Multisource monitoring and early warning system of rock burst in the Gaoloushan deep-buried tunnel

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Abstract. The Gaoloushan tunnel is a two-hole, deep-buried, extra-long rocky cross-ridge tunnel with a maximum depth of approximately 1,680 m. Due to the dual effects of tectonic stress and self-weight stress field, 90% of the tunnel body is subject to extremely high-stress and high-stress, and strong-moderate rock burst likely occurs in hard rocks, such as metamorphic sandstone and schist. To prevent human casualties and equipment damage caused by rock burst, this article investigates the layout of the multisource monitoring and early warning system for disasters in the Gaoloushan deep-buried tunnel. Early warning methods for potential destructive disasters and other ground pressure phenomena are also proposed by adopting important monitoring methods, such as microseismic monitoring, electromagnetic radiation monitoring, ground sound monitoring, surrounding rock stress monitoring, and acoustic emission monitoring. Therefore, this study has important significance and engineering application value for the prevention and control of rock burst disasters in deep-buried long tunnels.

1. Introduction
Rock burst, a common phenomenon of rock stability in deep underground projects, is specifically manifested as the sudden, violent ejection and catapult of rocks into the excavation space. Rock burst likely results in damaged supporting equipment and deformed excavation profile, and even damaged engineering infrastructure, casualties, local earthquakes, surface collapse, and other disasters[1]. Rock burst is induced by internal and external factors, of which the former refers to the fact that when rock is sufficiently brittle, the elastic strain energy stored in the rock is enough to convert into kinetic energy for ejecting the rock when it is destroyed; and the latter refers to the redistribution and concentration of surrounding rock stress caused by the changes in the surrounding space environment during construction[2].

The mechanism of rock burst is complex, and many influencing factors exist. Determining whether rock burst will occur and quantitatively estimating the severity of rock burst are difficult. Gao[3] performed monitoring and early warning by using all-digital multichannel microseismic monitoring technology, developed a comprehensive quantitative scoring system on the basis of multimicroseismic parameters for the probability of rock burst, and conducted multiple effective rock burst monitoring and early warning. Wang[4] thoroughly analyzed the correlation among seismic wave velocity, seismic wave velocity gradient, and rock burst and initially established seismic wave velocity anomaly
coefficient and wave velocity gradient coefficient as a model for evaluating the risk of rock burst. Zhang[5] monitored the whole process of roadway rock burst by using infrared thermal imaging camera and established a real-time early warning method on the basis of infrared spatiotemporal evolution to provide theoretical guidance for the establishment of early warning system for mining disasters. On the basis of the acoustic emission (AE) monitoring results and rock burst records, Lu[6] predicted and graded the rock burst of the Gaoligongshan tunnel and provided the criteria for predicting the AE rock burst of the tunnel. Jiang[7] proposed the design idea of an intelligent tunnel monitoring system on the basis of the Internet of Things; the corresponding technical system, which wirelessly transmitted various sensor information to the tunnel management center with the help of the Internet of Things technology, was also built to further realize the remote, real-time, and dynamic management of the tunnel. Liu[8] proposed a rock burst prediction method by combining rock mass structure analysis and electromagnetic radiation monitoring to predict the occurrence and intensity of rock burst on the basis of the changes in electromagnetic radiation energy and pulse. The combination was proven to be a feasible method for predicting rock burst during underground cavern construction. Ma[9] used microseismic monitoring technology as a rock burst monitoring and early warning method to reveal the relationship between the temporal and spatial evolution of microseisms and rock burst, including the 3S principle in seismology, as the basis for rock burst judgments. Four rock burst criteria were also proposed. Zhang[10] performed rock burst monitoring and early warning for deep-buried tunnel by microseismic monitoring technology in the construction of water diversion tunnels; the relationship between the temporal and spatial evolution of microseisms and rock burst was also preliminarily discussed, providing a new research idea for tunnel rock burst prediction. In view of the deficiency of existing research on rock burst monitoring, Zhang[11] conducted a uniaxial compression test and full ultrasonic monitoring of complete hard rock burst, analyzed its failure characteristics and the law of ultrasonic precursor, and discussed the prediction method of complete hard rock burst.

