sustainability

MDPI

Article

Predicting the Accuracy and Applicability of Micro-Seismic Monitoring of Rock Burst in TBM Tunneling Using the Data from Two Case Studies in China

Yalei Yang [1], Lijie Du [2,*], Qingwei Li [1], Xiangbo Zhao [3], Weifeng Zhang [4] and Zhiyong Liu [4]

1 School of Mechanical Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, China
2 Collaborative Innovation Center for Performance and Safety of Large-Scale Infrastructure, Shijiazhuang Tiedao University, Shijiazhuang 050043, China
3 Xinjiang Irtysh River Investment and Development (Group) Co., Ltd., Urumqi 830002, China
4 PowerChina Chengdu Survey and Design Research Institute Co., Ltd., Chengdu 610072, China
* Correspondence: dulj@stdu.edu.cn

Abstract: Rock burst in TBM construction will have a great influence on the construction safety and construction speed. At the same time, there are few practical projects using micro-seismic monitoring, and the accuracy of prediction is not satisfactory. Therefore, this paper was based on a large number of micro-seismic monitoring reports and data from two hard rock TBM projects in China. The actual rock burst situation was continuously tracked and recorded on site for comparison and verification. The accuracy of rock burst monitoring was statistically analyzed from the aspects of rock burst grade and location. The applicability was analyzed from the perspective of rock burst construction safety, advance rate, and prevention measures. It was concluded that the accuracy of micro-seismic monitoring increased with the increase in the rock burst risk level. The precision location of Grade I and Grade II rock burst could be realized basically, while Grade III rock burst prediction was relatively low. It is suggested that micro-seismic monitoring should be adopted when there are Grade I and II rock burst risks. The research results will have important guiding significance for the TBM construction of deep-buried tunnels in the future.

Keywords: TBM; micro-seismic monitoring; rock burst; accuracy; applicability

check for updates

Citation: Yang, Y.; Du, L.; Li, Q.; Zhao, X.; Zhang, W.; Liu, Z. Predicting the Accuracy and Applicability of Micro-Seismic Monitoring of Rock Burst in TBM Tunneling Using the Data from Two Case Studies in China. *Sustainability* **2023**, *15*, 4232. https://doi.org/10.3390/su15054232

Academic Editor: Jianjun Ma

Received: 20 December 2022
Revised: 19 February 2023
Accepted: 21 February 2023
Published: 27 February 2023

1. Introduction

The great risk faced by deep-buried tunnels with complex geological conditions is rock burst such as the C–Z Railway, Gaoligongshan Tunnel of Dali–Ruian Railway, Shaanxi Yinhanjiwei Project, Xinjiang ABH Project, etc. Once strong rock burst occurs in these projects, it will seriously affect the construction progress of TBM and threaten the safety of construction personnel and equipment [1]. A large number of strong rock burst, even extremely strong rock burst, occurred during the excavation of Jinping II Hydropower Station. This led to the active suspension of the construction of two TBMs and the destruction and burial of one TBM, resulting in casualties and huge economic losses [2]. The Yinhanjiwei Project, which is under construction, has also encountered strong rock burst, which has damaged the existing support many times. At the same time, the impact of rock burst caused serious damage to the TBM equipment, which had a great impact on the construction safety and progress [3]. Both TBMs of the N–J Hydropower Project tunnels in Pakistan suffered frequent rock burst impacts, causing casualties and serious damage to equipment [4]. The TBM construction of the Kobbelv HPS water conveyance tunnel in Norway also had casualties due to rock burst [5]. Due to the large burial depth, high geostress, complex structure, and a large number of brittle hard rocks such as granite and marble along the line, the C–Z Railway Project to be constructed will face a strong rock burst risk during the tunnel construction process, causing great difficulties to the planning, design, and construction of the project [6]. Therefore, effective prevention and control measures must be taken to solve the rock burst problem in TBM construction.

In order to prevent and control rock burst, it is necessary to study the mechanism and influence of rock burst. For example, Nooraddin Nikadat et al. [7] studied the stress distribution of tunnel excavation in jointed rock mass, and pointed out that the joint dip angle and joint spacing have an important influence on the stress distribution of the tunnel's surrounding rock. Rohola Hasanpour et al. [8] studied the mechanism of TBM jamming and carried out a three-dimensional simulation of the machine and surrounding rock by using finite difference software FLAC3D, effectively evaluating the influence of an adverse geological environment on TBM construction. Jamal Rostami [9] summarized the existing models of TBM performance prediction in order to develop better models to improve the accuracy of performance estimation and improve the utilization rate of TBM. On one hand, there is a need to carry out research on the theoretical criteria for rock burst prediction. For example, C.S. Ma et al. [10] proposed a new rock burst criterion based on the Pakistan N–J Hydropower Project, that is, to judge rock burst according to the ratio of rock mass strength to the horizontal stress of the vertical tunnel axis. On the other hand, the research is to introduce a microseismic monitoring system to monitor and forecast rock burst during TBM construction such as the Jinping II Hydropower Station Project, Shaanxi Yinhanjiwei Project, Xinjiang ABH Project, etc. Zhao Zhouneng et al. [11], based on the microseismic monitoring data and rock burst cases of the Jinping II Hydropower Station Project, analyzed the space–time law of rock burst from the perspective of microseismic monitoring results, indicating that there is a strong space–time correlation between microseismic events and rock burst. Yu Qun et al. [2] analyzed the change of microseismic monitoring data before and after rock burst at the Jinping II Hydropower Station. He found that most rock bursts have micro fracture precursors that can be monitored, which preliminarily proved the feasibility of applying a microseismic monitoring system for the early warning of rock burst risks in TBM construction. Chen Bingrui et al. [12] found that the faster the TBM tunneling speed, the stronger the microseismic activity through the analysis of the microseismic activity law in the TBM tunneling process. When the TBM starts tunneling again after maintenance, 4~6 h is the high incidence period of rock burst. Wang Jun [13] obtained statistics on the rock burst microseismic monitoring results and rock burst conditions at the upstream and downstream of Qinling Tunnel #3 and #4, and believed that the prediction accuracy rate was 95.89%, 90.00%, and 88.46%. Ma Tianhui et al. [14] analyzed the rock burst at Jinping II Hydropower Station and found that the accuracy of rock burst prediction in this project could reach 80.6%. It can be seen that the application of a microseismic monitoring method in TBM construction is making progress, but whether rock burst microseismic monitoring and prediction systems are used in TBM construction still produces some confusion.

First of all, there are a few cases of rock burst projects constructed by TBM, and even fewer projects using microseismic monitoring. The first one that introduced a microseismic monitoring system into domestic TBM construction was the Jinping II Hydropower Station Project. The accuracy of the initial prediction was not satisfactory, and its role is controversial among all parties involved in the construction. Later, with the deepening of the practical understanding, the prediction effect was continuously improved. A microseismic monitoring system has also been introduced into the Yinhanjiwei Project and Xinjiang ABH Project under construction. The systematic research and analysis on the accuracy and applicability of its monitoring and prediction will play an important role in guiding the introduction of microseismic system to other TBM projects in the future.

Second, the microseismic monitoring system predicts whether there is rock burst and whether the rock burst grade and location are accurate, which directly affects the safety of personnel and equipment, what construction prevention and control measures are taken, and the construction progress. Prediction results lower than the actual rock burst level will bring security threats, and the prevention and control measures taken for higher than the actual rock burst prediction will reduce the construction progress and increase the construction cost.

