Evaluating the Effect of Meteorological Conditions on Blast-Induced Air Over-Pressure in Open Pit Coal Mines

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Abstract. Air blast waves are recognized as one of the negative effects induced by blasting operations in open pit mines. The intensity of air over-pressure is taken into account as the primary parameter to determine the damages on the surrounding environment. Many researchers commented on the effects of meteorology on blast-induced air overpressure, such as temperature, relative air pressure, wind direction and speed, air humidity, to name a few. However, they were not fully addressed. Therefore, this study aims to fully address the effect of meteorology conditions on blast-induced air over-pressure in open pit mines through the air over-pressure predictive models. Nui Beo open pit mine in Quang Ninh province of Vietnam, where suffers significantly from tropical climate with two generally rainy and dry seasons, was selected as a case study for this aim. The results revealed that the meteorological conditions have a great effect on blast-induced air over-pressure, especially air humidity and wind speed. These contribute to enhance the effect of blasting operation for Nui Beo coal mine in particular, and for all coal mines in Vietnam.

Keywords: Blast · Meteorological conditions · Over-pressure · Open pit mine · Nui Beo · Quang Ninh · Vietnam

1 Introduction

The influence of intense monsoons characterizes Vietnam's climate, but with much sunshine, high rainfall, and high humidity. The regions near the tropics and the mountainous areas have a temperate climate. Monsoon climate also affects the change of

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tropical moisture. In Vietnam, there are generally two seasons: the hot season is from May to October and the cold season is from November to next April. The difference in temperature between the two seasons in the South is almost imperceptible, with an average of 3 °C. Most notably, in the North, the difference of 12 °C is observed. There are four distinct seasons, most evident in the Northern provinces (from Hai Van toward the North): Spring, Summer, Autumn, Winter. The northeastern region includes the northern and northeastern provinces in Vietnam such as Lao Cai, Yen Bai, Hoa Binh, Ha Giang, Tuyen Quang, Phu Tho, Cao Bang, Lang Son, Bac Kan, Thai Nguyen and Quang Ninh.

Northeast monsoons strongly influence the climate. A cold, cloudy winter (little sunshine) is characterized by drizzle. The cold wave came earlier than other provinces. Summer is hot and rainy coincides with the rainy season. However, unlike in the northwest, drought conditions are rare due to low westerly wind frequency. The rainy season usually lasts from May to September, although it can vary from 4 to 10 months. The average annual temperature in the coastal areas is around 22 °C, with the coldest month having an average temperature of 15 °C and the hottest month having an average temperature of 38 °C. The average annual rainfall in coastal areas is about 1,800 mm. The annual average humidity is 84%, the lowest 81%, and the average humidity of many years is 82.3% [1].

For open pit mining, the blasting method can be considered as the most economical technique used to fragment rock blocks. However, only 20–30% of the energy is used for the fragmentation and movement of the rock. At the same time, the rest is wasted in the form of ground vibrations, air explosions, noise, and flying rocks [1]. Both ground vibrations and air explosions are of great concern as they will damage existing surface structures and cause a nuisance to residents near the mine areas, which have too much access to the populated area. To analyze problems related to vibrations, it is necessary to consider the combined effects of several factors such as site characteristics, surface propagation, underground muscle waves, and structural response. The best approach to estimate the weight of the load, which at a given distance generates vibrations below the safe limit, is to use instrumentation on bursts to determine the constants of the actual blasting conditions. Besides, the effective control of vibration-related problems requires the development of a reliable vibration monitoring system and the evaluation of the attenuation characteristics of various vibrations [2, 21, 22] (Fig. 1).

Airblast waves are air pressure waves produced by explosion operation. As vibrations on the ground, these pressure waves can be described by time histories where the amplitude is the air pressure instead of the particle's velocity [11–13]. The high-frequency portion of the pressure wave is audible and the sound accompanying the blasting; the low-frequency portion is inaudible but stimulates the structure and causes a secondary click and sound in the structure. Airblast may affect crack propagation in walls, windows, and human reaction [3, 27, 28]. The degree of damage depends on the air pressure waves. Since it is influenced by climatic conditions such as air temperature, air humidity, and wind speed, etc. The determination of the safe distance when blasting at surface coal mines in Quang Ninh near residents requires research on the effect of climatic conditions on air blasting [5–7].