The proposed Gaoloushan deep-buried tunnel, which reaches Longnan City and Jiuzhaigou in Sichuan Province, is a controlled project. Subject to tectonic stress and self-weight stress field, 90% of tunnels are located in extremely high-stress and high-stress areas, and strong-moderate rock burst likely occurs in hard rocks, such as metamorphic sandstone and schist. Therefore, studying rock burst monitoring and early warning in the Gaoloushan deep-buried tunnel, revealing the mechanical response mechanism of the deep surrounding rock in the construction process, predicting the rock burst of deep surrounding rocks, and evaluating the stability of the deep-buried tunnel during long-term operation are quite necessary to further prevent and control rock burst in the Gaoloushan deep-buried tunnel. This study provides the layout of the multisource monitoring and early warning system for disasters in the Gaoloushan deep-buried tunnel. Early warning methods for potential destructive disasters and other ground pressure phenomena are also proposed by adopting important monitoring methods, such as microseismic monitoring, electromagnetic radiation monitoring, ground sound monitoring, surrounding rock stress monitoring, and AE monitoring. Therefore, this research provides theoretical guidance for the prevention and control of rock burst in deep and long tunnels.

2. Engineering background
The Gaoloushan deep-buried tunnel, which reaches Longnan City and Jiuzhaigou in Sichuan Province, is a controlled project. The project is located in Wen County, Longnan, Gansu Province, which passes through Fangma Mountain, with a length of 12,180 m on the right and 12,272 m on the left and a maximum buried depth of approximately 1,680 m. It is a double-hole, deep-buried super-long rocky cross-ridge tunnel, as shown in Figure 1. The Gaoloushan deep-buried tunnel is located in the south of the West Qinling Mountains where frequent seismic activities, complex geological structures, large undulations on the surface, and vertical and horizontal ravines are observed; thus, geological conditions in the tunnel are complex. It is a typical example of deep-buried and extra-long highway tunnels under complex geological conditions, with high ground stress (maximum principal stress is 27–51 MPa), high seismic intensity (degree-VIII earthquake zone), and high ground temperature (maximum ground temperature may exceed 30 °C), with large buried depth (maximum buried depth is 1,680 m), the length
of 9 km buried depth is more than 500 m), large water volume (maximum inflow is 0.38 m³/s), and large temperature difference (the temperature difference between the top and the bottom of the mountain is 10 °C), with inclined shaft length (with a maximum value of 2.28 km) and long ventilation distance for construction tunneling and with many fault fracture zones (fault zones can be found at the entrance and exit), including many bad geological factors (faults, water inrush, and rock burst in high ground stress areas). The tunnel is seated in a landform with mountains and canyons where complex geological structures can be observed; hence, the buried depth of the tunnel is large (more than 1,000 m), whose length accounts for approximately 30% of the total length.

![Geographical location map of the Gaoloushan deep-buried tunnel](image)

**Figure 1.** Geographical location map of the Gaoloushan deep-buried tunnel

The Gaoloushan deep-buried tunnel faces serious risks of deep-buried and high-in-situ rock burst during the construction process, and the prediction and control of rock burst must be considered. Therefore, ensuring the safety of deep-buried tunnel construction under complex geological conditions is essential to control the smooth passage of expressway from Wudu to Jiuzhaigou and provide a technical reference for the construction of deep-buried long tunnels crossing high geostress and complex geological conditions, which demonstrate important theoretical and engineering application values.

3. **Construction of a multisource system platform for rock burst monitoring in the Gaoloushan deep-buried tunnel**

3.1. **Research and development (R&D) framework of system platform**

The monitoring system of rock burst in the Gaoloushan deep-buried tunnel was improved by repositioning and developing Newtonian force change monitoring and early warning system on the basis of a cloud service platform, which promoted the efficient processing and release of information related to rock burst and data flow. The R&D and construction of the new system platform are illustrated in Figure 2.
3.2. System composition
The composition of the multisource monitoring system for rock burst in the Gaoloushan deep-buried tunnel is as follows:

(1) Data acquisition subsystem: It is composed of quartz piezoelectric sensor, data acquisition equipment, data transmission module, and solar power supply system.

(2) Zigbee communication subsystem: The Newtonian force data collected by each node are aggregated to the master node through the Zigbee link (using mesh networking mode or linear networking mode).

(3) Data transmission subsystem: Using GPRS and Beidou satellite dual communication mode, it automatically discards the data obtained in the later stage and avoids data duplication according to the principle of “first come, first served.” When the signal communication on one channel is disconnected, the system on the other channel automatically switches over to ensure that data are not lost.

(4) Cloud platform subsystem: The receiving program deployed on the cloud server automatically stores the data in the cloud database after receipt to facilitate the retrieval of cloud websites, APPs, and monitoring workstations.

4. Monitoring system and early warning for rock burst in the Gaoloushan deep-buried tunnel

4.1. Microseismic monitoring layout and design
4.1.1. Principle of microseismic monitoring. During tunnel excavation, the elastic potential energy accumulated in the rock mass is gradually or suddenly released outwards along the surrounding medium in the form of shock waves, leading to microseismic events in the rock mass. After the occurrence of a microseismic event, the shock wave generated by the event propagates outwards, and the sensor placed in the hole close to the rock wall receives and converts its original microseismic signal into an electrical signal. The signal is then sent to the signal acquisition device and transmitted to the computer through data transmission line. A microseismic event is a microcrack whose time, location, and magnitude can be monitored by processing the AE signal generated by the microseismic (signal acquisition, data filtering, and inversion analysis) using multiple sensors. The development trend of rock rupture can be inferred, and rock burst can be predicted according to the size, concentration, and density of microfractures.

