Rock blasting vibration velocity and excavation damaged zone for the high-level radioactive waste geological disposal

Ke Man\textsuperscript{a}, Xiaoli Liu\textsuperscript{b} and Zhifei Song\textsuperscript{a}

\textsuperscript{a}College of Civil Engineering, North China University of Technology, Beijing, China; \textsuperscript{b}State Key Laboratory of Hydroscience and Hydraulic Engineering, Tsinghua University, Beijing, China

\textbf{ABSTRACT}
Based on Beishan Exploration Tunnel (BET), the blasting test has been carried out and studied deeply, especially the blasting vibration velocity and excavation damaged zone (EDZ) have been monitored immediately along the blasting cycles. It has obtained that the maximum blasting vibration velocity ranged from 4 cm/s to 60 cm/s. Meanwhile, the EDZ tested by the radar system is ranged from 17 cm to 24 cm. Furthermore, as the cutting method, surrounding hole distance and specific charge are different, the maximum blasting vibration velocity and EDZ are also diverse caused by the blasting energy release, distribution, absorbing, and transfer. Finally, the controlling method with rock damaged depth using the maximum blasting vibration velocity at the distance 10 m is proposed. Through the blasting vibration velocity attenuation law and rock damaged characteristic, the threshold of the maximum blasting vibration velocity at the distance 10 m has been confirmed, i.e. when the maximum blasting vibration velocity is under 100 cm/s, the rock damaged depth could be controlled within 30 cm. Then the blasting damaged zone could be ensured and confirmed. The research and theoretical knowledge could be applied to the blasting and excavation of the deep geo-engineering and the HLW geo-disposal.

\textbf{ARTICLE HISTORY}
Received 10 February 2021
Accepted 13 August 2021

\textbf{KEYWORDS}
Blasting vibration velocity; excavation damaged zone; blasting vibration velocity monitoring; radar monitoring; geological disposal of the high-level radioactive waste

\section{1. Introduction}
Drilling & blasting method and TBM (Tunnel Boring Machine) method have been applied to the rock engineering project, especially for the high-level radioactive waste geological disposal. No matter which excavation method is adopted, the rock breaking effect and the disturbance to the surrounding rock are two main considerable factors in the construction and monitoring progress, while these two factors restrict each other (Yi et al. 2017; Costamagna et al. 2018; Hu et al. 2018). Not only the over excavation is required, but also the under excavation is demanded. It means that the
positive energy should be promoted, while the negative energy should be limited, which corresponding to a relative high excavation speed and a rather small rock damaged zone separately (Fu et al. 2010; Li et al. 2011; Chen et al. 2016; Li et al. 2018; Verma et al. 2018; Xu et al. 2018). How to control the excavation concisely and induce the initial crack of the rock occurs, growths, penetrates and generates a pre-fractured surface are key problems for the permanent stability of rock engineering (Wang et al. 2008; Yang et al. 2010, 2014, 2017; Deng et al. 2014; Yue et al. 2015; Liu et al. 2018, 2019; Yang et al. 2018; Xie et al. 2020), such as the underground engineering, mine mining, tunnel construction, railway application and so on (Lin et al. 2013; Du et al. 2017; Xu et al. 2018; Sun et al. 2019, 2020; Huang et al. 2020).

Definitely, the characteristics of the High-level radioactive waste geological disposal demands a higher safety grade. As rock permeability increases along the formation of new cracks in the damaged area and the expansion of the original fissure in the rock, the potential channel for the nuclide migration should be limited. In addition, the mechanical properties of the rock and the operation period of the disposal repository are strongly influenced by the excavation damage. Therefore, the damage degree of the surrounding rock is more important for the nuclear power station infrastructure construction, and the vibration monitoring distance is required as close as possible. According to the blasting vibration data obtained from blasting test, combined with the EDZ (Excavation Damaged Zone) scope, it is significant to understand the formation mechanism and influence factors of the EDZ. At the same time, blasting design and damage verification for rock mass are still a hot topic in blasting engineering, especially for the geological disposal of high-level radioactive waste. Therefore, how to check the blasting damage of engineering rock mass is a challenge.

