Research Status and Development of Blasting Vibration Monitoring Technology for Tunnel Construction Adjacent to Ancient Buildings

Yu Jia[1], Bin Li[1], Jia Wen[1], Jinqiang Jin[1], Shijie Lin[1], Xianghao Sun[2,*]

[1]CCC Road and Boad and Bridge Construction Group Ltd., Beijing, 100010, China
[2]College of Resources and Safety Engineering, Central South University, Changsha, 410083, China

*235512149@csu.edu.cn

Abstract. China, as an ancient civilization with a long history, has many well-preserved ancient buildings. However, the construction of tunnels near these structures during China's urbanization process make a serious threat to their security due to the vibrations caused by tunnel blasting. Therefore, extensive research and application of blasting vibration monitoring technology have been conducted. This paper comprehensively summarizes the content, methods, and techniques of blasting vibration monitoring while also providing an overview of the current research progress and status on explosion vibration monitoring both domestically and internationally. Additionally, it evaluates the issues associated with explosion vibration monitoring technology in relation to nearby ancient buildings and predicts future development trends.

Keywords: ancient architecture; tunnel blasting; vibration monitoring; development direction.

1 Introduction

China is an ancient country with a vast territory and a brilliant culture. These ancient buildings serve as the best evidence of this fact. The heritage of Chinese civilization consists of various ancient structures, all of which play an integral role in history. As time passes, these ancient buildings are becoming increasingly fragile. Drastic changes in the surrounding environment can cause unimaginable damage to them. With the rapid pace of urbanization in China, the level of urban road transportation is struggling to meet the needs of production and daily life for people. Consequently, tunnels have emerged as a solution. Blasting is a common method used in tunnel construction. However, it generates vibrations that can significantly impact both people's daily lives and the safety of ancient structures, necessitating effective monitoring.

This paper focuses on the research of explosive vibration monitoring technology in tunnels, summarizes its application in engineering and proposing future development directions to address current deficiencies.

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2 Development and present situation of blasting vibration monitoring technology for adjacent ancient buildings

2.1 Blasting vibration monitoring technology for tunnel construction

In the process of tunnel construction, the strong vibrations generated by blasting operations pose a potential threat to the surrounding environment and buildings. It is evident that monitoring ancient buildings in complex environments for blasting vibrations is necessary. Monitoring design and analysis of monitoring data are required before and after monitoring to guide blasting construction. The safety of the ancient building can be ensured through processing the measurement data. The "Technical Specifications for Blasting Vibration Monitoring" include the monitoring target, monitoring scheme, monitoring section, progress of monitoring, point arrangement, and expected effects in designing blasting vibration monitoring[1].

The criteria for evaluating the safety of blasting vibration have gone through a process from single to complex. Previously, the evaluation of explosion vibration's safety was mainly based on a single factor index. Most countries in the world taken the vibration rate as a safety index. Nowadays, it has been found that vibration frequency serves the same purpose. Therefore, in the safety assessment of blasting vibration, it is necessary to monitor the vibration velocity, frequency and other parameters of each position in real time. At present, China adopts the maximum vibration velocity of the surface mass as a criterion for damage to the surrounding buildings during blasting vibration, and uses frequency as a secondary reference[2] .

The magnitude of vertical, horizontal radial, and horizontal tangential vibrations must be monitored in real time to protect buildings near construction. Additionally, monitoring points need to be set up around the roadway and the protected buildings. It has been shown[3] that the maximum vibration points of the building are at the corners of its foundation. Therefore, sensors should be dispersed at the corners of the building's foundation. Following this arrangement principle, Chen et al.[4] adopted the IDTS-3850 hand-held blasting vibration test device to monitor blasting vibrations in residential underground passages. Subsequently, research on controlling blasting vibrations in underground passages was conducted.

Blasting vibration monitoring relies on a system consisting of sensors, vibrometers, and computers. The sensors detect vibration parameters and convert them into electrical signals, which are then processed by the vibrometer and transmitted to a computer. Based on this, the measurement results are analyzed using relevant software. Sadowski's Soviet Union blasting empirical formula can be used to forecast and fit the particle's vibration velocity, the highest charge in one detonation, and the blasting distance for guiding significant building construction near blasting sites after acquiring tunnel blasting vibration data from engineering projects.

Sadowski's empirical formula for the Soviet Union can be used to forecast and estimate the vibration velocity of particles, determine the maximum charge in a single detonation, and calculate the blasting distance. This information is crucial for guiding the construction of significant buildings near the blast site after engineering projects have obtained tunnel blasting vibration data.

Sadowski's Soviet Union blasting empirical formula:

$$v = \kappa(\frac{\sqrt[3]{Q}}{R})^{\alpha} \quad (1)$$

v— Vibration speed of the protected object, cm /s;
Q—Maximum amount of charge in one detonation, kg;
R—The distance from the source center to the monitoring object,m;
k, α—Coefficient related to blasting conditions and rock properties.