![Image of microseismic monitoring technology principle]

Figure 3. Diagram of the microseismic monitoring technology principle

4.1.2. Monitoring scheme design. According to the grade of the surrounding rock and the distance between the tunnel face and the secondary lining, two different sensor arrangement schemes were adopted in the Gaoloushan deep-buried tunnel. Two sensors were arranged in the grade-III surrounding rock tunnel, and one sensor was arranged for every three sensors. As the construction of the waterproof board proceeded, when the last sensor was touched, the last sensor was recovered and rotated forward to the front row, as displayed in Figure 5.

![Image of microseismic monitoring system for the Gaoloushan deep-buried tunnel]

Figure 4. Schematic of the microseismic monitoring system for the Gaoloushan deep-buried tunnel
4.2. Layout and design of electromagnetic radiation monitoring

4.2.1. Principle of electromagnetic radiation monitoring. When the rock mass is deformed and destroyed under load, electromagnetic energy radiates outwards, known as electromagnetic radiation. Electromagnetic radiation originates from the heterogeneity of rock mass and closely related to the inhomogeneous process of rock mass deformation and fracture. Information about electromagnetic radiation fully reflects the main factors affecting dynamic rock mass disasters, such as rock burst. Electromagnetic radiation intensity mainly reflects the load degree of the rock mass and the strength of deformation and rupture, whereas the number of pulses mainly reflects the frequency of rock mass deformation and microfracture. Such an intensity is highly consistent with the load and increases as the load increases. Electromagnetic radiation intensity is generally small before the rock burst occurs, but it will suddenly increase after the rock burst occurs.

4.2.2. Monitoring scheme design. Electromagnetic radiation signal was affected by the monitoring distance and position; hence, establishing uniform regulations on the monitoring method was necessary. The electromagnetic radiation monitor is equipped with an inductive high sensitivity broadband directional receiving antenna (referred to as antenna), which realizes noncontact prediction. When using an electromagnetic radiation monitoring system, the antenna opening must first be directed toward the rock mass area that needs to be predicted. The layout of the probe is shown in Figure 6. During the excavation process, the protective area of the working face was monitored, during which electromagnetic signals were collected in a mobile mode, and data for each point were collected every two minutes, covering areas 200 meters away from the face of the tunnel on both sides. The arrangement was as follows: the measuring points on both side walls of the tunnel were arranged every 10 meters from the face to the outside to detect the side walls, with a total of $20 \times 2 = 40$ measuring points. The
maximum electromagnetic radiation amplitude, the average amplitude, and the number of pulses were monitored. Each measuring point was monitored for two minutes once every other day. The specific layout plan is shown in Figure 7.

Figure 6. Schematic of the electromagnetic radiation probe layout of the Gaoloushan deep-buried tunnel

The first monitoring section was set 30m away from the tunnel face, and another monitoring section was added every 10m, for a total of 5 monitoring sections.

Figure 7. Diagram of the electromagnetic radiation measuring point layout of the Gaoloushan deep-buried tunnel

4.3. Geophone monitoring layout and design

4.3.1. Ground tone monitoring principle. The principle of the monitoring system is to monitor ground sound events on the spot by using a monitoring equipment. After a certain period of monitoring, the hazard level of the monitored area in the next period can be predicted on the basis of existing data to realize the prediction and forecast of dynamic disasters, such as rock burst in the monitored area.

4.3.2. Monitoring plan design. The ARES-5/E geo-acoustic monitoring system was used to monitor the Gaoloushan deep-buried tunnel. It is a special equipment for the early warning of rock burst trend in the tunnel through acoustic monitoring in which geo-acoustic events in the area are observed in real time and provide early warning. Its system structure is illustrated in Figure 8.
The ground tone monitoring system included 16 monitoring probes. During the excavation of the tunnel face, two ground acoustic monitoring probes were arranged on both sides of the tunnel. The specific positions of the probes are indicated in Figure 9. When the face of the tunnel was advanced to 20 m from the nearest probe, the nearest set of probes was moved to a position 80 m away from the farthest probe, and the probes were cyclically moved in this manner.