Airblast waves are recognized as one of the negative effects induced by blasting operations in open pit mines [23–26]. The intensity of air over-pressure is taken into account

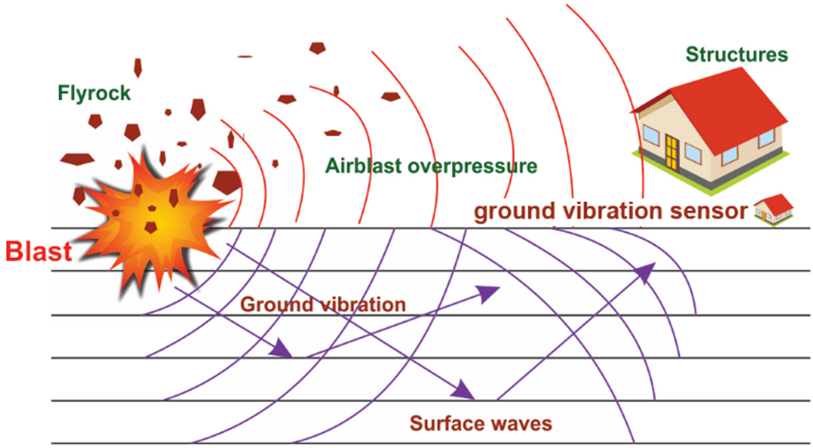

Fig. 1. Influence of shock waves, airwaves to the protective structures when conducting blasting

as the primary parameter to determine the damages on the surrounding environment [14–17]. Many researchers commented on the effects of meteorology on blast-induced air overpressure, such as temperature, relative air pressure, wind direction and speed, air humidity, to name a few [9, 10, 29–31]. However, they were not fully addressed. In this study, the data measurements of air blast waves in Nui Beo coal mine of phosphate were analyzed according to several established criteria of damage to evaluate the ground vibrations characteristics resulting from production blasts and to evaluate the vibrations impact on the nearby structures. This study aims to fully address the effect of meteorology conditions on blast-induced airover-pressure in open pit mines through the air over-pressure predictive models. An open pit mine in Quang Ninh, Vietnam was selected as a case study for this aim. The results revealed that the meteorology conditions have a significant effect on blast-induced airover-pressure, especially air humidity and wind speed [8].

2 Materials and Methods

2.1 Study Site

The study area is the Nui Beo open pit coal mine located in the Ha Long city, Quang Ninh province, Vietnam, about 160 km east of the Hanoi city. This mine is managed by the Nui Beo Coal Joint-Stock Company belonging to the Vietnam National Coal and Mineral Industries Group (VINACOMIN). The total coal field is around 3.75 km^2 for the open pit coal mine and 5.6 km^2 for the underground coal mine. In terms of topographical, the Nui Beo coal mine has complicated terrain conditions where the center is the open pit mining area (Fig. 2) [1, 2, 4].

Fig. 2. Overview of Nui Beo open pit coal mine (Vinacomin)

Quang Ninh province is located in tropical climates [1]. Climate is divided into two seasons, and the rainy season starts from May to October and the dry season from November to April next year. Dry season temperature changes from 16–21 °C, the lowest year 4 °C. The rainy season temperature changes in the range of 24–35 °C, average 28–30 °C, the highest 38 °C. The average annual humidity is 84% (the highest is 90% in 2007, the lowest is 81% in 2003), and the average humidity is 82.3% for recent years (Figs. 3, 4 and 5).