Usually, the blasting vibration velocity is a fundamental factor for assessing the blasting effect. Meanwhile, the excavation damaged zone is rather a significant factor for quantifying the damaged area caused by the excavation. However, there are few researches on the relationship between blasting vibration effect and rock damaged zone under blasting action. It just mainly focuses on the attenuation law of blasting vibration or the damage characteristics of surrounding rock purely. Based on the mechanical properties and the blasting parameters of bedrock in LingAo Nuclear Power Station in Guangdong Province, China, Xia et al. (2007) have simulated the stress wave propagation process of rock mass under different explosion loading conditions and analyzed the vibration attenuation characteristics. The vibration accelerated velocity data of LingAo Nuclear Power Station II phase project have been analyzed in detail, and the attenuation law of the blasting vibration has been obtained (Tang and Li 2008). The blasting vibration parameters are checked and optimized by comparison with the I phase project. Meanwhile, the blasting vibration monitoring and sound wave testing are carried out respectively. Combined with the blasting construction, the threshold value of the vibration monitoring data outside the explosion source 30 m has been put forward, and the influence of blasting on the damage of the surrounding rock is quantified (Xia et al. 2008; 2010). Zhang (2001) has carried out the in-site blasting test on the weakly weathered granite of the Three Gorges Project. The rock sound wave velocities before and after the blasting have been compared, it is believed that the radius of the micro-crack zone is $1.4 \sim 2.0$ m and the damaged
depth is 0.2~0.7 m, thus the critical rock vibration velocity is determined to be 13.8~16.6 cm/s. According to the rock blasting process and breaking mechanism, Liu et al. (2016), Chen et al. (2011) and Zhu and Lu (1998) have analyzed the rock broken state using drilling and blasting method. And the rock damaged variable is used to characterize the fracture degree of rock mass, then the critical damage threshold of the broken rock mass was determined to be 0.75~0.85. At the same time, Hu et al. (2013) compared the rock damaged zone during the dynamic and static excavation process, covering the characteristics of drilling and blasting method and TBM excavation method.

Moreover, ONKALO, the URL (Underground Research Laboratory) in Finland for nuclear waste disposal, has carried out the ground penetrating radar test to trap the rock damaged area. The resolution of the radar antenna with different frequencies to the excavation disturbed area is analyzed. It is proved that the radar antenna with high frequency is effective for the detection of the EDZ (Excavation Damage Zone) (Silvast and Wiljanen 2008). Other scholars (Siren et al. 2015; Xu et al. 2017, 2021; Fu et al. 2020) have compared and analyzed the URL’s EDZs in ASPO (locates in Sweden) and in ONKALO (locates in Finland). Mostly are about the blasting effect, attenuation of vibration law and the damage of surrounding rock caused by blasting. However, it is deficient with a description on the blasting vibration and surrounding rock damage degree.

Taking the BET (Beishan Exploration Tunnel) in Beishan area, Gansu Province, China, as an example, the vibration control method and the excavation damaged control of the blasting are introduced here, which is intended to provide reference and experience for the geological disposal of URL and other geo-engineering.

### 2. Blasting vibration testing

In order to study the damage degree and blasting vibration effect of different blasting parameters on rock mass, 5 cycles of drilling and blasting tests are carried out at the crossing vehicle lane position in BET. It should be noticed that the EDZ monitoring chamber is excavated ahead of the crossing vehicle lane, and the EDZ monitoring chamber is made up of chambers which are vertical and parallel to the drilling and blasting test section.

The geological disposal facilities of high level radioactive waste extend from the surface to a certain depth in the deep underground, which requires that the surrounding rock damage caused by the excavation is as small as possible, because the fracture of the surrounding rock will continue to initiate, expand, or even interconnect in the rock mass, resulting in the loss of the disposed nuclear waste in a certain

| No. | Cutting way        | Surrounding hole space (mm) | Specific charge unit (kg/m³) |
|-----|--------------------|-----------------------------|-----------------------------|
| 1   | Parallel cut       | 400                         | 2.07                        |
| 2   | Single wedge cut   | 400                         | 2.02                        |
| 3   | Double wedge cut   | 400                         | 2.00                        |
| 4   | Double wedge cut   | 300                         | 2.07                        |
| 5   | Parallel cut       | 300                         | 2.69                        |
period of time, which is absolutely not allowed. The accurate characterization of each blasting parameter can be realized by the blasting vibration monitoring, and then the blasting parameters can be optimized.

Five kinds of in-site blasting schemes are designed in the BET facility, and the corresponding blasting experiments are carried out. The effects of different cutting schemes and surrounding hole parameters are compared and analyzed. The comparison of the main blasting parameters for the five blasting tests is shown in Table 1. The blasting effect is subject to the cutting way and specific charge unit, while the damage degree is depended on the surrounding hole space. Therefore, these three blasting parameters have been provided in Table 1.

