Geotech Geol Eng (2016) 34:1047–1056
DOI 10.1007/s10706-016-0025-7

ORIGINAL PAPER

The Blasting Test and Blasting Vibration Monitoring of Vertical Crater Retreat Mining Method in the Luohe Iron Mine

Zhenbin Rao · Sijing Cai

Received: 10 September 2015 / Accepted: 29 April 2016 / Published online: 4 May 2016

Abstract Because the land requisition and demolishing became difficult more and more, the mining scheme of Luohe iron mine was changed from caving method to filling method. In order to ensure the safety of the residence and the underground tunnel cavern within the mobile belt of the underground mining, the Luohe iron mine did the blasting test on the vertical crater retreat mining method and blasting vibration monitoring. The blasting experiments use common emulsified oil explosives and non-electric initiation system. The way of caved ore adopts the cutting groove and bench side. The NUBOX-6016 intelligent vibration monitor was chosen in the blasting vibration monitoring. Twice experiments on the blasting vibration monitoring were done on the surface or in the underground refuge cavern. The first test select the three monitoring points on the ground and the second select two monitoring points on the ground and a monitoring point in the underground refuge cavern. The blasting vibration monitoring data were conducted by the regression analysis in the Sodev's empirical formula. The vibration attenuation formula about the underground blasting vibration transmitting in three directions is derived. The blasting test on the vertical crater retreat mining method and the blasting vibration were analyzed. It is estimated if the vibration damage possibly the surface buildings and related facilities of mine.

Keywords Iron mine · Vertical crater retreat mining method (VCR) · Blasting test · Vibration monitoring

Z. Rao (✉) · S. Cai
School of Civil and Environmental Engineering,
University of Science and Technology Beijing,
Beijing 100083, China
e-mail: rzbin2012@163.com

Z. Rao · S. Cai
Key Laboratory of the Ministry of Education for High Efficiency Exploitation and Safety of Metal Mines,
Beijing 100083, China

1 Introduction

The initial design scheme of the Luohe iron mine was sub-level caving mining. In the collapse area, the requisition of lands were 2940 acres and the resettlement were about 3–4 villages. After 4 years of construction, it has greatly been changed that the requisition and the resettlement compare with the condition of original preliminary design. The construction of several large mining projects lead to tension of land resources near the mining area. The fees of requisition and resettlement rise substantially. The complicated external environment lead the land acquisition and resettlement to difficult. It impact on the mine's relationship with the local resident. Later the filling method was used in the mobile belt of underground mining. Within the scope, the upper houses are not resettled and the land are not requisitioned.

In order to improve the efficiency of production and ensure the residents' housing and the safety of underground roadway and cavern, the Luohe iron mine did blasting test and vibration monitoring in the underground stope. The blasting test parameters is designed with reference to previous blasting parameters and some literature. The Luohe iron mine use segmented blasting technology and develop a reasonable differential time research to reduce the influence of blasting vibration on the surrounding environment. The test results of blasting vibration are researched by using professional software. It is analyzed that the mining and blasting parameters how to effect the frequency of blasting vibration. It is estimated if the vibration possibly damages or not the surface buildings and related facilities of mine.

Various studies have been performed to improve the efficiency of blasting. Zhengrong and Xiliang (2014) researched the reasonable differential time of deep hole blasting in Meishan Iron mine. Xu (2013) analyzed the impact of geological terrain and blasting parameters of the open-pit iron hole-by-hole blasting vibration and optimized the original blasting parameters. It reduced pit slope and nearby residential location of blasting vibration effect. Deng (2015) did the normal cast blasting crater experiments and orthogonal industrial tests, and analyzed the dynamite consumption, the row spacing, the hole bottom spacing and the caving interval. Studies have shown that the peak particle velocity (PPV) is the most representative parameter to describe the ground motion and tunnel response (Dowding 1984). Many investigations have been done to predict PPV, the most accepted predictor equation was proposed by the United States Bureau of Mines (USBM) and is the most widely applied equation (Siskind et al. 1980). But the Sodev's empirical formula is applied in the Safety regulations for blasting in china (The National Standards Compilation Group of Peoples Republic of China 2003). So we apply the Sodev's empirical formula to predict PPV.

During the study, the blasting parameters are designed and the blasting vibration monitoring are done near the house, the refuge, the wind well and the ramp in the experiments to sure the safety and the vibration attenuation formula on the transmission in three directions are derived with the unary regression analysis theory after collecting the data of experiment.

2 The Geological Conditions of Luohe Iron Mine

Luohe iron mine is located in the south of Jianghuai hilly region for the low mountain hilly terrain in Anhui province (Shao and Chen 2009). The surface water of Luohe iron mine is mainly pool. The west is LuoChang River and the eastern is ZhuQiao reservoir. The eastern larger rive is the Yellow River and its upstream is Qingshan reservoir. The water diversion channels of Qingshan reservoir is through the eastern mining area. In the rainy season the upstream reservoir should be collected and lead outside the mining area.