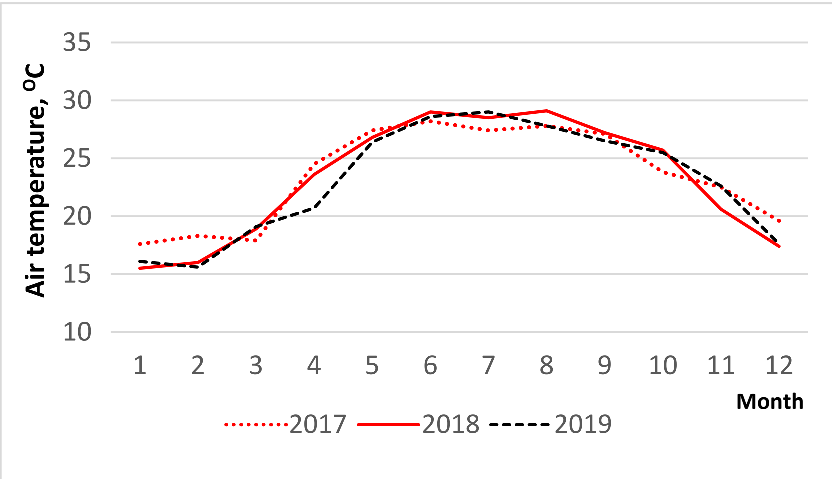

Fig. 3. The average temperature changes annually in Quang Ninh - Vietnam

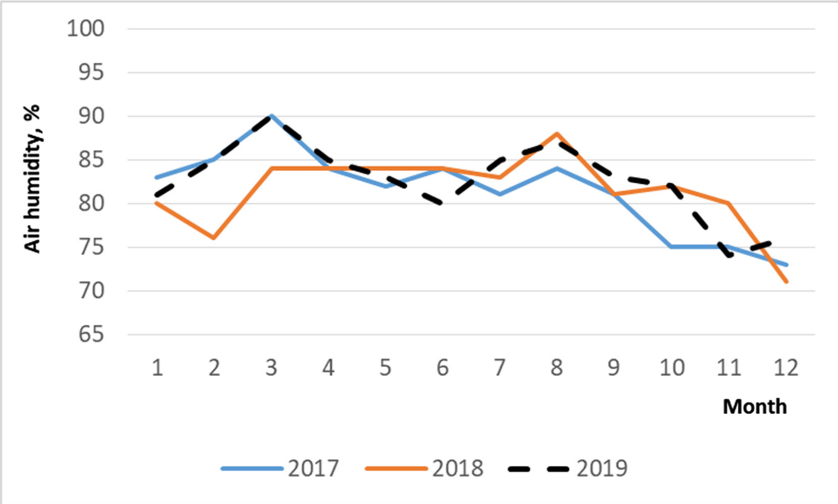

Fig. 4. The average humidity changes annually in Quang Ninh - Vietnam

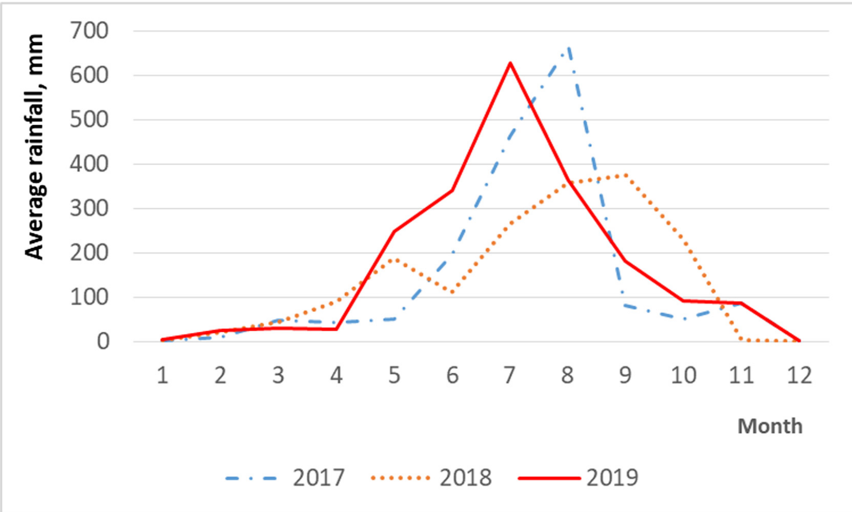

Fig. 5. Average rainfall varies from year to year in Quang Ninh - Vietnam

2.2 Multiple AQ (Air Quality) Monitoring System

The AQ sensors are designed and built to monitor the ambient (indoor & outdoor) air quality over the large space such as mining and construction sites. Since the wireless real-time monitoring system is equipped with XBee technology has long-term continuous monitoring capability. The built-in multiple gas and dust modules can measure most of the regulated hazardous pollutants generated from the industrial working sites and monitor the atmospheric conditions simultaneously [8, 18–20]. Multiple sensors for indoor and outdoor ambient monitoring is installed and can be used to measure the regulated gases, dust levels, and other parameters such as:

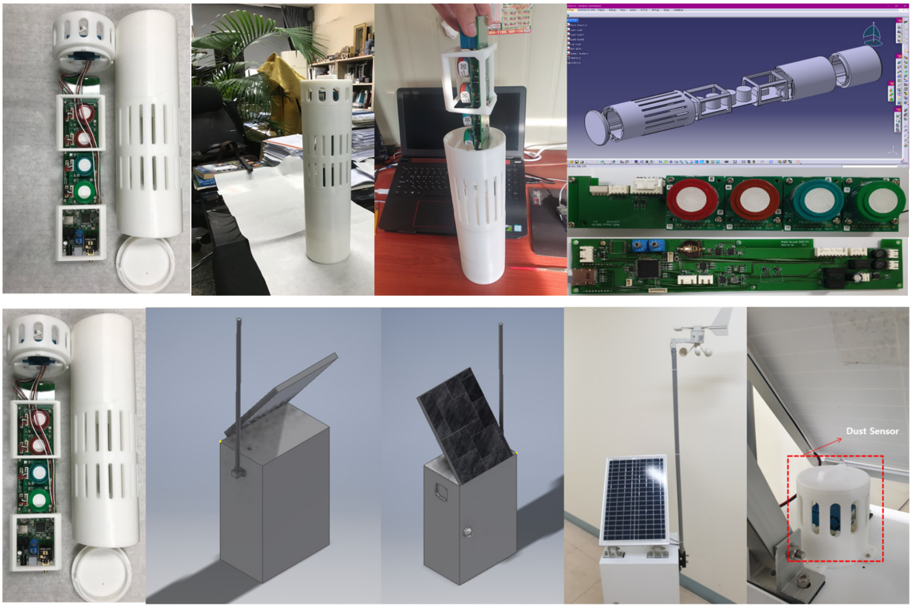

Fig. 6. Multiple sensors and attachments installed for indoor and outdoor ambient monitoring

– Gases: CO, CO_2, NO, NO_2, SO_2, VOC.
– Dust: Airborne dust.
– Atmospheric pressure and temperature/humidity.
– Wind speed and direction.

The sensors can be also positioned over a large area as each sensor can act as a repeater; sensor networks can span kilometers. GPS module will locate sensors exactly at the position. Multiple sensors can be relayed to the router connected to the PC. Individual sensors can do a repeater.

Multiple sensors and Xbee router are deployed at target locations. Readings are transmitted between the sensors and also to Xbee route. PC will receive all the measured data through USB. If the data is connected to the cellular network, it will be transmitted to mobile devices (Fig. 7).

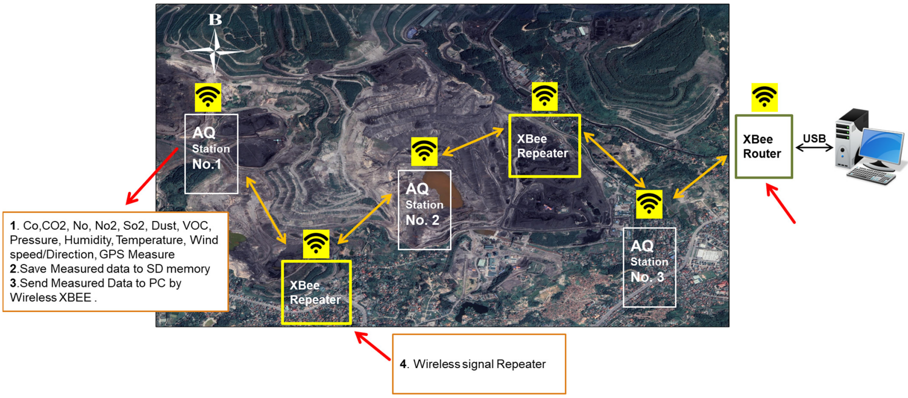

Fig. 7. Multiple sensors and Xbee router are deployed on Nui Beo coal mine (Vinacomin)

Output management: According to the user's intention, measurement data can be displayed on the PC monitor and managed in real-time. Optionally, mobile devices can be logged in to show the real-time data (Fig. 8).

Fig. 8. mobile devices can be logged in to show the real-time data

Fig. 9. Installation of the monitoring systems for temperature, humidity and wind speed at Nui Beo coal mine

2.3 Blasting Vibration and Tilt Wireless Monitoring Solutions

Real-Time Wireless Sensors are built to be deployed on mining and construction sites, tunnels, bridges, pathways, and other structures. The system is designed with the ultimate goal of understanding challenges and provide solutions to protect assets by the low-cost system with high accuracy and reliability.

Structural Safety Monitoring System are used primarily for structural safety monitoring to ensure assets such as mines, tunnels, buildings, bridges, and other structures are protected. Our sensors also have the ability to monitor both vibration and tilt simultaneously. Thanks to this ability, the effects of blasting vibration on structural safety can be understood in real-time.