The rock type of this project is mainly granite, and its static compressive strength is \(150 \sim 180\) MPa. The surrounding rock is relatively complete, and there is no obvious crack. The longitudinal wave velocity of the rock is \(3200 \sim 3500\) m/s.

No.2 rock emulsion explosive is selected for this blasting. The diameter of explosive is 32 mm, the density of which is \(0.95 \sim 1.30\) g/cm\(^3\). And the detonation velocity is above 3500 m/s, the explosion heat is about 4015333 J/kg, the detonation temperature is 2654 °C, and the detonation pressure is 395000 N/cm\(^2\). The explosive weight of each volume is 300 g. For the surrounding blasting holes, the explosive is cut into several segments on average, using air spacing with uncoupled charge.

With the damage degree monitoring and blasting vibration monitoring of different blasting parameters, the blasting parameter should be maintained the same, except the variable value, i.e. cutting way, surrounding hole space and specific charge unit. For the blasting parameters, each cycle footage keeps the same, which is 2 m. A millisecond delay with non-electric detonator is used to detonate, and the cutting holes adopt continuous coupling charge, the auxiliary holes and the bottom holes adopt continuous non-coupling charge, the surrounding holes adopt the air interval with non-coupling charge to bind the interval of the explosive to the detonator.

2.1. Blasting vibration test scheme

Firstly, to estimate the distribution of vibration intensity on the roadway excavation section, and find out the most powerful location of blasting vibration.

Secondly, according to the previous data analysis, it is considered that the blasting vibration speed at the top of the roadway is the largest, and that the top vibration resistance of the roadway is the worst. The maximum value of blasting vibration velocity generally appears at the position of maximum tensile stress, while the position of maximum tensile stress of excavation roadway is generally at the top of roadway. Therefore, one of the vibration velocity sensors has been installed at the top of roadway. Therefore, there are three blasting vibration velocity sensors are arranged on the top of the roadway, and the sensor is arranged at the side wall of the roadway at the same position. In which, a three direction (radial, vertical, tangent) sensors are placed at each measuring point. The base is fixed on the rock surface by lime powder coupling.

Thirdly, the first measuring sensor point is arranged 10 m away from the blasting face, and the other sensors are arranged at intervals of 5 m. That is, three sets of
sensors and six measuring points are linearly arranged along the top and side of the roadway from the blasting face. As it is shown in Figure 1.

The damage of blasting vibration to surrounding rock is different due to the difference of each charging parameter, cutting way and geological condition. Therefore, the measuring points of blasting vibration are closely followed after each blasting cycle, and the distance between the sensors and the blasting face and the sensors of each measuring point are consistent with the former blasting cycle. Only this, the same objective condition of test data could be ensured and each blasting vibration value is more comparable. And the blasting preparation, progress and monitoring have been shown in Figures 2–5 respectively.

Meanwhile, the instrument needs to be pre-tested carefully before every blasting vibration test, and the blasting vibration test procedure is referred to the blasting vibration detection instruction.

2.2. Blasting vibration test process

The key to complete the blasting vibration monitoring depends on whether the monitoring system selected is reliable and whether it can fully meet the requirements of blasting vibration or not. Therefore, the frequency range and amplitude range of the monitored signal should be estimated and grasped in advance. And then the suitable blasting vibration recorder can be chosen.

The TC-4850 blasting vibration recorder produced by Chengdu Zhongke Measurement & Control Co., Ltd. is used in this test. The radial, vertical and tangential direction data can be obtained through the data acquisition equipment, which can reflect the characteristics of blasting vibration signals more comprehensively. The sensors’ installation position on the rock surface must be kept smooth. The harmonic binder is generally bonded with lime paste, and the vibration measuring sensors are fixed at the corresponding test positions to ensure that the sensors are fixed and not easy to fall off.

Figure 1. Blasting vibration observation point layout diagram.
It should be observed that there is no gap between the vibration measuring sensors and the rock wall, so that the blasting vibration data can be directly transmitted to the vibration measuring system through the vibration of the rock wall induced by the blasting. The connecting wire is drawn out from the vibration measurement sensor, and the blasting vibration monitoring equipment is installed. The corresponding protective measures are given to the monitoring equipment to prevent the blasting shock wave and the blasting flying stone damage. Turn on the monitoring equipment, set the frequency range and the amplitude range of the monitoring, and then wait for the blasting to start.