In addition, the monitoring and prediction of only a few TBM construction microseismic monitoring projects have been carried out by contractors with microseismic monitoring systems. The accuracy of the prediction results provided to the public is relatively general, and a detailed, specific, comprehensive, and systematic analysis is insufficient. At the same time, there is a lack of research suggestions on the applicability of microseismic monitoring from the perspective of construction impact and construction prevention and control measures, leading to differences in the recognition of microseismic monitoring by all parties involved in the project.

Based on the above situation, this paper took Xinjiang ABH Project and Shaanxi Yinhanjiwei Project as the supporting project cases, and according to a large number of microseismic monitoring reports and data, continuously tracks and records the actual rock burst situation on site for comparative verification. The accuracy of rock burst monitoring was statistically analyzed from the aspects of rock burst grade, location, etc., and the applicability of a rock burst microseismic monitoring system was analyzed from the perspective of rock burst construction safety, prevention and control measures, and the impact of construction speed to provide a reference for deep buried tunnel projects such as the C–Z Railway.

2. Description of the Projects Used for This Study

2.1. Xinjiang ABH Project

The total length of the main tunnel of the Xinjiang ABH Project is about 41 km, 9 km has been excavated by the drilling and blasting method, and 32 km excavated by two open TBMs. Among them, the planned excavation stake number of Section III studied in this paper is K9+600~K23+600, with a total length of 14 km and a tunnel diameter of 6.53 m. The ground elevation of the tunnel is 1750~3777 m. The tunnel section with a buried depth of more than 1500 m is about 7700 m, accounting for 53.4% of the total length of the bid section. The maximum buried depth is 2253 m. The tunnel is located in the strongly uplifted area of the North Tianshan Mountains, with developed folds and fractures, strong seismic activity, and high geostress. Along the line, there are hard and brittle rocks such as siltstone, metamorphic mudstone, granodiorite, etc. The compressive strength of the rocks is 55.6~148.7 MPa, which is in the geological conditions for rock burst.

As of July 2019, the stake number of the microseismic monitoring system is K11+569~K17+452, the driving mileage is 5883 m, and 110 microseismic monitoring reports have been submitted. During this period, 119 rock bursts actually occurred including 72 minor rock bursts, 17 minor to medium rock bursts, 30 medium rock bursts, and no strong to extremely strong rock bursts.

The geological conditions along the construction line of Bid Section III of the ABH Project are shown in Figure 1.

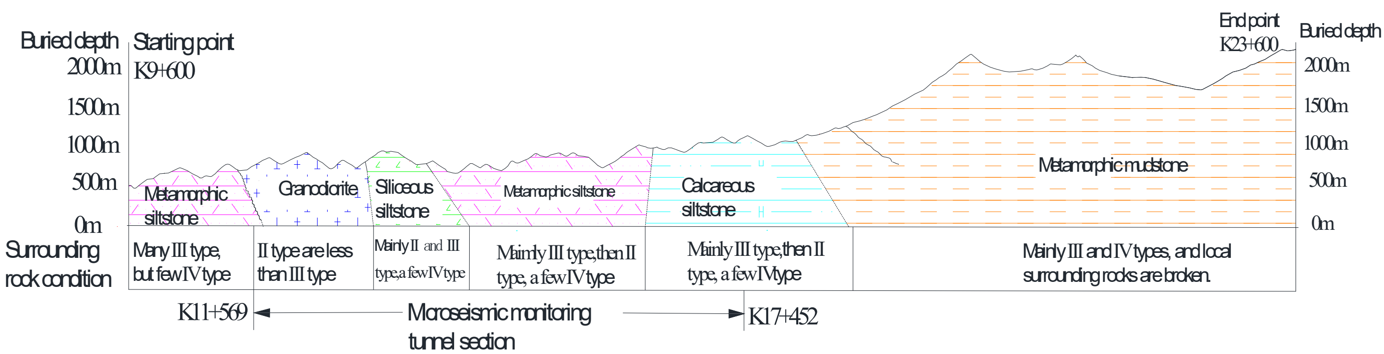

Figure 1. Geological profile of the Bid Tunnel Section III of the ABH Project.

2.2. Shaanxi Yinhanjiwei Project

The Yinhanjiwei Project is located in the Qinling Mountains in south central Shaanxi Province, with a total length of 98.3 km. It is jointly excavated by the drilling and blasting method and two open TBMs with a diameter of 8.0 m. The Lingnan section of the bid section under study is planned to be constructed with a total length of 18.28 km. The excavation stake number is K28+085~K46+360. The stake number K28+490~K37+011.5 is the first TBM excavation section, and the stake number K39+511~K46+360 is the second TBM excavation section. The elevation of the tunnel ranges from 1050 to 2420 m, the maximum burial depth is about 2012 m, and the geostress is high. Along the tunnel, there are mainly hard rocks such as quartzite, granite, diorite, etc. The compressive strength of the rocks is 107 to 317 MPa, with an average of about 170 MPa. In the dry and waterless tunnel section, there are conditions for strong rock burst [15].

As of November 2019, the stake numbers of the microseismic monitoring system deployed in the TBM construction section are K33+860~K37+011.5 and K39+511~K40+434, and the TBM tunneling mileage is 4074.5 m. A total of 531 microseismic monitoring reports were submitted, during which 731 rock bursts occurred successively including 247 minor rock bursts, 83 minor to medium rock bursts, 150 medium rock bursts, 80 medium to strong rock bursts, and 171 strong rock bursts.

The geological conditions along the south section of the Yinhanjiwei Project are shown in Figure 2.

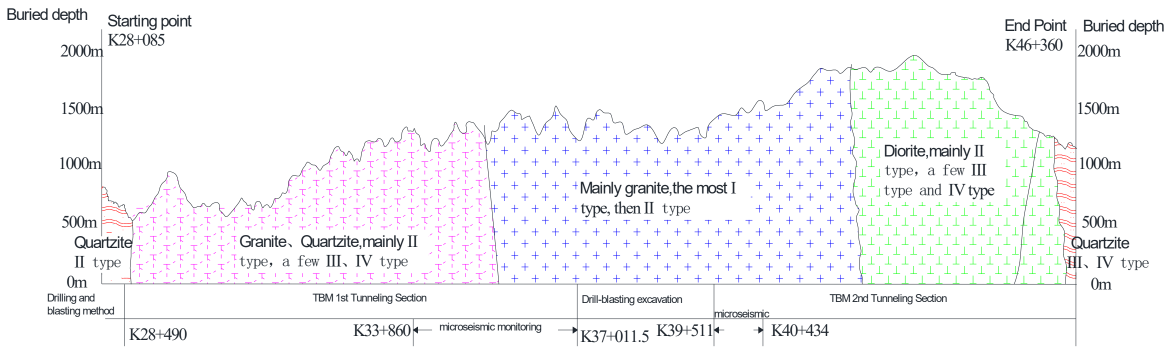

Figure 2. Geological profile of the Lingnan Tunnel Section of the Yinhanjiwei Project.