Sensor & Gateway for monitoring & routing: Tilt & Vibration wireless sensor provides real-time monitoring data. Gateway products quickly route data and alerts to the desired locations (i.e., mobile phones, FTP Server, GIS). USB Management Node is a dongle attached to the PC and establishes a wireless mesh network. It enables bi-directional communication with a maximum 100 sensors. Sensors have been designed for easy installation and wireless remote management with the objective of providing readings and alerts when user-defined allowable limit is exceeded (Fig. 10).

Fig. 10. Real-Time Wireless Sensors

Sensors can be positioned over a large area as each sensor can act as a repeater; sensor networks can span kilometers. Multiple sensors are deployed at target locations. Readings are transmitted to the Management Node (Management dongle) connected to PC. Since our sensors have built-in router function, all readings are sent to the sensor near the Management Node, and, in turn, to the Node (Fig. 11).

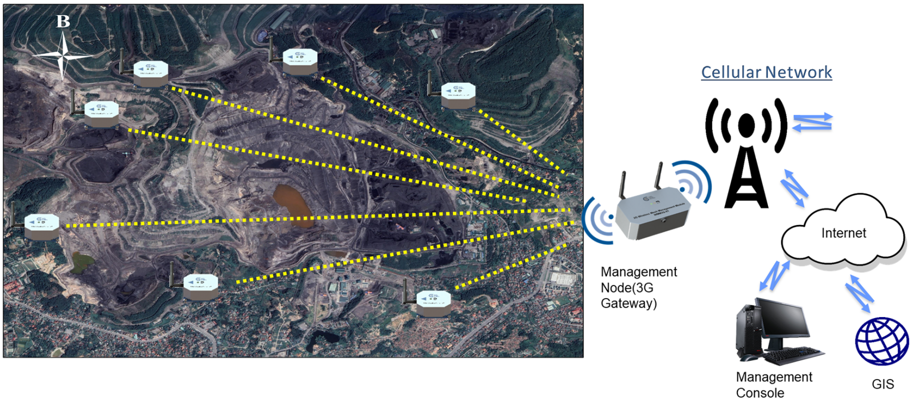

Fig. 11. Mining & construction site monitoring on Nui Beo coal mine

3 Results and Discussion

The blasting test parameters at the Nui Beo coal mine is shown in Table 1 and the monitoring results of air blast overpressure at this mine is presented in Table 2. From these results, we can determine the effect of air humidity on the intensity of air blast waves (Fig. 12); the effect of wind speed on the intensity of air blast waves (Fig. 13); the effect of wind direction on the intensity of air blast waves (Fig. 14).

Table 1. Blasting test parameters at Nui Beo coal mine

Hole diameter, mm	Bench high, H, m	Powder factor, q (kg/m3)	Burden, m	Hole spacing a, m	Row spacing b, m	Subdrill, LKT, m	Stemming, Lb, m	Powder column length Lt, m
105	8 ÷ 10	0,3 ÷ 0,35	9,5 ÷ 11,5	3,8	3,8	1,5	4,9	6,6

Table 2. The monitoring results of air blast overpressure from the blast at Nui Beo coal mine

Blast log number	Air temperature T, oC	Air humidity φ, %	Wind speed v, m/s	Total charge, Q, kg	Charge hole per delay Qvs, kg	Distance R, m	Scale distance $R/\sqrt[3]{Q}$	Air blast, P, Pa	Wind direction
01-TT3/HCKNM	32	50	2,34	9212	830	677	72,04	8,4	–
			1,26	9212	830	715	76,08	9,7	–
			2,74	9212	830	495	52,67	13,4	+
02-TT3/HCKNM	30	52	2,86	10060	880	481	50,19	14,6	–
			2,42	10060	880	523	54,58	16,9	–
			0,68	10060	880	338	35,27	28,8	+
03-TT3/HCKNM	34	59	9,04	2889	315	392	57,61	37,3	+
			4,20	2889	315	339	49,82	11,5	+
			3,38	2889	315	499	73,34	6,0	–
04-TT3/HCKNM	35	65	10,36	6874	905	138	14,27	78,7	+
			4,09	6874	905	563	58,20	8,3	–
			7,11	6874	905	302	31,22	18,0	–
05-TT3/HCKNM	29	62	9,95	4919	205	122	20,69	92,0	+
			0,75	4919	205	683	115,83	4,8	–
			2,45	4919	205	481	81,58	10,2	–
06-TT3/HCKNM	28,5	48	5,03	1943	302	335	49,93	9,8	–
			5,11	1943	302	267	39,80	15,5	+
			6,23	1943	302	285	42,48	9,3	–
07-TT3/HCKNM	22	96	18,0	10171	905	133	13,7	260,0	+
			19,7	10171	905	199	20,6	179,0	–