The blasting vibration data are recorded automatically. The monitoring equipment and the vibration measurement sensors are taken out after the blasting operation. The blasting vibration data is derived and data analysis and processing are carried out with the corresponding data software on the computer.
2.3. Blasting vibration data

Three vertical values of particle vibration should be simultaneously measured during the blasting vibration monitoring. The direct analysis method of blasting vibration signals has been applied to analysis the measured blasting waveforms, and the blasting vibration characteristic quantity is determined from the waveform diagram.

The vibration waveforms of each component for one monitoring sensor are shown in Figure 6. For each blasting cycle, the same vibration instrument test parameters and acquisition parameters are used to maintain a uniform vibration test condition. The maximum particle vibration velocity at the distance 10 m away from blasting source can be obtained by changing the pre-designed blasting parameters. The maximum blasting vibration velocity of all the five blasting cycles are 4.4 cm/s, 41.06 cm/s, 16.27 cm/s, 35.34 cm/s, and 60.0 cm/s separately.
Figure 6. Vibration waveforms of component for one monitoring sensor
3. Rock excavation damaged testing

For the geological disposal of high level radioactive waste, it is very important to recognize the relationship between the elastic modulus, deformation, permeability coefficient, heat conduction coefficient, and solute diffusion coefficient of the excavation zone. The geophysical methods are based on different response of media in physical properties.

In particular, GPR (Ground Penetrating Radar) technology, which is based on high frequency electromagnetic wave propagation, realizes the detection of underground medium by the reflection and refraction of high frequency electromagnetic wave in the medium. For different media, these parameters have great difference. GPR radar is a geophysical method to image the underground by using radar pulse. This method uses the electromagnetic radiation in the microwave band of the radio spectrum to detect the reflection signal of underground structure. GPR can be used in various media, including rock, soil, ice, fresh water, pavement and buildings. Under the appropriate conditions, GPR radar could be used to detect the changes of underground objects, material properties, cavities and cracks. Rock damage changes are obviously by blasting disturbance, and the field monitoring tests of ground penetrating radar, micro seismic monitoring, ultrasonic testing and borehole television technology have been carried out in combination with the drilling and blasting tests on the BET site. This paper mainly introduces the related results of radar test.

3.1. GPR test scheme

The GSSI with 1.5 GHz high frequency air coupled antenna made by the United States has been applied in the radar test. After each drilling and blasting cycle, the 1.5 GHz high frequency radar antenna is used in the tunnel to determine the damaged zone. The measured lines are layout on the top, the side and the bottom of the tunnel, with a equal internal (1 m).

It is found that the wavelength is longer due to the low frequency of test comparing the results of 1.5 GHz high frequency antenna. It shows that the high frequency GPR (1.5 GHz) is very effective and has high resolution for detecting the change of rock physical properties in the damaged area. The typical results of GPR test are shown in Figure 7.

3.2. Damaged zone

GPR was used to trap the range of EDZ and the EDZ depth of each cycle was calculated from 17 to 24 cm. Through the GPR monitoring technology, the damaged zone of the five blasting cycles are 17 cm, 23 cm, 21.5 cm, 22 cm, and 24 cm separately.

Through the morphology of EDZ, it showed that the EDZ characteristics of each cycle were basically the same. The damage range close to the excavation face is large, and it is also large at the end of the excavation direction. However, the damage range is small at the middle position along the blasting hole.

The reason is that there is more energy induced by the blasting can cause the damage at the end of the excavation direction, which is strongly held by the
surrounding rock. While, when it is close to the excavation face, the rock is directly shocked by the blasting impact, and it is much easier to be damaged, and the damage is not as bigger as that at the end of the excavation direction because this area is nearer to the free surface. Of course, the range and shape of each blasting damaged zone are controlled by many factors, such as geological condition, explosive quantity, detonator paragraph, construction level and so on.

At the same time, the AE (acoustic emission) monitoring was carried out. It was found that the average thickness of EDZ of each cycle is in good agreement with the number of acoustic emission hits of each cycle. At the moment of blasting, the number of acoustic emission impact increases sharply. The AE duration proves that the rock damage caused by blasting has a gradual evolution process. When the impact number of acoustic emission is higher, the thickness of the corresponding EDZ is thicker and the EDZ range is larger, which fully indicates the consistency of the above GPR test and AE test in characterizing the EDZ.