3. Overview of Rock Burst

3.1. Rock Burst Mechanisms

Rock burst is a phenomenon where rock mass in a high stress area is disturbed by excavation and other activities, so the elastic strain energy stored in it is suddenly released, which leads to rock mass fracture and ejection or throwing. Stress field and rock mass conditions are two main factors that control the occurrence of rock burst. TBM tunneling destroys the initial stress balance state, causing stress redistribution in the surrounding rock, stress unloading in the direction perpendicular to the excavation boundary, and the local stress concentration in the direction parallel to the excavation boundary. Under the condition of deep burial and high stress, this stress redistribution process may directly lead to rock burst and related damage in the surrounding rock [16]. For a long time, researchers have been investigating the stress evolution, rock burst, and related damage distribution of the surrounding rock during tunnel excavation by various means. Elastic–plastic mechanics provides a reference for the stress analysis of the surrounding rock of the TBM tunnel [17,18]. Regarding the rock mass conditions, the intact rock has a high elastic modulus, and TBM excavation does little damage to the rock, which can better maintain the integrity of the surrounding rock. However, once the balanced geostress of the rock at the airport surface is changed, it can only be distributed to the airport surface. In the process of stress wave propagation, the integrity of the rock in [19,20] is damaged, which leads to rock burst.

3.2. The Evaluation Method of the Influence Range of Rock Burst on TBM Excavation

The influence range of rock burst includes the length of a single rock burst section and the occurrence position of rock burst. To facilitate the statistics, the length of a single rock burst can be expressed by D. The length of a single rock burst section refers to the distance between the starting pile number and the ending pile number of rock burst after the rock burst occurs, and 5 m, 15 m, and 20 m can be used as grouping nodes. Statistical analysis of the daily footage of each rock burst section was conducted by summarizing the rock burst data of the same grade to obtain an average daily footage. The influence of different grades of rock burst on construction was obtained by comparing the average daily footage of the rock burst section with that of the conventional section under similar surrounding rock.

3.3. Monitoring Method of Rock Burst

Along with the development of science and technology, monitoring methods of rock burst are becoming more and more advanced. Nowadays, monitoring methods commonly used in the field mainly include microseismic, microgravity, seismological prediction, and the drilling cuttings method. The microgravity method can predict rock burst early, and the prediction range is wide, but the cost is high and the predicted position is not accurate enough. The seismological prediction method can realize real-time monitoring and accurately find out the source position, but it is very expensive and is easily affected by the blasting operation. The drilling cuttings method is limited in space, takes up the workers' working time, and the judgment result is easily influenced by the subjectivity of the monitor.

4. Microseismic Monitoring System and Classification of Rock Burst

4.1. Rock Burst Microseismic Monitoring System

The rock burst microseismic monitoring system can monitor the rock burst by monitoring the micro fracture generated in the process of the stress release of the rock mass. The microseismic monitoring method was initially mainly used in the mining field. In recent years, some deep buried water tunnels in China have also adopted microseismic methods to monitor and warn of rock bursts [21], mainly including the Jinping II Hydropower Station Project, Xinjiang ABH Project, and Shaanxi Yinhanjiwei Project.

The rock burst microseismic monitoring system in a TBM construction project is generally composed of one Paladin data acquisition instrument, six acceleration sensors, and one monitoring host [22,23]. Three monitoring sections are arranged in the direction of the tunnel axis, each section is equipped with two sensors, and the spacing of the monitoring sections is 40~50 m. This can be adjusted flexibly according to the specific construction situation on site, but at least four sensors will work normally. The monitoring host system and the receiving substation are placed on the TBM trolley, and the sensors are connected with the substation by communication cables. The substation and host processing system are connected by an optical fiber to realize signal transmission. The microseismic monitoring system monitors the rock burst in real-time as the working face advances. The monitoring system layout is shown in Figure 3.

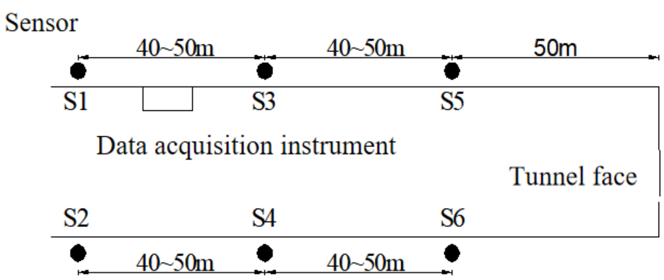

Figure 3. Sensor layout of the microseismic monitoring system. Note: S1–S6 are acceleration sensors.

When a microseismic event occurs, each acceleration sensor can determine the distance from the microseismic event to the sensor, so a circle can be obtained with the acceleration sensor as the center and the distance from the microseismic event as the radius, so several different circles can be obtained, and the specific position of the microseismic event can be determined through their intersection points. Generally speaking, the more sensors are laid, the more accurate their positioning. However, due to the fact that the sensors can only be laid along the axis of the tunnel and the harsh construction environment, the positioning accuracy is affected to some extent. Moreover, microseismic events often have a distance from the tunnel excavation surface, and the rock burst recorded in the actual construction process is only observed from the surrounding rock of the excavated tunnel, which leads to certain errors in the monitoring results. Therefore, in some cases, the monitoring grade and position of rock burst often have a certain deviation, so it is necessary for the on-site monitoring personnel to gradually eliminate this part of the influence through the continuous accumulation of experience to obtain more accurate rock burst prediction results.

A microseismic monitoring system can monitor microseismic events in the surrounding rock during excavation. It can determine the location of rock burst according to the location of the concentration of microseismic events as well as the grade of rock burst according to the number and energy level of microseismic events. The magnitude of microseismic events is the main purpose of microseismic monitoring, and it is also one of the bases to measure the energy of rock fracture [24]. The magnitude used in microseismic monitoring is generally the local magnitude, and its calculation formula is as follows:

$$\mathrm{m} = 0.344\lg E + 0.516\lg M - 6.572 \quad (1)$$

where M is the seismic moment and E is the microseismic energy.

The criteria are as follows: the number of microseismic events within 24 h is not less than 20, which can be considered as rock burst risk; if there are no less than three microseismic events reaching a certain energy level, it is considered that there is a rock burst risk corresponding to that energy level. In order to ensure the safety of construction, the highest rock burst risk level shall be the final prediction result [25,26]. The energy levels of different rock bursts are shown in Table 1.

Table 1. Energy levels of different grades of rock burst.

Rock Burst Grade	Slight Rock Burst	Medium Rock Burst	Strong Rock Burst	Extremely Strong Rock Burst
Energy level (kJ)	10~100	100~1000	1000~5000	>5000

Due to the complex tunnel construction environment, sensors can only be deployed along the tunnel axis. Moreover, the microseismic events are mostly in the rock mass, and there is a distance from the excavated surrounding rock, which leads to a certain deviation between the monitoring results and the actual rock burst [27]. Therefore, the characteristics of the rock burst microseismic monitoring system should be explored so that the monitoring results can guide the construction more accurately.

4.2. Rock Burst Classification in TBM Construction

During TBM construction, the prediction results of rock burst grade are subdivided into: slight rock burst, slight~medium rock burst, medium~strong rock burst, strong rock burst, and extremely strong rock burst. Different levels of rock burst have different impacts on the construction, and the prevention and control measures taken are also different. According to the characteristic laws and the prevention and control technologies of rock burst in TBM construction analyzed by Wang Jiaxing [28], and considering the prediction level of rock burst and its impact on TBM construction safety, construction speed, and the prevention and control measures, rock burst in TBM construction can be further classified into three risk levels, namely, III, II, and I, as shown in Table 2. The accuracy analysis of rock burst prediction classified into three risk levels is more significant for engineering practice.