The strata are mainly the brick bridge group in the mining areas. It is young bay red layer and ShuangMiao group red layer (Lianzhong 1983; Zhou et al. 2011). The weathering residual and slope deposit of diluvial clay layer are widely distributed in the mining surface. So that the bedrock fissure water in the bottom and surface-water can't contact. The rock mass of mining area are mainly the tuffaceous silt-stone, coarse andesite, tuff, paste pyroxenite, secondary quartzite, etc. (Huang 1984). The properties of upper rock mass on the ore body is changeable and fracture. The whole rock is medium stable. Local area is influenced by rock alteration and the rock mass is soft and broken rock, poor rock mass stability.

There are two larger faults within the mining area. The northeast fault is F001 that is the biggest development. Its total width is about 50–150 m. It controls the layout of the second phase of the mining project and the scope of surface deformation of the mined ore body. The largest Northwest fault is F201 fault that growths in the west of the mining area. Its strike is the 300°–320°. The width of F201 fault is 2–16 m. The rock in the both sides of fault zone is broken and control the deformation range of mining surface. The other more than 30 small faults are located in the upper rock mass. They don't impact the mining of the iron ore deposit (Fig. 1).

3 The Mining Methods and Blasting Test Plan

According to the mining conditions of Luohe iron mine, the most suitable method for north ore-body of II longitudinal prospecting line is the VCR stoping and later filling mining method. The marginal part adopts deep hole sub-level open stoping method or the

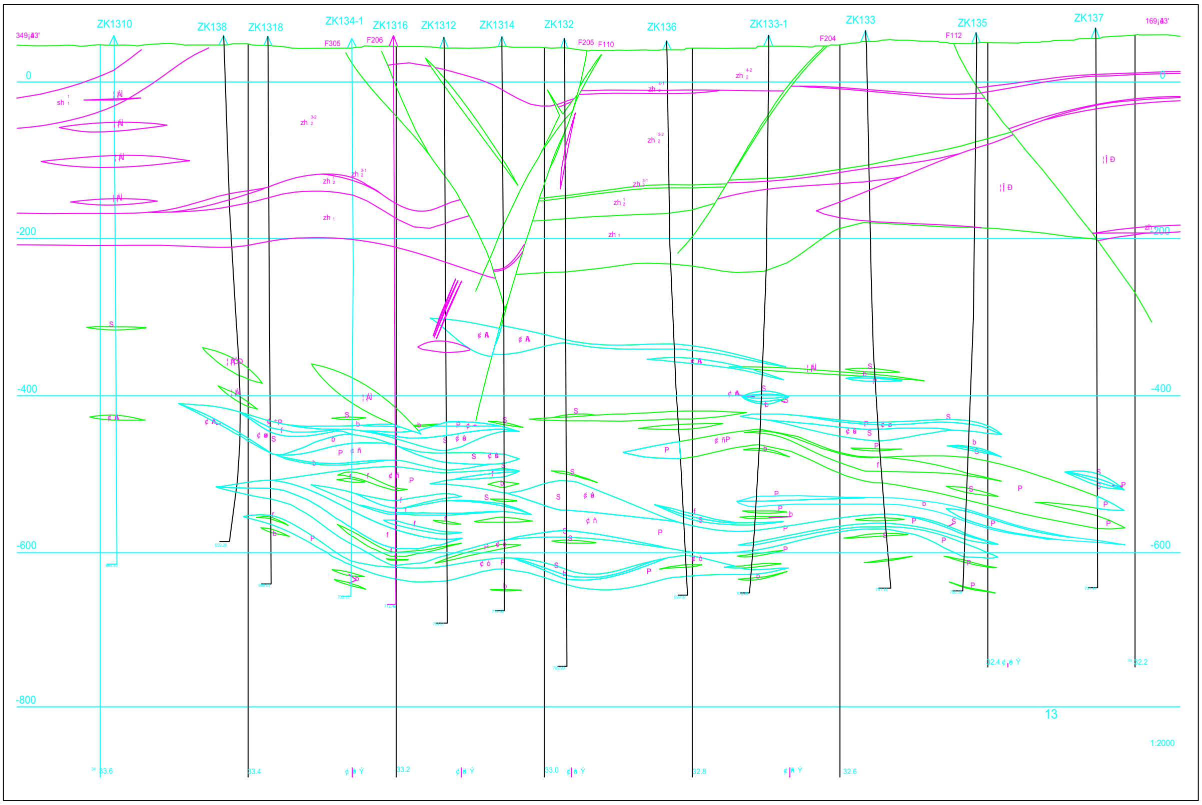


Fig. 1 The Luohe iron geological profile of 13# exploratory line

pointed pillars with filling method. The most suitable method for the south ore-body of II longitudinal prospecting line is deep hole flat-back cut and sub-level open stoping filling mining method and the corner part of ore-body adopts point to slice stoping method on the pillars.

At present, the used mining method is the VCR and later filling method. Blasting experiments use common emulsified oil explosives and non-electric initiation system. The way of caved ore adopts the cutting groove and bench side. VCR method of mining stope is divided into plate area. The arrangement of each blasting test hole within stope shown in Fig. 2a. In a stope the layout of blasting hole is 6 row and 25 hole per row. The space of row can be divided into two kinds. One is 2.8 m and the other is 2.2 m near the middle. The pitch of holes is 3 m. There are cutting hole slots in the middle of the stope. The middle two rows is inclined hole. The scallop hole is at the bottom of the stop. Transverse section drawing of Stope blasting hole as shown in Fig. 2b. Blasting of Stope need to cut and drill the fan blasting hole at the bottom.