Furthermore, the sound wave test (including single hole wave velocity and cross hole wave velocity) is corroborated. The results of sound wave tomography show that the wave velocity in the range of 0.3 m~0.5 m away from the tunnel wall is reduced to 10%~45% of the original rock velocity. The density of the fissure is significantly higher than that of the undisturbed rock mass. It is considered that the area is the blasting damaged area. It can be considered that the wave velocity test is also a
powerful tool for quantifying the damaged degree of the surrounding rock. Compared with the GPR testing results, the EDZ depth by the sound wave testing could be achieved as $30 \sim 50$ cm. Above all, the EDZ scope of this blasting test should not exceed 30 cm.

4. Result analysis

In addition to the geological environment of the construction site, the excavation unloading phenomenon is closely related to the dynamic response of different excavation methods, as well as the mechanical response of strain energy release of the rock. Therefore, it attempts to put forward the threshold of blasting vibration, combining with the blasting test in the BET site, depict each blasting cycle’s effect and its damage to the surrounding rock. It also aims at to explore the internal correlation mechanism of blasting vibration and EDZ, evaluate the suitability of blasting design, and optimize the blasting parameters subsequently.

It is found that the blasting vibration velocity is different caused by many kinds of blasting parameters, which are also related to the rock physical and mechanical properties and distribution characteristics of the rock fracture. The blasting condition and blasting vibration velocity values of each blasting vibration monitoring process are determined by these factors. The cumulative effect of the rock damaged degree is related to the grade of the blasting impact load. The greater the load, the more obvious the cumulative effect is. And the cumulative effect on the EDZ of the rock can be ignored if the blasting load below a certain threshold.

In the BET project, the cumulative effect of surrounding rock is also studied by sound wave test. Under a small blasting load grade, the current blasting can only affect the damage of the surrounding rock this cycle, and there is no effect on the rock damage caused by the previous cycle and the subsequent cycle of blasting operation.

In other words, it exists that a cumulative effect on the damage degree of the surrounding rock only if the vibration velocity above a certain threshold. And the cumulative effect is not obvious when the vibration velocity is below this threshold.

The blasting vibration velocity corresponding to the first three blasting modes is inconsistent, which is mainly due to the different cutting ways. The first cutting way was straight parallel hole cutting, the second was the single wedge cutting, and the third was the double wedge cutting. It is found that the explosive energy distribution of straight parallel hole cutting is larger than that of wedge cutting, as it is shown in Figure 8.

The frequency of the 250 Hz range is divided into 8 sub-bands by the 31.25 Hz interval, and then the variation trend of each sub-band’s energy percentage under three different cutting ways is revealed. As it can be seen from the above Figure 3, all the three cutting modes’ energy are mainly concentrated in the vicinity of the main frequency band, and the energy distribution of other frequency bands is small. The main frequency of blasting vibration for straight parallel hole cutting is low and the main frequency band range is narrow and small, especially the ratio of low frequency energy in the signal is larger.
No matter the single wedge or double wedge cutting, the explosive energy has not been fully affected by the explosive stress, especially at the edge of the cutting cavity. Thus, the blasting energy had to be absorbed much higher by the surrounding rock. Therefore, either single wedge and double wedge cutting, the blasting vibration velocities of these two cutting ways are higher than that of straight parallel hole cutting.

In advance, the energy distribution of double wedge-shaped cutting is more uniform than that of the single wedge cutting, so the maximum blasting vibration velocity of double wedge-shaped cutting is lower than that of single wedge cutting.

The unit charge consumption of explosives at the fourth and the fifth cycles is higher, especially in the fifth blasting operation. And the explosive’s unit charge of the fifth cycle is increased by about 30% compared with the previous cycle, which induces that the blasting vibration is obviously enhanced and the blasting vibration velocity reaches the maximum at the five cycles. It also shows that the blasting vibration velocity is mostly affected by the explosive charge among many different kinds of influence factors.

For the fourth blasting cycle, compared with the third cycle, the unit charge consumption of explosive is higher, and the surrounding hole space is changed from 400 mm to 300 mm. Therefore, the distribution of the surrounding holes become denser, and it obtains a better blasting effect. However, the blasting vibration velocity is still higher than the third cycles due to the higher consumption of explosives. It is also proved that besides the cutting way, the blasting vibration velocity is much more susceptible to the explosive charge.