Table 2. Rock burst risk level classification.

Risk Level	Rock Burst Grade
Grade III	Slight rock burst, slight~medium rock burst
Grade II	Medium rock burst, medium~strong rock burst
Grade I	Strong rock burst and rock burst of above grade

- Grade III risk rock burst.

If the number of microseismic events is $\geq$20, and there are more than three microseismic events with an energy of 10~100 kJ, it is considered that there is a Grade III risk rock burst in this tunnel section. When there is a Grade III rock burst risk in TBM construction, TBM tunneling and initial rock support shall be carried out at the same time, and the shield and initial support can protect the construction personnel. The Grade III risk rock burst energy is low, and most of them cannot damage the shield and the initial support behind the shield. Therefore, rock burst has a small impact on the TBM construction speed and safety.

- Grade II risk rock burst.

If the number of microseismic events is $\geq$20, and there are more than three microseismic events with an energy of 100~1000 kJ, it is considered that there is Grade II risk rock burst in this tunnel section. When there is a Grade II rock burst risk in TBM construction, the rock burst will reduce the construction speed to a certain extent, and the support and TBM equipment will not generally be threatened with serious damage. It is necessary to comprehensively judge whether it is necessary to take corresponding measures to reduce the severity of rock burst according to the surrounding rock conditions and microseismic monitoring results, and the support operation should closely follow the excavation operation. Safe, fast, and effective support measures should be selected according to the surrounding rock type and rock burst prediction.

- Grade I risk rock burst.

If the number of microseismic events is $\geq$20, and there are more than three microseismic events with an energy >1000 kJ, it is considered that there is a Grade III risk rock burst in this tunnel section. When a Grade I rock burst risk exists in TBM construction, the rock burst will greatly reduce the construction speed, which may cause casualties, equipment damage, large-scale shutdown, and even a single extremely strong rock burst may destroy the project. When there is a Grade I rock burst risk in the project, the machine should be stopped immediately to judge whether there are effective measures to allow the TBM construction to pass through safely. If necessary, stress release in advance can be considered. When TBM is required to pass through a strong rock burst tunnel section, the TBM cutterhead and shield should be designed in a robust way, tunneling and support should be coordinated and controlled, the advance rate should be actively controlled, and an effective support scheme should be adopted to ensure construction safety. No strong or above rock burst occurred.

During the construction of the tunnel section where the microseismic monitoring system was deployed in the ABH project, 72 minor rock bursts and 17 minor to medium rock bursts occurred, which were classified as Grade III risk rock bursts; 30 medium rock bursts were classified as Grade II risk rock bursts.

During the construction of the tunnel section where the microseismic monitoring system was deployed in the Yinhanjiwei Project, 247 minor rock bursts and 83 minor to medium rock bursts occurred, which were classified as Grade III risk rock bursts; 150 medium rock bursts, and 80 medium strong rock bursts were classified as Grade II risk rock bursts; 171 strong rock bursts were classified as Grade I risk rock bursts.

5. Accuracy Analysis of Rock Burst Microseismic Monitoring

Based on the actual rock burst records at the construction site, the prediction accuracy of the rock burst risk level and location can be obtained by comparing the rock burst microseismic monitoring results.

5.1. Accuracy of Rock Burst Risk Grade Prediction

Based on the microseismic monitoring report, the actual rock burst risk levels within the predicted pile number range in the microseismic monitoring report were counted when the rock burst prediction results were Grade III, Grade II, and Grade I, respectively, and the actual rock burst probability of each grade was obtained when different rock burst prediction results were obtained.

The rock burst occurred in the supporting project should be classified according to the construction risk level, and the early warning results of the microseismic monitoring system before the occurrence of Grade III, II and I rock bursts are counted respectively. In this way, the accuracy of the rock burst risk prediction can be obtained, as shown in Figure 4.

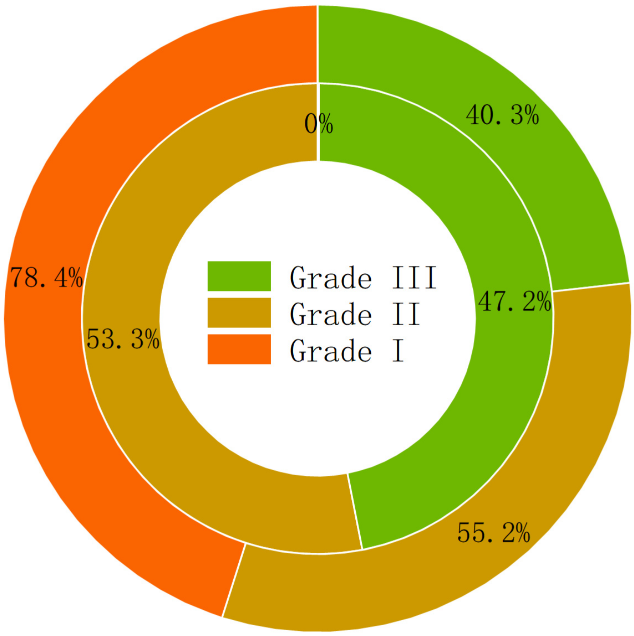

Figure 4. Accuracy of the rock burst risk grade prediction. Note: The inner ring is the ABH Project and the outer ring is the Yinhanjiwei Project.

It can be seen from Figure 4 that for Grade III and Grade II rock bursts, the accuracy of rock burst risk prediction for the ABH Project and Yinhanjiwei Project at the same level was not different, and the accuracy was relatively low at 47.2% and 40.3% for Grade III and 53.3% and 55.2% for Grade II, respectively. Regarding the Grade I rock burst, the ABH Project has not experienced it yet. The prediction accuracy of the Yinhanjiwei Project was 78.4%, reaching a high level. Based on the results of the rock burst prediction of the two projects, it was found that with the increase in the rock burst risk level, the prediction accuracy of the microseismic monitoring system gradually improved.

5.2. Accuracy of Rock Burst Location Prediction

Based on the records of the actual rock burst, the position prediction and position prediction deviation of different grades of rock burst were counted, respectively. The position prediction deviation could be divided into three categories, as shown in Figure 5. Figure 5 shows the rock burst risks predicted by stations A~B and C~D, but there were no rock burst risks predicted by stations B~C, and rock bursts occurred in stations 1~2.

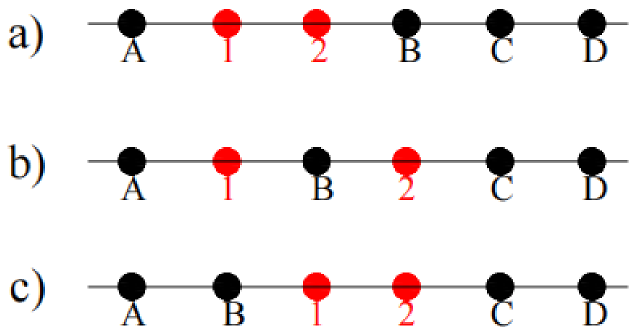

Figure 5. Error classification of the rock burst position prediction. Note: (**a**) rock burst risk in the microseismic monitoring report before it occurred. (**b**) rock burst risk in the microseismic monitoring report before its occurrence, and the rest were predicted to have no rock burst risk. (**c**) no rock burst risk in the microseismic monitoring report before it happened.

i. Completely monitored: The range of the actual rock burst pile number was predicted to have rock burst risk in the microseismic monitoring report before it occurred, as shown in Figure 5a. This kind of rock burst can be considered as no deviation in position prediction, and recorded as 0.
ii. Partial monitoring: Some parts of the actual rock burst pile number range were predicted to have rock burst risk in the microseismic monitoring report before its occurrence, and the rest were predicted to have no rock burst risk, as shown in Figure 5b. The deviation of the predicted position of this kind of rock burst can be approximately regarded as the length of the rock burst that is predicted to have no risk of rock burst, that is, the distance from station B to station 2.
iii. Not monitored: The range of the actual rock burst pile number was predicted as no rock burst risk in the microseismic monitoring report before it happened, as shown in Figure 5c. In this case, from the monitoring report submitted before the rock burst, the data report closest to the rock burst location can be selected as the judgment basis, and the maximum value of the rock burst pile number from this group of predicted data can be calculated as the predicted position deviation, that is, the minimum value of the distance from pile number B to pile number 2 and the distance from pile number 1 to pile number C.