The detonation of blasting test is inverted trapezoidal blasting. The segmented blasting is done to reduce the blasting vibration of the surficial buildings and the influence on the surrounding rock of underground stope. (Li et al. 1996; Li and Shu 2005; Ma et al. 2000; Zhang and Lin 2005; Ling and Li 2004). Blasting test area and segmented plan as shown in Fig. 3.

There are cutting holes in the middle of the stope. The blasting are upward and inverted trapezoidal from the bottom at a time. Division of the blasting region as shown in Fig. 4.

In the Fig. 4, the numbers in the circle is blasting sequence number. They are divided into two parts to blasting. The scallop-hole blasting is below and the vertical deep-hole blasting is above. The segment charge and the total amount of charge every time are controlled according to the blasting condition.

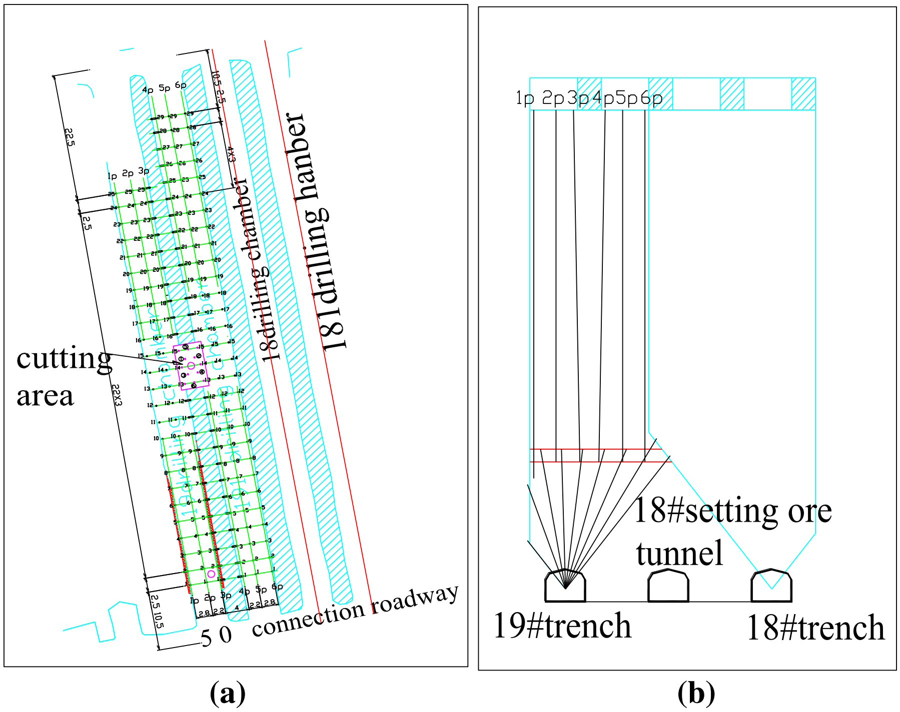
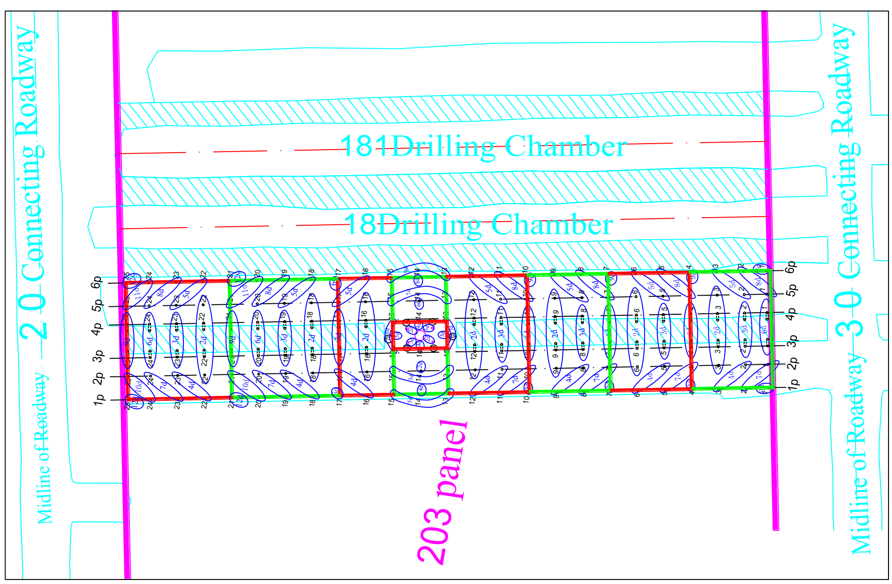


Fig. 2 **a** Plan of hole arrangement. **b** Cross-section of the stope

Fig. 3 Plan of sectional blasting test in stope



4 Blasting Test Parameters

The number of blasting is divided into 55 times in the experimental scheme. The diameter of Vertical deep-hole is 120 mm and the depth of hole is 54.5 m. The inclination of two rows in middle of holes is 89.16° and the declination of remaining hole is 90° (Wang 2011; Brady and Brown 1985; Saadat et al. 2014; Ren et al.