![Diagram of ARES-5/E system structure](image)

**Figure 8.** Diagram of ARES-5/E system structure

**Figure 9.** Layout plan of the geo-acoustic sensor during the excavation of the face of the Gaoloushan deep-buried tunnel

4.4. *Layout and design of the online monitoring of surrounding rock stress*

4.4.1. *Principle of the online monitoring of surrounding rock stress.* Rock mass stress monitoring has been widely used in the monitoring and forecasting of rock burst tendency. This method can perform continuous monitoring and can directly obtain the relative stress of the rock mass. Therefore, it can intuitively reflect the degree of rock burst tendency at the monitoring location. The KJ21 rock burst stress online monitoring system was used by burying high-precision stress sensors in the surrounding
rock of the excavation space, real-time monitoring the load accumulation and changes in the surrounding rock near-field system, monitoring and warning the stress or energy state from the perspective of the internal cause of the rock burst to provide guidance for disaster mitigation and avoidance. The structure diagram of the online rock burst stress monitoring system is displayed in Figure 10.

![Structure diagram of the online rock burst stress monitoring system](image)

**Figure 10.** Structure diagram of the KJ21 rock burst stress online monitoring system

4.4.2. Monitoring scheme design. Considering that a millisecond sampling stress gage was used for monitoring the Gaoloushan deep-buried tunnel, the data transmission frequency was high, and the data volume was large, and optical fiber must be used as the transmission line. For these reasons, the stress monitoring program was designed, as shown in Figure 11: nine sets (a total of 18) of high-precision stress sensors were arranged in the range of 360–670 m on the side wall of the tunnel to achieve the real-time online monitoring of the strong rock burst area. The group spacing was 30 m, and the depth of each group of holes was a combination of two shallow and deep measuring points. The hole depths were 6 and 15 m, the aperture was 42–45 mm, and the distance between each group of measuring points was 3 m.

![Layout scheme of borehole stress gage for the outer section of the face of the Gaoloushan deep-buried tunnel](image)

**Figure 11.** Layout scheme of borehole stress gage for the outer section of the face of the Gaoloushan deep-buried tunnel

4.5. Layout and design of AE monitoring

4.5.1. Principles of AE monitoring. The AE method is also known as geophone method. The vibration frequency ranges from 150 Hz to 3,000 Hz, and the vibration energy is generally 0–103 J. Compared with microseism, AE is a kind of high-frequency, low-energy vibration. According to the microcracks
detected by the sensor, the location of abnormally high-stress area can be determined, and the propagation direction of the stress can be identified by comparing the time of receiving noise signals by acoustic detectors in different places. When the rock is about to break, the number of AE events increases rapidly. If the number of events received by the sensor is greater than a certain threshold, then it indicates a high risk of rock burst. The energy rate $E$ and the frequency of large events $N$ are the basic parameters of the AE method, which can reflect the fracture degree and stress growth rate of the rock mass. The energy must be accumulated inside the rock mass until the rock burst occurs. During the energy accumulation, AE is temporarily in a quiet period, which is a precursor to the occurrence of rock burst. AE can only monitor small local rock masses, as it monitors high-frequency and low-energy events (energy decays quickly, and propagation distance is limited).

4.5.2. Monitoring scheme design. The SF-BC1 rock mass AE monitor was used to monitor the Gaoloushan deep-buried tunnel, as shown in Figure 12. The instrument is widely used for monitoring the AE of rock burst in the field of geotechnical engineering, with an effective range generally being 50 m. This instrument was equipped with AE signal data processing software whose basic parameters included the number and rate of AE events, the number and rate of ringing counts, the number and rate of large events, the energy and energy efficiency, including the waveform of rock AE signals.

![Figure 12. SF-BC1 rock mass acoustic emission monitor](image)

The sensor should be close to the relatively complete rock face of the tunnel or inserted into the blasthole to monitor the rock burst in the surrounding rock of the tunnel. The duration of AE monitoring was set to 10 minutes, and the rock masses within an area 50 m away from the monitoring point were monitored. Monitoring the background sound of the tunnel was also important in the comparison and analysis of the AE in the surrounding rock. The monitoring duration was set to five minutes to eliminate the interference of the background sound on the accurate prediction of rock burst.

5. Conclusion
Taking the Gaoloushan deep-buried tunnel as an example, this study analyzed and investigated rock burst monitoring, built a multisource system for monitoring the rock burst in the Gaoloushan deep-buried tunnel, and proposed various monitoring schemes and early warning methods. The following results were obtained:

1) By repositioning and developing the “Newtonian force change monitoring and early warning system,” a multisource system platform for monitoring the rock burst in the Gaoloushan deep-buried
tunnel was established to promote the efficient processing and release of disaster information and data flow.

(2) The multichannel microseismic monitoring technology, which combines electromagnetic radiation, ground sound, surrounding rock stress online, and AE monitoring technologies, was used to provide an early warning of rock burst during the construction of the Gaoloushan deep-buried tunnel for preventing damage to engineering infrastructure and casualties.

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