safety Principles for the Storage of Military Ammunition and Explosives. (NOTE: This manual supersedes NATO Document AC/258-D/258). North Atlantic Treaty (NATO), Organization Military Agency For Standardization (MAS).

GAN, E. C. J., REMENNIKOV, A., RITZEL, D. & UY, B. 2020. Approximating a far-field blast environment in an advanced blast simulator for explosion resistance testing. *International Journal of Protective Structures,* 11**,** 468-493.

HELSETH, E. S. 1985. Blast Effects From Accidental Explosions. Oslo, Norway: Norwegian Defence Construction Service.

KINGERY, C. N. 1989. Survey of Airblast Data Related to Underground Munition Storage Sites. Aberdeen Proving Ground, Maryland: U.S. Army Laboratory Command.

MINE ACCIDENT AND DISASTER DATABASE. 2021. *Pike River NZ 2010* [Online]. Mining Accident Database. Available: http://www.mineaccidents.com.au/mine-event/120/pike-river-nz-2010 [Accessed May 15 2021].

MIU-931 2019. Inertisation (MIU) Operational Procedure – Version 3. Queensland Mines Rescue Service (QMRS).

NATIONAL INSTITUTE FOR OCCUPATION SAFETY AND HEALTH 2019. Underground Coal Mine Disasters by Accident Type, 1839-2019. August 27 ed.

SKJELTORP, A. T., JENSSEN, A. & RINNAN, A. 1977. Blast Propagation Outside a Typical Underground Ammunition Storage Site. *Fifth International Symposium on Military Applications of Blast Simulation.* Stockholm.

STIRLING SIMULATION SERVICES LIMITED 2020. Viper::Blast User Manual and Examples for Version 1.17.0.

SWISDAK, M. M. & WARD, J. M. 2000. The DDESB Blast Effects Computer—Version 4.0. Minutes of the 29th DoD Explosives Safety Seminar.

ZIPF, R. K. & CASHDOLLAR, K. L. 2007. Explosions and Refuge Chambers. Columbus, OH: NIOSH Docket Number 125. National Institute for Occupational Safety and Health.