(*continued*)

Table 2. (*continued*)

Blast log number	Air temperature T, oC	Air humidity φ, %	Wind speed v, m/s	Total charge, Q, kg	Charge hole per delay Qvs, kg	Distance R, m	Scale distance $R/\sqrt[3]{Q}$	Air blast, P, Pa	Wind direction
			4,5	10171	905	339	35,0	35,0	–
08-TT3/HCKNM	18	92	6,9	9199	823	330	35,2	14,3	–
			6,9	9199	823	189	20,2	51,3	+
			5,7	9199	823	301	32,1	23,0	–
09-TT3/HCKNM	14	95	5,1	6901	922	327	33,6	22,8	–
			4,2	6901	922	206	21,2	66,5	+
			4,7	6901	922	291	29,9	43,5	–
10-TT3/HCKNM	15	88	4,7	5114	213	196	32,8	25,0	+
			3,8	5114	213	719	120,4	9,0	–
			4,7	5114	213	399	66,8	18,0	–
11-TT3/HCKNM	15, 5	80	4,3	2562	288	218	33,0	26,0	+
			1,2	2562	288	682	103,3	6,3	+
			4,0	2562	288	391	59,2	18,3	–
12-TT3/HCKNM	19	82	6,2	2134	312	335	49,4	29,0	+
			5,0	2134	312	267	39,4	32,0	–
			3,4	2134	312	291	42,9	18,0	+

Forward wind direction (+); Weak wind direction (-).