Based on the study of blasting vibration effect of Yellow Crane Tower, according to the function among vibration velocity , maximum amount of charge in one detonation and explosion source distance proposed by Sadowski's Soviet Union blasting empirical formula, various factors K and a related to explosion environment and rock mass characteristics were obtained by linear fitting[5].From this, the seismic wave propagation characteristics of Yellow Crane Tower were obtained.

Internationally, to mitigate the risks of blasting vibration, experts made predictions on the occurrence of such vibrations. In 2016, Ghoraba, S.[6] proposed an empirical model using artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS). The ANFIS model was found to be the most effective with a root mean square error value of 4.644 for the test data set when compared against 115 monitoring data points in iron ore blasting.

2.2 Blasting vibration monitoring system development

The trend in explosion vibration monitoring technology is characterized by lightweightness, remoteness, and intelligence. The development of a blast vibrometer is crucial for advancing blast vibration monitoring technology. Qi, et al.[7] have categorized the development of a blast vibrometer into four stages. Therefore, based on this categorization, the blast vibration monitoring system can be divided into four components. The monitoring system communication development diagram[8] is shown in Fig.1.

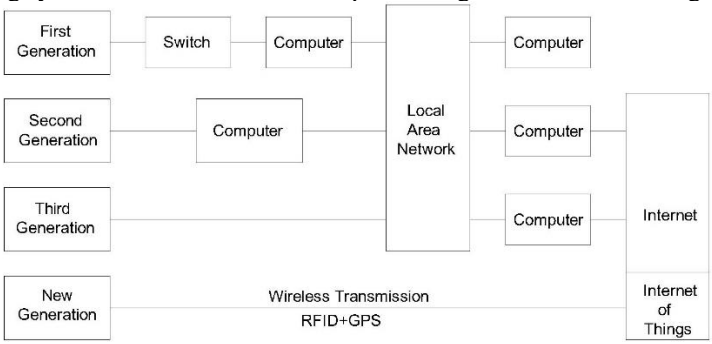

Fig. 1. Monitoring system development diagram

The first generation of the blasting vibration monitoring system consists of sensors, blasting vibration recorders, switches, and computers. However, this system occupies

a large space and requires staff to manually record data for an extended period before transmitting it to the computer through a switch. As a result, the process is complex and less efficient[7].

The second generation of blasting vibration monitoring is a conventional device composed of sensors, blasting vibration recorders, and computers. It can store, process, and display data through its functions. However, it still requires a wired connection to the computer, preventing remote and real-time monitoring of the scene[7].

The third generation of the blasting vibration monitoring system is designed for remote monitoring. It consists of sensors, blasting vibration recorders, computers, and servers. The system allows remote control of the blast vibration recorder from a background computer. It is capable of automatically converting dynamic waves into digital signals for storage and wirelessly transferring the data to a server[7].

The new generation of blasting vibration measurement system is an intelligent monitoring system for measuring blast vibrations. It incorporates the concept of the Internet of Things into previous recorders, enabling real-time wireless transmission of measured data to the internet. Blast vibration information measured by this system can be accessed through a relevant website or software. Furthermore, this system achieves lightweight integration between vibrometer and sensor. The system principle[8] is shown in Fig.2.

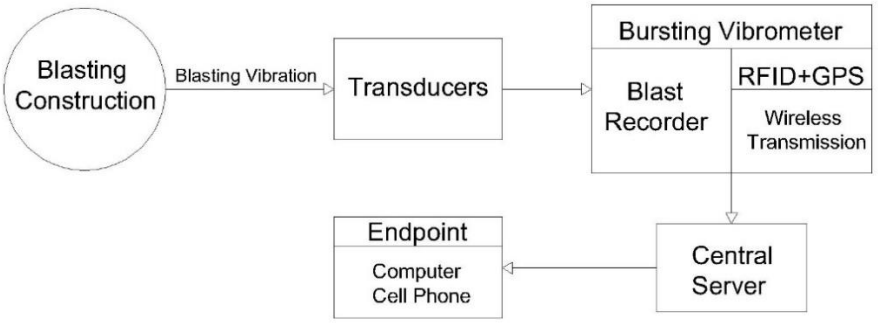

Fig. 2. System schematic diagram

2.3 Problems

The following problems still exist in the tunnel construction blasting vibration monitoring technology near ancient buildings:

(1) There are relatively few researches on blasting monitoring technology of an-cient buildings as protection objects.

(2) It is not only the blasting vibration frequency and particle velocity that affect ancient buildings, but also the duration of blasting vibration and its accumulation effect that do serious harm to ancient buildings. At present, there are few researches on blasting vibration duration and so on, which have not been paid attention to. Zhang carried out relevant research and found that when the vibration duration changed from 1s to 50s, the destruction capacity would increase by 40 times[9].

(3)The development of blasting vibration monitoring technology lags behind that of science and technology.

(4) As a new blasting vibration monitoring technology, intelligent blasting vibration monitoring technology still needs to be improved in technical standardization.

3 Application of blasting vibration monitoring technology

3.1 Application of a remote monitoring system for blasting vibration

Blast vibration monitoring systems are essential for monitoring blasting construction near significant buildings in tunnels. Some commonly used vibration measurement systems[10] are shown in Table 1.