5. Discussion

It should be considered that the damage radius is not clearly limited during the construction of the nuclear waste underground laboratory and disposal repository, only
the damage depth of the bedrock is limited to ensure the integrity of the base. According to the analysis results of the maximum blasting vibration velocity and the damage range of surrounding rock, the relationship between the rock damage depth and the maximum blasting vibration velocity at the distance of 10 m away from the blasting source is fitted, as shown in formula (1) and Figure 9.

It shows that there is a good correlation between the blasting vibration velocity of rock and the excavation damaged zone under blast loading.

$$H_d = 0.11V_{10\text{max}} + 18$$  \hspace{1cm} (1)

In which, $V_{10\text{max}}$ is the maximum vibration velocity (cm/s) of the rock at the distance of 10 m away from the blasting source, and $H_d$ is the rock EDZ depth (m). And the data correlation coefficient $R^2=0.8$.

According to the rock damage scope obtained by various monitoring methods, it is proposed that the rock damage depth during the blasting excavation test should not exceed 30 cm. Based on the formula (1), the corresponding safety threshold of blasting vibration velocity $V_{10\text{max}}$ is 109 cm/s. Taking into account a certain safety reserve, the actual $V_{10\text{max}}$ of the BET project is taken as 100 cm/s. Blasting damage has been effectively controlled by the safety threshold value during the subsequent construction, and the rock integrity of BET project has been fully ensured.

The relationship between blasting vibration velocity and EDZ range corresponding to different blasting cycles is shown in Figure 10. It can be seen that the EDZ values increase with the blasting vibration velocity, and the larger the blasting vibration velocity, the deeper the rock damaged depth is.

It should be noticed that it exists an uncoupling difference between the EDZ value and the blasting vibration velocity, which is not only due to the various blasting parameters of these two parameters themselves, but also because the different blasting characteristics of these two parameters.
As each impact of blasting vibration is characterized by the blasting vibration velocity, the maximum vibration velocity only measures the instantaneous response of the blasting, and it could not describe the damaged depth of the blasting impact on the surrounding rock. After all, the rock damaged range occupies a property with time effect, which shows a longer time (relative to the instantaneous) accumulation. Meanwhile, the depth of the rock damage at the maximum blasting vibration velocity is often not the ultimate damaged range, but it is usually formed by the subsequent action of explosion shock wave, stress wave and detonating gas.

It needs to pay attention to that adopting different monitoring methods in blasting engineering is necessary and useful, and the blasting effect can be measured from diverse angles. However, there is a corresponding quantitative relationship between these two parameters. The blasting vibration velocity and the damaged zone of the rock are mutually confirmed. When the blasting is strong, the vibration velocity is large, and the EDZ value is correspondingly large. The quantitative description method and the threshold formula mentioned above play a very important role in evaluating the construction of URL engineering. It can confirm the difference and reliability of these two-monitoring data.

Above all, firstly, there are few research on the correlation mechanism between rock blasting vibration and surrounding rock damage, and the existing studies only focus on one aspect. Secondly, both the rock blasting vibration velocity and surrounding rock damage value are two different concept parameters, which reflect kinds of damage for rock blasting progress and situation. Whether there is a relationship between these two parameters, and what kind of link should to be studied in depth. Furthermore, the quantitative relationship between blasting vibration velocity and surrounding rock damage is given through blasting test, vibration velocity monitoring and surrounding rock damage monitoring, which is a major breakthrough.
6. Conclusion

Taking the BET facility in Gansu Province as an example, the blasting test was carried out, and the blasting vibration velocity and the EDZ of the rock have been monitored. Testing scheme of various monitoring methods was designed, and the test results were obtained and analyzed. The maximum blasting vibration velocity ranges from 4 cm/s to 60 cm/s, and the EDZ ranges from 17 cm to 24 cm.

A damaged controlling method has been proposed using the blasting vibration velocity at the distance of 10 m away from the blasting source should be not more than a certain threshold value. The damage characteristics of rock are analyzed by blasting vibration monitoring, sound wave test. The relationship between the EDZ and the peak vibration velocity at the distance of 10 m away from the blasting source is established. The safety threshold of BET engineering is determined, that is, when the rock peak blasting vibration velocity (10 m) is below 100 cm/s, the rock damage depth is less than 30 cm under the explosion load. Blasting damage is effectively controlled by the above controlling method and the safety threshold value proposed, and the integrity of BET bedrock could be ensured.