The accuracy of the rock burst location prediction can be obtained by separately counting the positioning of the rock burst by the microseismic monitoring system before the occurrence of Grade III, Grade II, and Grade I rock bursts, as shown in Figure 6. When the range of pile numbers where rock burst actually occurs is detected in advance, it can be considered that the location of the rock burst is accurate; if the range of the actual rock burst pile number is not completely monitored in advance, it is considered that there is a deviation in the positioning.

It can be seen from Figure 6 that the accuracy rate of rock burst positioning of the Yinhanjiwei Project was slightly higher than that of the ABH Project, which was mainly related to the number of rock bursts and personnel positioning experience. With the enhancement in the rock burst risk level, the accuracy of the microseismic monitoring system for rock burst location gradually improved. Among them, the accuracy of the prediction of the location of Grade I rock burst in the Yinhanjiwei Project could reach 100%. In general, the prediction accuracy of microseismic monitoring location was high, which is of great significance for rock burst prevention and control in TBM construction.

In conclusion, with the increase in the rock burst risk level, the accuracy of the rock burst risk level prediction and rock burst location had been improved. Therefore, from the perspective of the accuracy of the rock burst microseismic monitoring results, it is more reasonable to apply the microseismic monitoring system to the monitoring of high-risk rock burst.

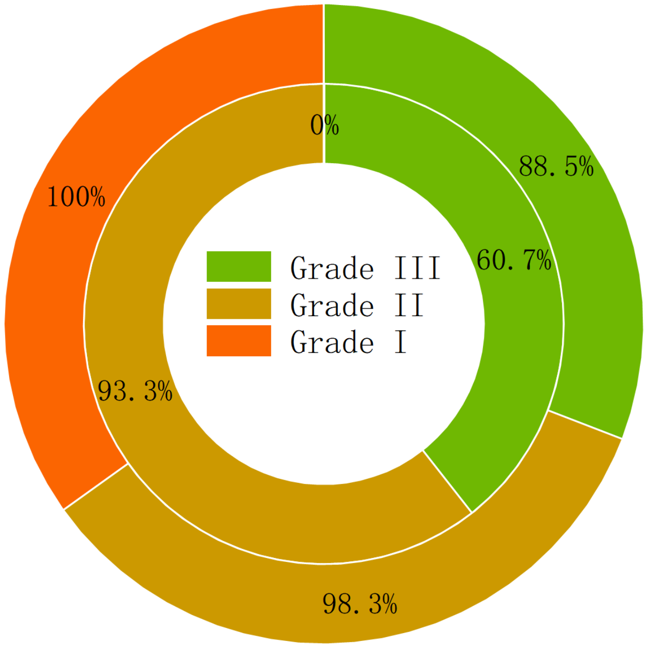

Figure 6. Accuracy of the rock burst location prediction. Note: The inner ring is the ABH Project and the outer ring is the Yinhanjiwei Project.

6. Applicability Analysis of Rock Burst Microseismic Monitoring

During TBM construction, the microseismic monitoring system is easy to deploy, which can realize real-time and continuous monitoring, with low monitoring cost and stable monitoring data. It is reasonable to apply a microseismic monitoring system to TBM construction. However, judging from the accuracy of rock burst warning and positioning, the microseismic monitoring system is more suitable for monitoring high-level rock burst. In order to further analyze the applicability of the microseismic monitoring system, according to the early warning of the microseismic monitoring system and the accuracy of rock burst positioning at all levels, we analyzed the effect and impact of construction according to the microseismic monitoring results when rock bursts of different risk levels occur to draw more reliable conclusions.

6.1. Applicability Analysis for Grade III Rock Burst

In the two supporting projects, the accuracy of the Grade III rock burst location was 60.7% and 88.5%, respectively. As Grade III rock burst has little impact on the construction, the prevention and control measures mainly focus on personnel protection, and there is no need to take advanced stress release measures. Therefore, the above results have little impact on the construction. The accuracy rate of early warning of Grade III rock burst risk was 47.2% and 40.3%, respectively. See Figures 7 and 8 for the specific early warning information.

Grade III rock burst had little impact on construction. Generally, normal construction can be carried out after the personnel and equipment are protected. If Grade III rock burst is predicted as no rock burst due to the low energy of the rock burst and the protective effect of the initial support, even if rock burst occurs, it will not have too much of an impact on the personnel or equipment. If Grade III rock burst is predicted to be Grade II or Grade I rock burst risk, certain prevention and control measures may be taken before construction, which will reduce the construction efficiency and increase the construction cost.

If rock burst monitoring is not carried out, the Grade III rock burst is regarded as the situation without rock burst. After rock burst, the impact on construction is small. After microseismic monitoring was adopted in the ABH Project, 22.5% of the Grade III rock burst was predicted to be of Grade II rock burst risk, which will increase some unnecessary construction costs. After microseismic monitoring was adopted for the Yinhanjiwei Project, 50.0% of Grade III rock bursts were predicted to be Grade II rock bursts, 7.6% of Grade III rock bursts were predicted to be Grade I rock bursts, and more than half of the Grade III rock bursts can only be constructed after prevention and control, which will greatly reduce the construction efficiency and increase the construction costs.

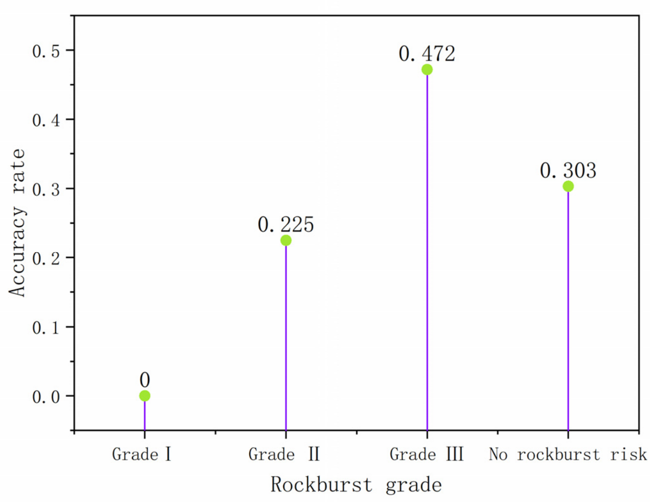

Figure 7. Grade III rock burst prediction at the ABH Project.