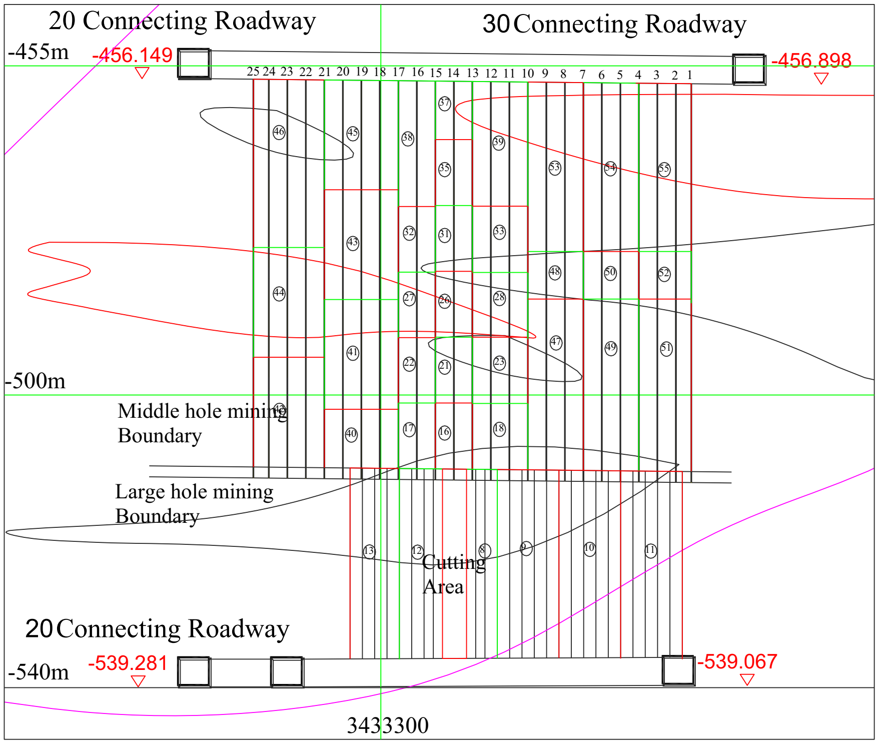


Fig. 4 Blasting area profiles

2012; Wang 1999). The blasting test parameters and specifications as shown in Table 1. Twice blasting vibration monitoring conditions as shown in Table 2.

5 Vibration Monitoring of Blasting Test

The monitoring instrument is NUBOX-6016 intelligent vibration monitor. Four times monitoring of blasting vibration were done on the surface and in the underground refuge cavern. The principle of selecting monitoring points is close to the village houses and other production facilities that are sensitive to the vibration of blasting.

First monitoring test select the three points on the ground. The second monitoring test select two points on the ground and a point in the underground refuge cavern. The vertical distance of first explosive point from the ground is confirmed about 600 m in line with the depth of the stope. The first monitoring point L27

Table 1 Parameters of blasting experiments

The number of blasting	40	41	42	43	44	45	46
Explosive amount (kg)	822	2600	3707	3707	3707	3707	5257
Amount of Caved ore (t)	2110	7441	8237	9404	10,133	9316	12,061
Height of caved ore (m)	4.0	10.0	15.0	15.0	15.0	15.0	23.0
Total length of caved ore hole (m)	89.0	313.0	360.0	360.0	360.0	360.0	552.0
Detonator segments	2–12 segment, a total of 11 guns						
Segment charge (kg)	274	349	365.5	302	618	618	879
Blasting compensating coefficient	2.75	>2.5	>2.5	>2.5	>2.5	>2.5	>2.5
Charge coefficient (%)	75.0	70	86.70	86.70	86.70	86.70	80.40
Caved ore amount per meter (t/m)	23.71	23.77	22.88	26.12	28.15	25.88	21.85
Explosive unit consumption (kg/t)	0.39	0.35	0.45	0.39	0.37	0.40	0.44

Table 2 Vibration monitoring conditions

Item	1st blasting	2nd blasting	3rd blasting	4th blasting
Blasting point	23-2# stope	49-4# stope	23-1# stope	25-1# stope
Explosive amount (kg)	822	2600	3707	3707
Segment charge (kg)	274	349	365.5	302
Amount of Caved ore (t)	2110	7441	8237	9404
Distance from 1 point (m)	600	615	854.98	885.31
Distance from 2 point (m)	632	643	583.31	621.23
Distance from 3 point (m)	676	–	712.45	730.56
Distance from 4 point (m)	–	–	1425.56	1447.33
Distance from 5 point (m)	–	–	1081.65	1117.37
Distance from refuge chamber (m)	–	1000	–	–

is directly above the first explosive point. So the distance of first monitoring point L27 is 600 m away from the first explosive point. The second monitoring L28 is 650 m; the third monitoring L29 is 700 m.