It should be pointed out that the proposed controlling methods can meet the safety requirements of engineering. However, in order to accurately and scientifically analyze the characteristics of blasting damage to a higher degree, it is necessary to define the initial blasting load, establish the rock damaged model and confirm the damage threshold value. The damage characteristics obtained by mathematical calculation and by the sound wave test should also be studied. The correlation between the safety threshold and the lithology and the blasting mode should be researched more deeply, which is also the main content on the basic safety control of the URL engineering. It can provide the experimental data and theoretical support for the blasting excavation of the high-level radioactive waste geological disposal, and it also has a certain guiding significance for the blasting excavation of the deep underground engineering.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China [Grant No.s 51522903, 51774184], Excellent project Fund in North China University of Technology [Grant No. 216051360020XN199/006] and Scientific Research Fund in North China University of Technology [Grant No. 110051360002].

Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.
References

Chen J, Li X, Zhang J. 2016. Study on blasting parameters of protective layer excavation of rock bench based on blasting induced damage. Chin J Rock Mech Eng. 35(1):98–108.

Chen M, Lu W, Li P. 2011. Elevation amplification effect of blasting vibration velocity in rock slope. Chi J Rock Mech Eng. 30(11):2189–2195.

Costamagna E, Oggeri C, Segarra P, Castedo R, Navarro J. 2018. Assessment of contour profile quality in D&B tunnelling. Tunn Undergr Space Technol. 75:67–80.

Deng XF, Zhu JB, Chen SG, Zhao ZY, Zhou YX, Zhao J. 2014. Numerical study on tunnel damage subject to blast-induced shock wave in jointed rock masses. Tunn Undergr Space Technol. 43:88–100.

Du QH, Liu XL, Wang EZ, Wang SJ. 2017. Strength reduction of coal pillar after CO2 sequestration in abandoned coal mines. Minerals. 7(2):26.

Fu TF, Xu T, Wasantha PLP, Yang T-H, Nara Y, Heng Z. 2020. Time-dependent deformation and fracture evolution around underground excavations. Geomatics Nat Hazards Risk. 11(1):2615–2633.

Fu Y, Li X, Dong L. 2010. Analysis of smooth blasting parameters for tunnels in deep damaged rock mass. Rock Soil Mech. 31(5):1420–1426.

Hu Y, Lu W, Chen M. 2013. Comparison of damage evolution process of high rock slope excavated by different methods. Chin J Rock Mech Eng. 32(6):1176–1184.

Hu YG, Liu MS, Wu XX, Zhao G, Li P. 2018. Damage-vibration couple control of rock mass blasting for high rock slopes. Int J Rock Mech Min Sci. 103:137–144.

Huang J, Liu XL, Zhao J, Wang EZ, Wang SJ. 2020. Propagation of stress waves through fully saturated rock joint under undrained conditions and dynamic response characteristics of filling liquid. Rock Mech Rock Eng. 53(8):3637–3655.

Li A, Xu NW, Dai F, Gu GK, Hu ZH, Liu Y. 2018. Stability analysis and failure mechanism of the steeply inclined bedded rock masses surrounding a large underground opening. Tunn Undergr Space Technol. 77:45–58.

Li HB, Xia X, Li JC, Zhao J, Liu B, Liu YQ. 2011. Rock damage control in bedrock blasting excavation for a nuclear power plant. Int J Rock Mech Min Sci. 48(2):210–218.

Lin P, Liu XL, Hu Y, Xu WB, Li QB. 2013. Deformation stability analysis of Xiluodu arch dam under stress-seepage coupling condition. Chin J Rock Mech Eng. 32(6):1145–1156. (in Chinese with English Abstract)

Liu L, Lu W, Chen M, Yan P. 2016. Statistic damage threshold of critical broken rock mass under blasting load. Chin J Rock Mech Eng. 35(6):1133–1140.

Liu XL, Han GF, Wang EZ, Wang SJ, Nawnit K. 2018. Multiscale hierarchical analysis of rock mass and prediction of its mechanical and hydraulic properties. J Rock Mech Geotech Eng. 10(4):694–702.

Liu XL, Wang F, Huang J, Wang SJ, Zhang ZZ, Kumar N. 2019. Grout diffusion in silty fine sand stratum with high groundwater level for tunnel construction. Tunn Undergr Space Technol. 93:103051.

Silvast M, Wiljanen B. 2008. ONKALO EDZ-measurements using Ground Penetrating Radar (GPR) method. Posiva Oy.