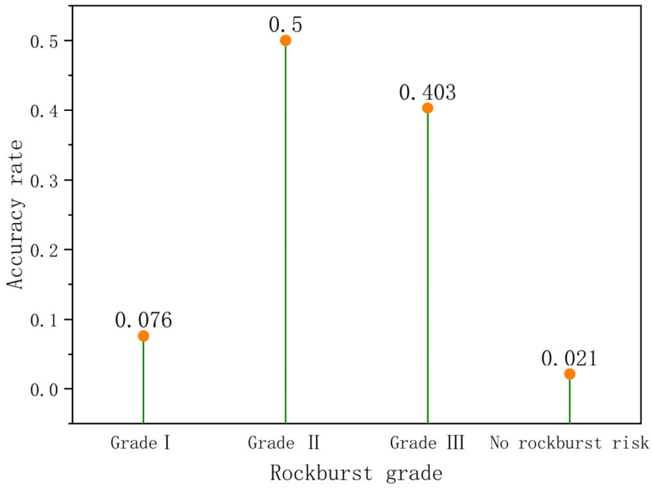

Figure 8. Grade III rock burst prediction at the Yinhanjiwei Project.

To sum up, when a TBM project only has a Grade III rock burst risk, the construction effect is not obvious after the introduction of a microseismic monitoring system, and many unnecessary construction costs will be increased. Therefore, in this case, it is not recommended to use the microseismic monitoring system for the early warning of rock burst risk.

6.2. Applicability Analysis for Grade II Rock Burst

In the two supporting projects, the accuracy of the Grade II rock burst location was 93.3% and 98.3%, respectively. As a result, some prevention and control measures will be properly taken for Grade II rock burst in combination with the construction situation. Therefore, there are certain requirements for rock burst positioning, and the two projects cannot achieve the complete positioning of Grade II rock burst. Therefore, it is still necessary to summarize the experience and strengthen the positioning accuracy of Grade II rock burst. The accuracy of Grade II rock burst warning was 53.3% and 55.2%, respectively; See Figures 9 and 10 for specific early warning information.

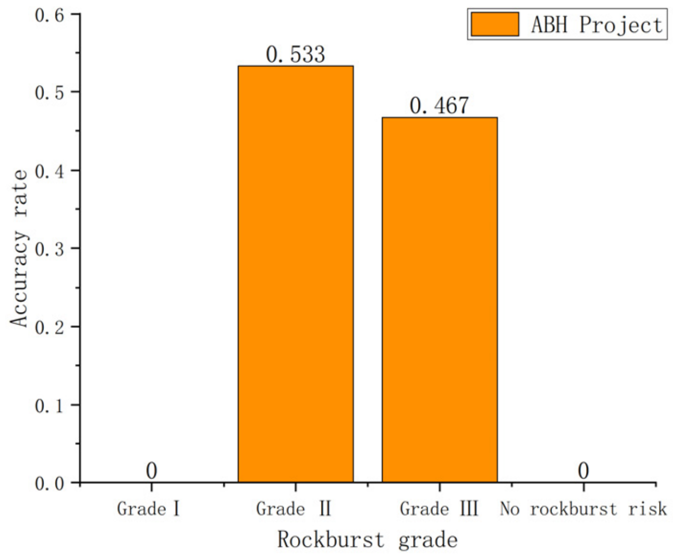

Figure 9. Grade II rock burst prediction at the ABH Project.

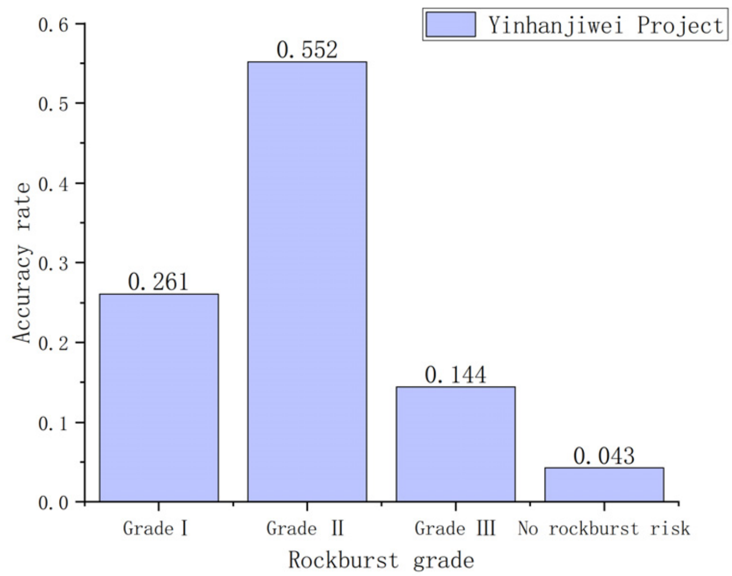

Figure 10. Grade II rock burst prediction at the Yinhanjiwei Project.

Grade II rock burst will have a certain impact on the construction, but the loss caused by Grade II rock burst can be greatly reduced after reasonable construction measures are taken. If Grade II rock burst is predicted as Grade III rock burst risk or there is no rock burst, the construction safety and efficiency may be affected due to a failure to take prevention and control measures. If Grade II rock burst is predicted as Grade I rock burst risk, greater prevention and control measures need to be taken to ensure safety before construction, which will also affect the construction efficiency.

If rock burst monitoring is not carried out, the Grade II rock burst will be regarded as the situation without rock burst, and the safety of personnel and equipment will be threatened in the case of Grade II rock burst. When the number of rock bursts is large, slag removal, arch repair, and damaged equipment will take a lot of time and affect the work efficiency. After microseismic monitoring was adopted in the ABH Project, 53.3% of Grade II rock burst could be effectively controlled; 46.7% of Grade II rock burst was predicted to be Grade III rock burst risk, which can effectively reduce the TBM construction risk due to the protection of personnel and equipment. After microseismic monitoring was adopted in the Yinhanjiwei Project, 81.3% of Grade II rock burst could be effectively controlled, but 26.1% of Grade II rock burst was predicted to be Grade I rock burst risk, which will increase the construction costs. In addition, 14.4% of Grade II rock burst was predicted to be Grade III rock burst risk, which can also effectively reduce the TBM construction risk after protection.

Through comprehensive analysis, when there is only Grade II rock burst risk in a TBM project, the introduction of a microseismic monitoring system can effectively reduce the construction risk of most rock bursts. Therefore, in this case, the use of a microseismic monitoring system for rock burst risk early warning is recommended.

6.3. Applicability Analysis for Grade I Rock Burst

Grade I rock burst has not occurred in the ABH Project, and the accuracy rate of the Grade I rock burst location in the Yinhanjiwei Project was 100%. This can realize the complete positioning of Grade I rock burst, which is of great significance for the prevention and control of Grade I rock burst. The accuracy rate of Grade I rock burst warning was 78.4%. See Figure 11 for the specific warning information.