The second explosive point is under the village including the service well. So the L20 of GPS near the measure well is selected for first monitoring point. The L19 point near the service well is selected for the second point so that it is conducive to the monitoring of blasting vibration on the well and the houses of the villages. The location of the underground blasting vibration monitoring L21 is in the refuge cavern.

The third and fourth monitoring test select the three monitoring points in the village, a monitoring point in the north of the west wind well and a monitoring point in the ramp. The third blasting test is in the 23-1# stope and the fourth blasting test is in the 25-1# stope. The distance of every monitoring point to the explosive point is calculated in the Table 2.

The monitoring points of the first test as shown in Fig. 5, and the monitoring points for the second test as shown in Fig. 6.

6 Monitoring Results and Discussion of Blasting Test

The first and second maximum vibration velocity of blasting vibration monitoring frequency and the corresponding time respectively as shown in Tables 2 and 3.

The propagation and attenuation law on blasting vibration generally uses Sodev's empirical formula (Wang et al. 2002; Zhang and Shutang 1981; Tao 1986; Si et al. 2002):

$$V = K\left(\frac{\sqrt[3]{Q}}{R}\right)^{\alpha} = K\rho^{\alpha} \qquad \text{cm/s} \qquad \rho = \frac{\sqrt[3]{Q}}{R} \tag{5-1}$$

Q Maximum priming dose per delay interval, Unit: kg;
R The linear distance from measuring point to blasting center, Unit: m;
K Coefficient related to factors such as geology, blasting method etc.
α Coefficient related to attenuation of seismic wave in the geological conditions;

After taking logarithm on both sides, (5-1) became $\lg V = \lg k + \alpha \lg \rho$; If $y = \lg V$; $a = \lg k$; b = α and $x = \lg \rho$, then

$$y = a + bx \tag{5-2}$$

Use least square method to determine α, b, then Q (α, b) value is the minimum (Figs. 7, 8, 9).

$$Q(a,b) = \sum_{i=1}^{n} (y_i - a - bx_i)^2 \tag{5-3}$$

$$\begin{cases} \dfrac{\partial Q}{\partial a} = -2\sum_{i=1}^{n}(y_i - a - bx_i) = 0 \\ \dfrac{\partial Q}{\partial b} = -2\sum_{i=1}^{n}(y_i - a - bx_i)x_i = 0 \end{cases} \tag{5-4}$$