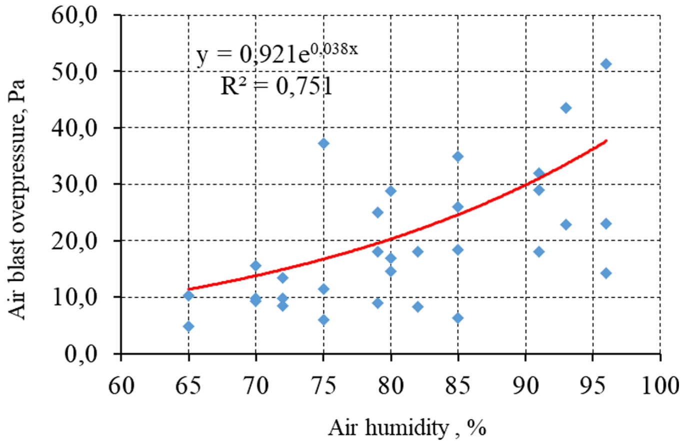

Fig. 12. The effect of air humidity on the intensity of air blast waves

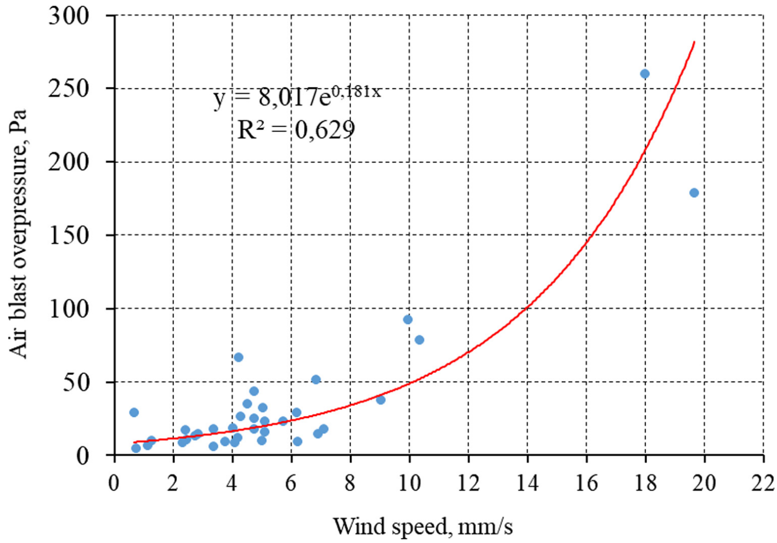

Fig. 13. The effect of wind speed on the intensity of air blast waves

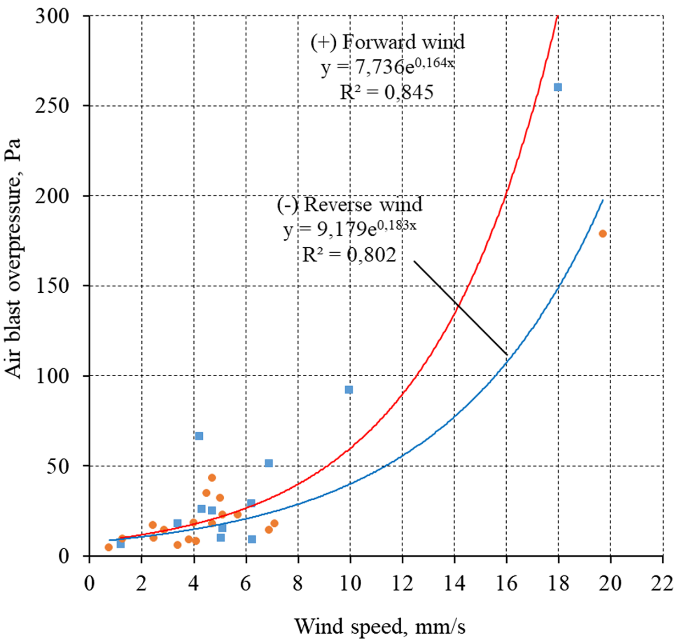

Fig. 14. The effect of wind direction on the intensity of air blast waves

Base on the monitoring results in Table 2, the authors have built the graphical relationship between the air blast and scale distance $R/\sqrt[3]{Q}$ as in Fig. 15.

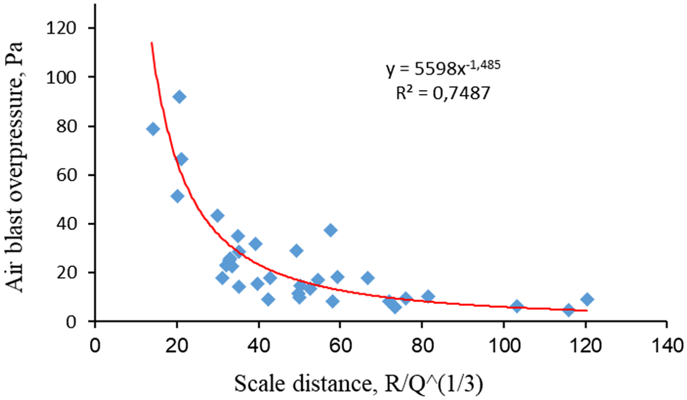

Fig. 15. Relationship between the air blast overpressure and scale distance $R/\sqrt[3]{Q}$

Then, air blast overpressure can be calculated as follows:

$$\Delta P = 5598\left(\frac{R}{\sqrt[3]{Q}}\right)^{-1,485}, \text{ Pa} \tag{1}$$

or

$$\Delta P = 0,05598\left(\frac{R}{\sqrt[3]{Q}}\right)^{-1,485}, \text{ kg}/\text{cm}^2 \tag{2}$$

When the wind is mentioned (use of the wind scale table), the air blast can be determined by the following equation:

$$\Delta P = 0,05598\left(\frac{R}{\sqrt[3]{Q}}\right)^{-1,485} + P_0\frac{\upsilon^2\mu}{2R_1T}, \text{ kg}/\text{cm}^2 \tag{3}$$

where: P_0 is atmospheric pressure during blasting operations, $P_0 = 101.325$ Pa; v is wind speed, m/s; μ is Molar mass of air, $\mu = 28{,}9.10^{-3}$ kg/mol; R_1 is gas constant for air, $R_1 = 8{,}31$ J/mol.K; T is air temperature during blasting operations (Kelvin, $T = 273 + t°C$).

According to legal documents [4], to protect the civil structures existing near the mining sites, air blast overpressure level must be in permitted limits (airblast overpressure limits depend on the distance from the blast, total charge and civil structures). That means $\Delta P \leq \Delta P_{cp}$. From Eq. (3), relationship between the safety distance for air blast overpressure and the total explosive charges per delay with any weather conditions can be defined as follows (in case $\Delta P = \Delta P_{cp} = 130$ Pa):

$$Q_{cp} = \left(17,86\Delta P_{cp} - \frac{P_o\nu^2\mu}{0.112R_1T}\right)R^3, \text{ kg} \tag{4}$$

Table 3. Total explosive charges per delay estimated by Eq. (4)