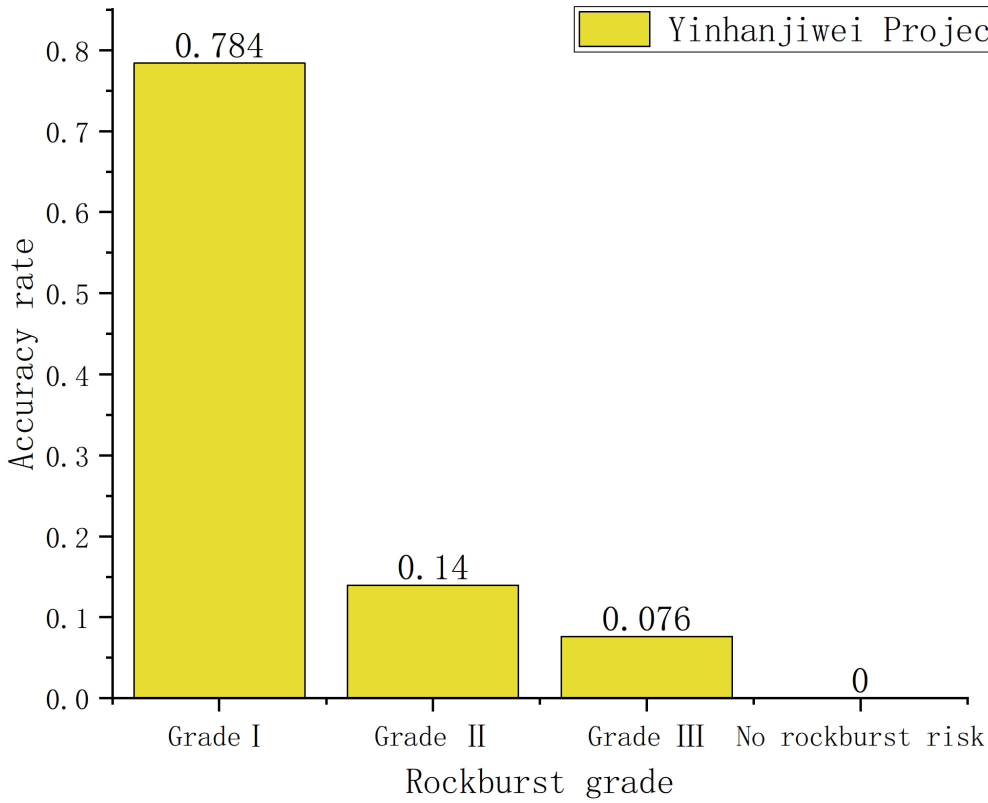

Figure 11. Grade I rock burst prediction at the Yinhanjiwei Project.

Grade I rock burst has a great impact on the construction. After implementing prevention and control measures in advance, certain prevention and control effects can be produced. If Grade I rock burst is predicted as Grade II or Grade III rock burst risk, the safety of the construction personnel can be improved, but the effect of rock burst prevention and control is not significant. If Grade I rock burst is predicted as no rock burst due to no or insufficient measures taken, not only are personnel and equipment greatly threatened, but the support measures taken may also be damaged, which is very dangerous for construction.

If rock burst monitoring is not carried out, the Grade I rock burst will be regarded as the situation without rock burst, which is very dangerous. After microseismic monitoring, 78.4% of Grade I rock burst could be forewarned, and a good control effect could be achieved after taking measures; 14.0% of Grade I rock burst was predicted to be Grade II rock burst. It can also be said that the sum of Grade I and Grade II rock burst was 92.4%. Grade I and Grade II rock burst are medium and strong rock burst, which have a great impact on the safety of the TBM construction. Although the prediction level was 14.0% lower, the monitoring system was still very useful for construction control, which can improve the safety of personnel and equipment; 7.6% of Grade I rock burst was predicted to be Grade III rock burst risk, so there is still a large safety threat.

When the TBM project only has a Grade I rock burst risk, the introduction of a microseismic monitoring system can greatly improve the safety of construction. In this case, the microseismic monitoring system should be used for rock burst risk early warning.

In conclusion, when there is only Grade III rock burst risk in a project, the use of a microseismic monitoring system for rock burst risk early warning is not recommended; in the case of Grade II and Grade I rock burst risks in a project, microseismic monitoring system should be adopted for rock burst risk warning.

7. Discussion

At present, there are only three cases in which a microseismic monitoring system has been introduced into the TBM construction of deep-buried tunnels in China including the Jinping II Hydropower Station Project, which has been completed and put into operation, and the ABH Project in Xinjiang and the Yinhanjiwei Project in Shaanxi, which are under construction at the time of writing this paper. There are still a few cases of microseismic monitoring, and the research on its accuracy and applicability is still lacking, and the accuracy of the monitoring and prediction results is disputed. However, the C–Z Railway, which is about to be built, plans to use TBM in large quantities, and its tunnels are deeply buried, complicated in structure, and high in in situ stress. Therefore, the conclusions of the two engineering case studies in this paper have important guiding significance for the construction of deep-buried tunnels such as the C–Z Railway. A further summary of the applications of microseismic monitoring in TBM construction projects will further improve the accuracy of microseismic monitoring. In this paper, the rock burst in TBM construction was further classified into three risk levels: III, II, and I. It is more valuable for engineering practice to analyze the accuracy of rock burst prediction classified into three risk levels.

8. Conclusions

In this paper, two TBM deep tunnel projects were taken as the studied cases to verify and analyze the microseismic monitoring results of rock burst. Among them, the microseismic monitoring tunnel of Xinjiang ABH Project is 5883 m long, and there were 110 microseismic monitoring reports, with 119 actual rock bursts. The microseismic monitoring of Shaanxi Yinhanjiwei Project is 4074.5 m, and the microseismic monitoring report was 531, with 731 rock bursts. The following conclusions can be drawn regarding the accuracy and applicability of microseismic monitoring in TBM construction:

- The higher the rock burst risk level in TBM construction, the higher the accuracy of the rock burst risk level and location prediction, and the accurate positioning of Grade I and Grade II rock bursts can basically be achieved.
- The accuracy rate of the Grade I rock burst prediction of the Yinhanjiwei Project reached 78.4%, and 14.0% of Grade I rock burst was predicted as Grade II.
- The accuracy rate of the Grade II rock burst prediction was 55.2%, and 26.1% of the Grade II rock burst was predicted as Grade I.
- The prediction accuracy rate of the Grade II rock burst of the ABH Project was 53.3%, and 46.7% of Grade II rock burst was predicted to be Grade III, and the prediction level and positioning accuracy of Grade III rock burst were relatively low.
- Through comprehensive consideration of the accuracy of rock burst prediction, the construction speed, construction safety, and the prevention and control measures, the rock burst in TBM construction was further divided into three risk levels: III, II, and I.
- When there is only a Grade III rock burst risk in a TBM construction project (i.e., rock burst below the medium level) due to the low prediction accuracy and the low risk of

construction safety and construction progress, the use of a microseismic monitoring system for the early warning of rock burst risk is not recommended.

- When the project has Grade II and Grade I rock burst risks, that is, above the medium rock burst, due to the high prediction accuracy and the high risk of construction safety and construction progress, it is advisable to use a microseismic monitoring system for the early warning of rock burst risk to ensure construction safety.