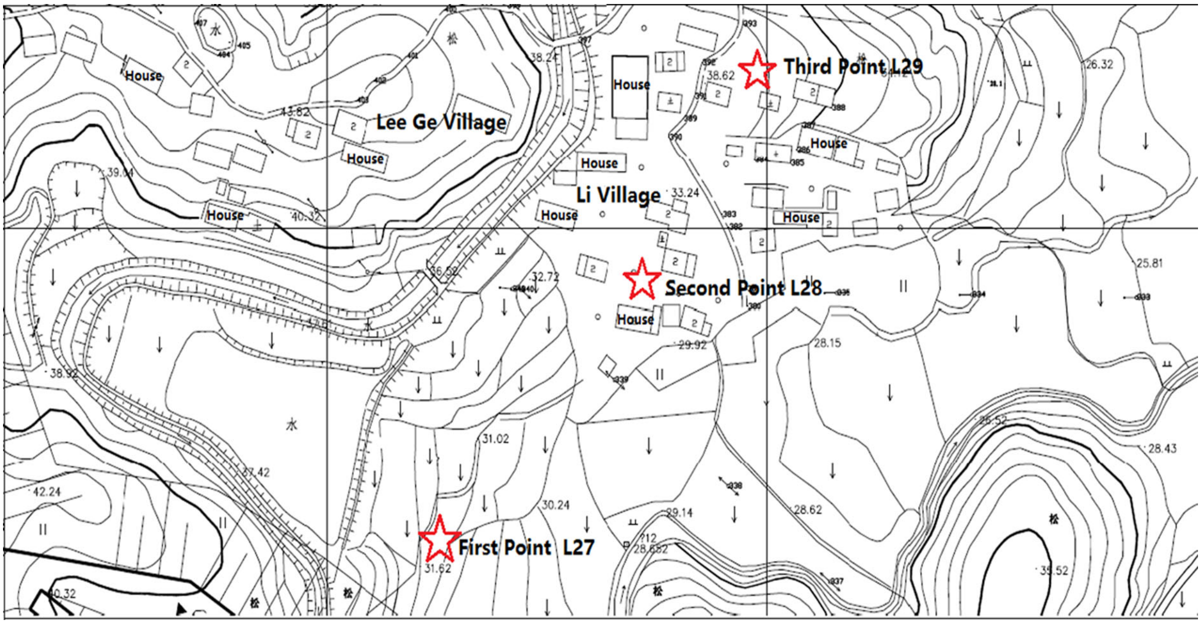


Fig. 5 Schematic of monitoring points for the first test

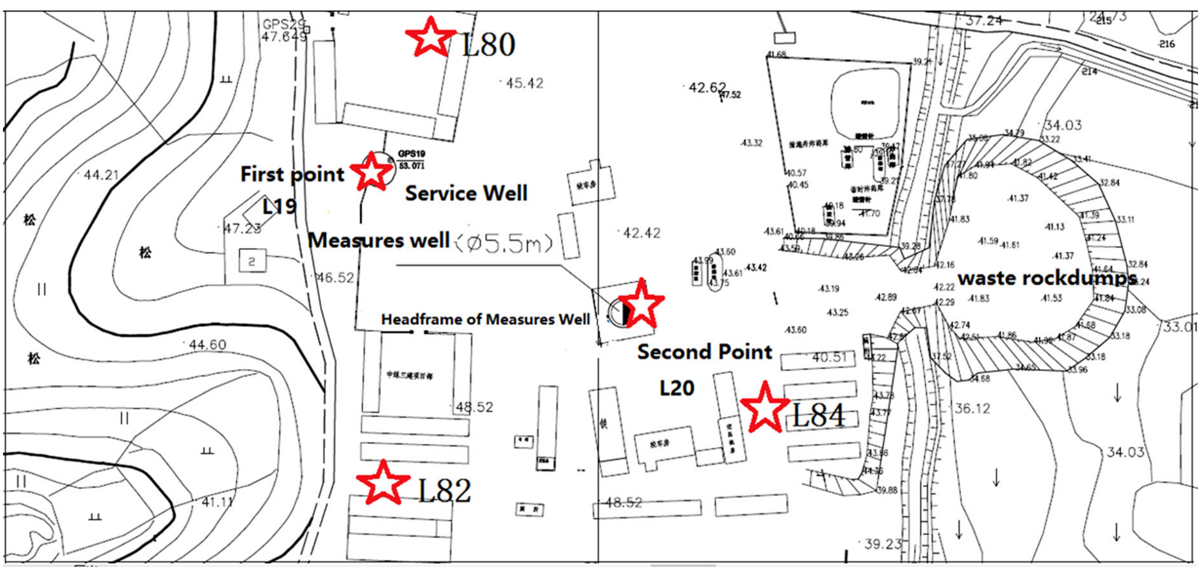


Fig. 6 Schematic of monitoring points for the second, third and fourth test

$$\begin{cases} a = \bar{y} - b\bar{x} \\ b = \dfrac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \end{cases} \tag{5 − 5}$$

$$\bar{x} = \sum_{i=1}^{n} x_i/n; \ \bar{y} = \sum_{i=1}^{n} y_i/n;$$

The coefficient of correlation:

$$r = \frac{\sum_{i=1}^{n} (x - \bar{x})(y - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x - \bar{x})^2 \sum_{i=1}^{n} (y - \bar{y})^2}} \tag{5 − 6}$$

Table 3 Vibration monitoring and frequency peak speed record for the blasting test

Blasting	Monitoring point	Segment charge Q (kg)	Distance to the explosion center (m)	PPV (cm/s)			PVS (cm/s)	Main vibration frequency (Hz)
				X	Y	Z		
1st	1 L27	274	600	0.210	0.234	0.104	0.331	33.203
	2 L28		632	0.126	0.167	0.058	0.217	13.428
	3 L29		676	0.081	0.132	0.035	0.159	17.578
2nd	1 L19	349	600	0.397	0.630	0.135	0.757	20.508
	2 L20		643	0.141	0.277	0.100	0.327	12.695
	Refuge L21		1000	0.103	0.141	0.203	0.268	212.891
3rd	1 L80	365.5	854.98	1.000	1.140	0.680	1.380	23.120
	2 L82		583.31	1.320	1.280	0.190	1.330	23.160
	3 L84		712.45	1.170	1.140	1.120	1.180	23.150
	4 Ramp L86		1425.56	0.340	0.320	0.530	0.560	28.660
	5 wind well L88		1081.65	0.440	0.410	0.680	0.720	20.670
4th	1 L80	302	885.31	1.100	1.120	1.160	1.190	30.050
	2 L82		621.23	1.160	1.140	1.200	1.200	31.050
	3 L84		730.56	1.180	1.200	1.250	1.280	30.050
	4 Ramp L86		1447.33	0.180	0.190	0.200	0.200	32.750
	5 wind well L88		1117.37	0.470	0.480	0.500	0.510	32.580

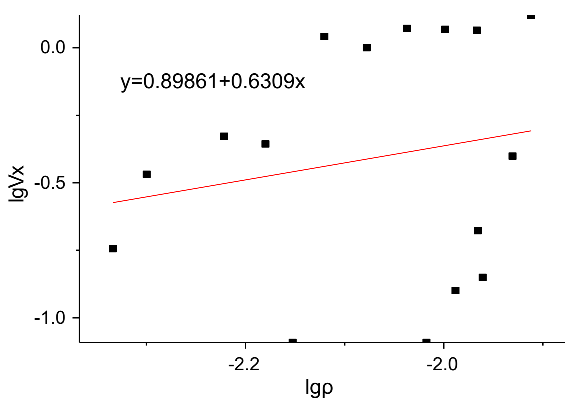


Fig. 7 PPV linear regression fitting result of Vx

$$\alpha = b = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})} \quad (5-7)$$

$$k = \ln^{-1}(\bar{y} - b\bar{x}) \quad (5-8)$$

The monitoring data on blasting vibration are analyzed with the unary regression analysis theory (Zhu and Li 1985; Wang et al. 2002; Long et al. 2000). We get the vibration attenuation formula on the transmission in three directions is as follows:

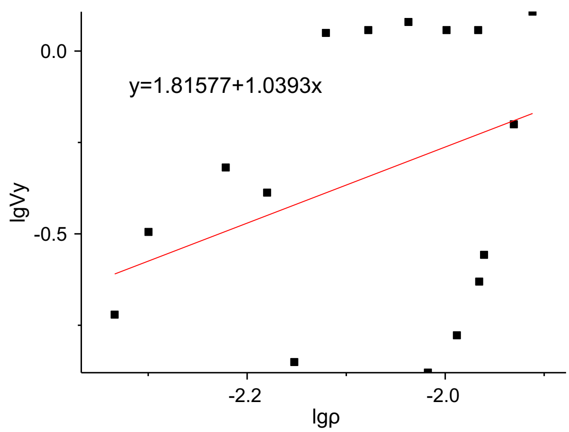


Fig. 8 PPV linear regression fitting result of Vy

$$V_{radial} = \mathbf{7.918}\left(\frac{\sqrt[3]{Q}}{R}\right)^{\mathbf{0.6309}} \quad \text{cm/s} \quad (5-9)$$

$$V_{\tan ential} = 65.429\left(\frac{\sqrt[3]{Q}}{R}\right)^{\mathbf{1.0393}} \quad \text{cm/s} \quad (5-10)$$

$$V_{vertical} = 10.059\left(\frac{\sqrt[3]{Q}}{R}\right)^{\mathbf{1.87492}} \quad \text{cm/s} \quad (5-11)$$

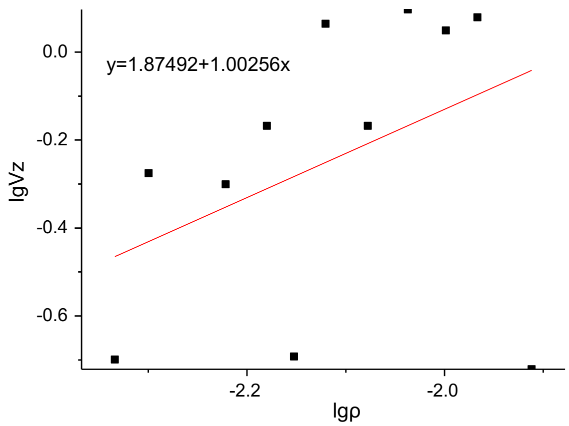


Fig. 9 PPV linear regression fitting result of Vz

The K, α values of blasting vibration attenuation formula are influenced by blasting conditions and topographical and geological conditions. The rock mass properties and local site conditions have greatly influence on K, α value (Li and Shu 2005; Xiao 2004). The surface water and the low mountain hilly terrain of Luohe iron mine greatly influence on K, α value. So the K, α value are scattered and the coefficient of correlation is not very high.

The intensity of ground vibration depends mainly on blasting parameters such as charge per delay, and distance from the blast. The spectrum structure of blasting seismic wave mainly depends on rock parameters, drilling parameters, distance from explosive source and so on. The attenuation of blasting vibration frequency is closely related to the factors such as the size of the explosive cavity, distance from explosive source and longitudinal wave speed of rock mass etc. (Lu et al. 2013; Pao and Mow 1973). The segment charge and the distance from explosive source are the main factors that effects the peak particle velocity (PPV) and the blasting vibration frequency. So PPV and the blasting vibration frequency of the surface buildings and related facilities of mine is high near the explosive source.

The main vibration frequency is 212.891 Hz and the PVS is 0.268 cm/s in the monitoring point L21. But the main vibration frequency is from 12.695 to 33.203 Hz and the PVS is from 0.200 to 1.380 cm/s in other monitoring points. According to the safety regulating for blasting, it is found out in this study that the house, the refuge, the wind well and the ramp are safe when the explosive amount is 3707 kg and the segment charge is 365.5 kg and the amount of Caved ore is increased from the 2110 to 9404 tons. We can increase the explosive amount, the segment charge and the amount of caved ore in the next experiment. So we improved the production efficiency and the economic benefit under the condition of safety.