Siren T, Kantia P, Rinne M. 2015. Considerations and observations of stress-induced and construction-induced excavation damage zone in crystalline rock. Int J Rock Mech Min Sci. 73:165–174.

Sun H, Liu XL, Zhang SG, Nawnit K. 2020. Experimental investigation of acoustic emission and infrared radiation thermography of dynamic fracturing process of hard-rock pillar in extremely steep and thick coal seams. Eng Fract Mech. 226:106845.

Sun H, Liu XL, Zhu JB. 2019. Correlation fractal characterization of stress and acoustic emission during coal and rock failure under multilevel dynamic loadings. Int J Rock Mech Min Sci. 117:1–10.

Tang H, Li H. 2008. Analysis for blasting vibration attenuation law in groundwork digging in the second stage project in Lingao Nuclear Power Station. Blasting. 25(4):88–91.
Verma HK, Samadhiya NK, Singh M, Goel RK, Singh PK. 2018. Blast induced rock mass damage around tunnels. Tunn Undergr Space Technol. 71:149–158.

Wang X, Shan R, Huang B. 2008. Application research on smooth blasting for cracked soft rock tunnelling. Blasting. 25(3):12–16.

Xia X, Li H, Li J. 2008. Research on vibration safety threshold for rock under blasting excavation. Rock Soil Mech. 29(11):2945–2952.

Xia X, Li H, Zhang D. 2010. Safety threshold of blasting-induced rock vibration for Honyanhe nuclear power plant. Explos Shock Waves. 30(1):27–32.

Xia X, Shi Y, Li H. 2007. Numerical analysis of explosive load of single hole blasting and multiple-hole simultaneous blasting in rock mass. Chin J Rock Mech Eng. 26(1):3390–3396.

Xie H, Zhu J, Zhou T, Zhang K, Zhou C. 2020. Conceptualization and preliminary study of engineering disturbed rock dynamics. Geomech Geophys Geo. 6(2):34.

Xu C, Liu XL, Wang EZ, Zheng YL, Wang SJ. 2018. Rockburst prediction and classification based on the ideal-point method of information theory. Tunn Undergr Space Technol. 81:382–390.

Xu NW, Wu JY, Dai F, Fan YL, Li T, Li B. 2018. Comprehensive evaluation of the stability of the left-bank slope at the Baihetan hydropower station in southwest China. Bull Eng Geol Environ. 77(4):1567–1588.

Xu T, Fu M, Yang SQ, Heap MJ, Zhou GL. 2021. A numerical meso-scale elasto-plastic damage model for modeling the deformation and fracturing of sandstone under cyclic loading. Rock Mech Rock Eng. https://doi.org/10.1007/s00603-021-02556-2.

Xu T, Zhou GL, Heap MJ, Zhu WC, Chen CF, Baud P. 2017. The influence of temperature on time-dependent deformation and failure in granite: a mesoscale modeling approach. Rock Mech Rock Eng. 50(9):2345–2364.

Yang JH, Jiang QH, Zhang QB, Zhao J. 2018. Dynamic stress adjustment and rock damage during blasting excavation in a deep-buried circular tunnel. Tunn Undergr Space Technol. 71:591–604.

Yang R, Ding X, Yang L, Wang Y. 2017. Experimental study on controlled directional blasting on PMMA mediums with flaws. Chin J Rock Mech Eng. 36(3):690–696.

Yang R, Gao X, Zuo J. 2014. Experimental study of blasting wave propagation mechanism on cutting seam cartridge. J Coal Ind. 35(8):1434–1440.

Yang R, Tong Q, Yang G. 2010. Experimental study on cut blasting with slotted cartridge. Coal Safety. 3:11–14.

Yi X, Feng G, Xingguang L, Xin L. 2017. Permeability and pressure distribution characteristics of the roadway surrounding rock in the damaged zone of an excavation. Int J Min Sci Technol. 27(2):211–219.

Yue Z, Guo Y, Xu P. 2015. Analysis of empty hole effect in directional fracture controlled blasting. Explos Shock Waves. 35(3):304–311.

Zhang J. 2001. Vibration characteristics of blasting in bed rock mass at Sanxia Project. Explos Shock Waves. 21(2):131–137.

Zhu C, Lu W. 1998. Blasting safety criterion for the rock wall between temporary ship lock and ship lift in Three Gorges Project. Explos Shock Waves. 18(4):375–380.