Author Contributions: Methodology, Y.Y. and X.Z.; Validation, W.Z.; Investigation, Q.L.; Resources, Q.L.; Writing-original draft, Y.Y.; Writing-review and editing, L.D. and Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research work was funded by the PowerChina Chengdu Survey and Design Research Institute Co. Ltd. (Grant No. NZL022) and Xinjiang Irtysh River Investment and Development (Group) Co. Ltd. (Grant No. EQ075/FY056).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Financial support from the PowerChina Chengdu Survey and Design Research Institute Co. Ltd. (Grant No. NZL022) and Xinjiang Irtysh River Investment and Development (Group) Co. Ltd. (Grant No. EQ075/FY056) are gratefully acknowledged. Valuable comments and constructive suggestions from Editor and anonymous reviewers are also acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Du, L.J. Progresses, Challenges and Countermeasures for TBM Construction Technology in China. *Tunn. Constr.* **2017**, *37*, 1063–1075.
2. Yu, Q.; Tang, C.; Li, L.C.; Li, H.; Cheng, G.W. Nucleation process of rockbursts based on microseismic monitoring of deep-buried tunnels for JinpingIIHydropower Station. *Chin. J. Geotech. Eng.* **2014**, *36*, 2315–2322.
3. Xue, J.P. Construction Technology of Open TBM Safely and Rapidly Pass through Strong Rockburst Formation of Lingnan Section on Qinling Tunnel of Hanjiang River-Weihe River Water Conveyance Project. *Tunn. Constr.* **2019**, *39*, 989–997.
4. Naji, A.M.; Rehman, H.; Emad, M.Z.; Ahmad, S.; Kim, J.J.; Yoo, H. Static and Dynamic Influence of the Shear Zone on Rockburst Occurrence in the Headrace Tunnel of the Neelum Jhelum Hydropower Project, Pakistan. *Energies* **2019**, *12*, 2124. [CrossRef]
5. Dammyr, O. Prediction of Brittle Failure for TBM Tunnels in Anisotropic Rock: A Case Study from Northern Norway. *Rock Mech. Rock Eng.* **2016**, *49*, 2131–2153. [CrossRef]
6. Ma, J.J.; Li, T.B.; Zeng, P.; Wang, D.; Wu, J.Y.; Wang, J.F.; Chen, W. Route Selection of Sichuan—Tibet Railway Based on the Prediction of Rockburst Intensity. *Railw. Stand. Des.* **2020**, *64*, 23–30.
7. Nikadat, N.; Marji, M.F. Analysis of stress distribution around tunnels by hybridized FSM and DDM considering the influences of joints parameters. *Geomech. Eng.* **2016**, *11*, 269–288. [CrossRef]
8. Hasanpour, R.; Schmitt, J.; Ozcelik, Y.; Rostami, J. Examining the effect of adverse geological conditions on jamming of a single shielded TBM in Uluabat tunnel using numerical modeling. *J. Rock Mech. Geotech. Eng.* **2017**, *9*, 1112–1122. [CrossRef]
9. Rostami, J. Performance prediction of hard rock Tunnel Boring Machines (TBMs) in difficult ground. *Tunn. Undergr. Space Technol.* **2016**, *57*, 173–182. [CrossRef]
10. Ma, C.S.; Chen, W.Z.; Tan, X.J.; Tian, H.M.; Yang, J.P.; Yu, J.X. Novel rockburst criterion based on the TBM tunnel construction of the Neelum-Jhelum (NJ) hydroelectric project in Pakistan. *Tunn. Undergr. Space Technol.* **2018**, *81*, 391–402. [CrossRef]
11. Zhao, Z.N.; Feng, X.T.; Chen, B.R. Activity laws of microseisms and rockbursts in deep tunnels by TBM tunneling. *Chin. J. Geotech. Eng.* **2017**, *39*, 1206–1215.
12. Chen, B.R.; Feng, X.T.; Zeng, X.H.; Xiao, Y.X.; Zhang, Z.T.; Ming, H.J.; Feng, G.L. Real-time microseismic monitoring and its characteristic analysis during TBM tunneling in deep-buried tunnel. *Chin. J. Rock Mech. Eng.* **2011**, *30*, 275–283.
13. Wang, J. Study on rock burst prediction of Hanjiang River-to-Weihe River Qinling Water Conveyance Tunnel based on microseismic monitoring. *Water Conserv. Constr. Manag.* **2019**, *39*, 7–12.
14. Ma, T.H.; Tang, C.; Tang, L.X.; Zhang, W.D.; Wang, L. Mechanism of rock burst forcasting based on micro-seismic monitoring technology. *Chin. J. Rock Mech. Eng.* **2016**, *35*, 470–483.
15. You, J.H.; Jiao, J.Q.; Yang, Y.D.; Zhao, Y. The exploration of the technology of open type TBM quickly passing the section of rock burst. *Constr. Mech.* **2016**, *37*, 48–51.
16. Huang, L.; Liang, J.; Ma, J.; Chen, W. A dynamic bounding surface plasticity damage model for rocks subjected to high strain rates and confinements. *Int. J. Impact Eng.* **2022**, *168*, 104306. [CrossRef]

17. Ma, J.; Chen, J.; Chen, W.; Huang, L. A coupled thermal-elastic-plastic-damage model for concrete subjected to dynamic loading. *Int. J. Plast.* **2022**, *153*, 103279. [CrossRef]
18. Huang, L.; Liang, J.; Ma, J.; Yang, H.; Gui, Y. Spherical cavity expansion in porous rock considering plasticity and damage. *Int. J. Numer. Anal. Methods Geomech.* **2021**, *45*, 2235–2259. [CrossRef]
19. Fan, L.; Wang, M.; Wu, Z. A Split Three-Characteristics Method for Stress Wave Propagation Through a Rock Mass with Double-Scale Discontinuities. *Rock Mech. Rock Eng.* **2020**, *53*, 5767–5779. [CrossRef]
20. Fan, L.; Jia, L.; Wang, M. Evaluation of the displacement discontinuity method on wave propagation through a thickly jointed rock mass. *Waves Random Complex Media* 2023, *ahead-of-print*. [CrossRef]
21. Feng, X.T.; Xiao, Y.X.; Feng, G.L.; Yao, Z.B.; Chen, B.R.; Yang, C.X.; Su, G.S. Study on the development process of rockbursts. *Chin. J. Rock Mech. Eng.* **2019**, *38*, 649–673.
22. Tao, L.; Shi, Y.L.; Dang, K.N.; Wang, J.M. Study on microseismic monitoring and early warning of rockburst in deep-butied hydraulic tunnel. *Water Resour. Plan. Des.* **2020**, *04*, 126–131.
23. Hu, S.B. Application of microseismic monitoring and prediction rock burst technology in Jinping diversion tunnel construction. *Sichuan Architecture* **2018**, *38*, 202–205.
24. Han, K.; Chen, X.F.; Yang, W.B.; Wang, B.Y. Research on the Rock Burst Prediction of a Tunnel in Sichuan—Tibet Railway Based on Microseismic Monitoring. *J. Railw. Eng. Soc.* **2020**, *266*, 90–95.
25. Huang, Z.P.; Tang, C.A.; Li, L.M.; Zhang, P.H. Research on Early Warning of Rock Burst Based on Microseismic Monitoring Technology. *J. Shenyang Jianzhu Univ. Nat. Sci.* **2018**, *34*, 614–622.
26. Li, L.M.; Tang, L.X.; Wei, J.Z.; Zhao, L.; Wang, J.M.; Li, Y.B. Study on Characteristics of Rock Burst Based on Micro-Seismic Monitoring Technology. *Yellow River* **2020**, *42*, 77–80+108.
27. Ma, C.C. *Microseismic Monitoring of Brittle Fracturing of Surrounding Rock in Deep-Buried Tunnel and Study on Interpretation and Early-Warning of Rockburst*; Chengdu University of Technology: Chengdu, China, 2017.
28. Wang, J.X. *Rockburst Risk Analysis and Prevention Technology for TBM Construction*; Shijiazhuang Tiedao University: Shijiazhuang, China, 2020.