7 Conclusion

1. The basis of drilling and blasting parameters and mining process must be suitable for mining area to determine the appropriate blasting scale. In order to improve the efficiency of production and ensure the residents' housing and the safety of underground roadway and cavern, Luohe iron mine must do well in the blasting vibration monitoring during the blasting process.
2. According to the Safety regulations for blasting, when the main frequency is 10–50 Hz, the blasting vibration velocity allowed in the general brick houses and no Seismic large block buildings is 2.3–2.8 cm/s. The max vibration velocity of monitoring point in the villages is 1.380 cm/s. It is far less than the range of Safety regulations for blasting. So underground blasting have no damage to the brick house and no seismic large blocks buildings.
3. When 49-4# stope is blasted, the blasting vibration velocity of the refuge cavern is 0.268 cm/s and the main frequency is 173.828–249.023 Hz. According to the Safety regulations for blasting, the blasting vibration velocity allowed in the mine roadway is 15–30 cm/s. The blasting vibration velocity of monitoring is far less than the allowable values. Therefore, blasting has no effect on the underground refuge cavern.
4. According to the Safety regulations for blasting, when the main frequency is 10–100 Hz, the blasting vibration velocity allowed in the mine roadway is 15–30 cm/s. The max vibration velocity of monitoring point in the west wind well is 0.720 cm/s and the max vibration velocity of the ramp is 0.560 cm/s. Therefore, blasting has no effect on the west wind well and the ramp.

References

Brady BHG, Brown ET (1985) Rock mechanics for underground mining. Kluwer Academic Publishers, New York, p 518

Deng F (2015) Experimental study on the optimized blasting parameters for medium-depth hole. Nonferrous Met Sci Eng 6(1):66–69

Dowding CH (1984) Estimating earthquake damage from explosion testing of fullscale tunnels. Adv Tunnel Technol Subsurf Use 4(3):113–117

Huang Q (1984) Theory of geological characteristics and genesis of Luohe iron ore deposit. J Depos Geol 1984:9–19

Li H, Shu D (2005a) Influential factors analysis of blasting vibration attenuation law. Eng J Wuhan Univ 38(1):79–82

Li H, Shu D (2005b) The influence factors of blasting vibration attenuation law. Eng J Wuhan Univer 38(1):79–82

Li H, Wang B-Q, Lin GAO (1996) Studies on some problems on explosion earthquake responses. Explos Shock Waves 16(1):61–67

Lianzhong W (1983) The ore-controlling structure of Luohe iron ore deposit and preliminary analysis of the ore-controlling tectonic system in Lu-polar region region. Geol Mech Inst Chin Acad Geol Sci 124:124–137

Ling T, Li X (2004) Time-energy analysis based on wavelet transform for identifying real delay time in millisecond blasting. Chin J Rock Mech Eng 23(13):2266–2270

Long Y, Feng C, Xu Q et al (2000) Study on propagation characteristics of blasting seismic waves in a rock medium and numerical calculation. Eng Blast 6(3):1–7

Lu W et al (2013) The theory analysis of the attenuation mechanism and attenuation law of blasting vibration frequency. J Blast 30(2):1–6

Ma G, Hao H, Zhou Y-X (2000) Assessment of structure damage to blasting induced. Eng Struct 22:1378–1389

Pao Y, Mow C (1973) Diffraction of elastic waves and dynamic stress concentrations. Russia & Company Inc., Crane

Ren F et al (2012) Optimization and application of blasting parameters based on the “pushing-wall” mechanism. Int J Miner Metall Mater 19(10):879–884

Saadat M, Khandelwal M, Monjezi M (2014) An ANN-based approach to predict blast-induced ground vibration of Gol-E-Gohar iron ore mine, Iran. J Rock Mech Geotech Eng 1:67–76

Shao Z, Chen P (2009) Introduction to the development new pattern of Luohe iron mine of Masteel in Anhui province. Mod Miner Ind 12:62

Si Y, Jinji L, Gu Y (2002) Engineering blasting practice. Press of University of Science and Technology of China, Hefei

Siskind DE, Stagg MS, Kopp JW, Dowding CH (1980) Structure response and damage produced by ground vibration from surface mine blasting. USBM Report RI 8507

Tao S (1986) Drilling and blasting. Metallurgical Industry Press, Beijing

The National Standards Compilation Group of Peoples Republic of China (2003) GB6722–2003 Safety regulations for blasting. Standards Press of China, Beijing

Wang W (1999) Determination of reasonable chamber blasting parameters by the blasting funnel test. Blasting 6(4):83–87

Wang X (2011) Handbook of blasting. Metallurgical Industry Press, Beijing

Wang Z, Zhang Q, Bai C-H (2002) Numerical simulation of influence of hole depth on explosion effect. Chin J Rock Mech Eng 21(4):550–553

Xiao Z (2004) Blasting seismic wave dynamical foundation and seismic effect. The University of Electronic Science and Technology Press, Chengdu

Xu Y (2013) Research on hole-by-hole blasting vibration reduction method in open-pit iron mine. Opencast Min Technol 1:86–90

Zhang L, Lin C (2005) Study about soil slope dynamic stability due to blasting vibration. Rock Soil Mech 26(9):1499–1501

Zhang X, Shutang H (1981) Blasting seismic effect. the Seismological Press, Beijing

Zhengrong C, Xiliang Z (2014) Research on the reasonable differential time of deep hole blasting in meishan iron mine. Mod Min 5:9–10

Zhou F, Yu F, Yuan F et al (2011) The diagenetic mineralization of volcanic basin in the middle and lower reaches of the Yangtze River metallogenic belt. J Geol 12:712–730

Zhu R, Li Z (1985) Critical failure vibration velocity of rock tunnel under blasting seismic wave. Metallurgical Industry Press, Beijing