Distance from blast R, m	100	150	200	250	300	350	400	450	500
Wind speed Air temperature T = 150 °C									
v = 5 m/s	420	1.417	3.358	6.559	11.334	17.998	26.865	38.252	52.471
v = 7 m/s	319	1.077	2.553	4.987	8.617	13.684	20.426	29.083	39.895
v = 9 m/s	206	697	1.652	3.226	5.575	8.852	13.214	18.815	25.809
v = 11 m/s	100	337	800	1.562	2.700	4.287	6.399	9.111	12.498
Wind speed Air temperature T = 200 °C									
v = 5 m/s	422	1.423	3.373	6.588	11.384	18.077	26.984	38.420	52.703
v = 7 m/s	322	1.088	2.579	5.038	8.706	13.824	20.635	29.381	40.304
v = 9 m/s	211	712	1.687	3.294	5.693	9.040	13.493	19.212	26.354
v = 11 m/s	105	353	836	1.634	2.823	4.483	6.691	9.527	13.069
Wind speed Air temperature T = 250 °C									
v = 5 m/s	423	1.429	3.388	6.617	11.434	18.157	27.102	38.589	52.934
v = 7 m/s	326	1.099	2.605	5.088	8.791	13.960	20.839	29.671	40.701
v = 9 m/s	215	726	1.721	3.361	5.808	9.222	13.766	19.600	26.887
v = 11 m/s	109	368	872	1.704	2.944	4.676	6.979	9.938	13.632
Wind speed Air temperature T = 300 °C									
v = 5 m/s	425	1.435	3.402	6.645	11.482	18.233	27.217	38.753	53.159
v = 7 m/s	329	1.109	2.630	5.136	8.875	14.093	21.037	29.952	41.087
v = 9 m/s	219	740	1.754	3.426	5.920	9.400	14.032	19.979	27.407
v = 11 m/s	114	383	908	1.773	3.065	4.866	7.264	10.343	14.188
Wind speed Air temperature T = 350 °C									
v = 5 m/s	427	1.441	3.416	6.672	11.529	18.308	27.329	38.911	53.376
v = 7 m/s	332	1.119	2.654	5.183	8.956	14.222	21.229	30.226	41.462
v = 9 m/s	223	754	1.787	3.489	6.030	9.575	14.292	20.350	27.914
v = 11 m/s	118	398	943	1.842	3.183	5.054	7.545	10.743	14.736

4 Conclusions

1. Studying the combined effect of the temperature factor and wind speed on ΔP and, in general, on the parameters of blast-blowing, which is typical in winter in Vietnam, from the results in Table 3, we note that for ΔP = 130 Pa at a fixed value with wind speed of 7–9 m/s and air temperature of 15 °C–25 °C, the explosion power decreases by 1,02–1,1 times, and when the temperature changes from 25 °C to 35 °C, the explosion power decreases by 1,07–1,2 times.

2. When the air temperature T is lower than 25 °C, in comparison with the normal condition of the standard atmosphere, it is necessary to reduce the power of explosive by at least 20–30%. During blasting operations in wind conditions, there is a significant decrease in the maximum permissible value of excess pressure in the front of the shock wave and the magnitude of the explosion power at various distances to protect objects. In particular, in the case of T = 25 °C in Table 3, it can be seen that for $\Delta P = 130$ Pa and a distance interval of $100 \leq R \leq 500$ m at wind speeds v = 7–9 m/s, in comparison with the condition of no wind ($v \leq 5$ m/s), the maximum allowable explosion power decreases approximately by 1,5–2,2 times. At the wind speeds v = 9–11 m/s, in comparison with the condition of without wind ($v \leq 5$ m/s), the maximum allowable explosion power decreases approximately by 2,2–6,2 times.
3. Thus, from the calculated experimental studies carried out in this study, it follows that when carrying out massive explosions at the Nui Beo coal mines in autumn-winter climatic conditions, when the air temperature in the region is around 15 °C, compared to T = 25 °C, the power of explosions must be reduced by about one third.
4. Based on the air blast overpressure monitoring at the residential sites next to Nui Beo coal mine (Vinacomin), it is found that air blast overpressure depends on air temperature and wind speed during blasting operations. According to the results in Table 3 the total explosive charge per delay and safety distance depend on weather conditions. Careful estimation of the blasting charge based on the weather condition is necessary to improve blast efficiency in limestone quarries and minimize adverse impacts on the environment.

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