To achieve wireless and remote development, Yang et al.[11] developed a blasting vibration remote monitoring system equipped with the TC-4580N wireless network vibrometer based on modern wireless network technology. This system includes cell phone network and internet connectivity, comprising of the TC-4580N wireless network vibration meter, high-precision three-way vibration velocity sensor, and a dedicated data server.

The remote monitoring of explosion vibration using this system was successfully implemented in July 2011 and has been effectively utilized in projects such as the telemetry of demolition blasting vibrations at Jingfeng Power Plant and the telemetry of blasting vibrations at a limestone mine.

Internationally, experts have made innovations in vibration monitoring sensor technology to ensure the structural health of buildings. In 2019, Ragam, P.[12] described a research and application of an accelerometer wireless sensor system based on Micro-Electro-Mechanical-Systems (MEMS). This system utilizes MEMS technology and network topology communication technology to not only monitor the condition of building facilities but also transmit the monitoring data wirelessly for evaluating blasting intensity.

Table 1. Commonly used vibration measurement system

System	Vibrometer model	Research unit	peculiarity
Third generation	TC-4850N	China academy of railway Sciences.	1.Vibrometer built-in network equipment; 2.Remote transmission of data; 3.View data remotely; 4.Vibrometer remote control.
	Nubox-601	Measurement and control technology company of tuopu.	
	L20	Southwest Jiaotong University.	
New generation	TC-6850	Zhongke measurement and control company.	1.Use RFID, GPS and wireless communication technology; 2.lightweight.

3.2 Application of intelligent blast vibration monitoring systems

Previous blasting vibration monitoring technology has many shortcomings, such as a poor decision-making function, low level of informatization, visualization and automation, and excessive human intervention. These deficiencies have led to both high labor costs and a lack of timely feedback. This is not conducive to the safety of ancient buildings near the blasting construction.

To address such problems, Zhu et al.[13] conducted research on an intelligent blasting vibration automated monitoring system based on the TC-6850 network vibrometer. This system comprises data acquisition and transmission components, a data center, a client interface, a risk management platform, and supporting auxiliary parts.

Based on Line 4 of Qingdao Metro, Zhu Ming et al. compared the intelligent detection technology equipped with TC-6850 network vibrometer with traditional blasting vibration monitoring technology. The difference between the results obtained in the examples in the same environment was very small. This not only confirms the feasibility of TC-6850 network vibrometer, but also highlights the real-time and intelligent nature of the system. At present, this system has been widely used in Qingdao Metro Line 4 project.

4 Development direction of blasting vibration monitoring technology

The development of blasting vibration detection technology is based on advancements in science and technology. For instance, the digitization of the blasting vibration monitoring system has been made possible by the progress in computer technology. Additionally, with the advancement of Internet and communication technologies, wireless transmission has replaced wired transmission for blasting vibration monitoring. Finally, With the development of Internet of Things technology, the interconnection of everything in blasting vibration monitoring has been realized.

Nowadays, the rapid development of artificial intelligence technology, the research and development of intelligent blasting vibration monitoring robot will be an important direction of its development. Based on artificial intelligence technology, monitoring robots can independently form monitoring plans and implement monitoring and analysis by establishing field models. Monitoring by artificial intelligence robots can greatly reduce human errors and improve the accuracy and efficiency of monitoring.

Vibration prediction is now based on vibration data already obtained in the field. Prediction methods include empirical method, ANN[14] and ANFIS. Direct blasting construction without test will cause unpredictable consequences to the ancient buildings near the site. Nowadays, big data technology has been developed and mature. Combining big data technology with prediction technology and establishing a shared database of blasting vibration data [10] to predict the intensity of vibrations at upcoming blasting sites is an important development direction.

Blasting vibration monitoring needs to consider the impact of blasting vibration time and its cumulative effect on nearby ancient buildings[15], taking this as the criterion for

blasting vibration monitoring to establish a multi-factor standard for identifying vibration hazards. The establishment of a multi-factor criterion for vibration hazards can enhance the sensitivity and accuracy of detection results. Therefore, the establishment of such a criterion and the research and development of a multi-factor vibrometer will be directions for future development.

5 Conclusions

This paper investigates the development and current situation of blasting vibration monitoring technology for nearby important buildings, based on the background of tunnel construction and ancient building protection. It introduces the evolution of criteria for evaluating vibration hazards from single to complex, the analysis of vibration locations and prediction techniques for vibration intensity at home and abroad.

In addition, the blasting vibration system of nearby ancient buildings is mainly studied. Based on the innovation of blasting vibrometer, the development of blasting vibrometer system is divided into four parts. By analyzing that the development direction of blasting vibration system is intelligent and wireless, it is concluded that its development is based on the progress of science and technology. On this basis, the development direction of monitoring technology is forecasted. The predictions are as follows:

(1) Research and development and application of artificial intelligence-based automatic intelligent blasting vibration monitoring robot.

(2) Research and development and application of prediction system for vibration intensity of unimplemented blasting site based on big data technology and prediction technology.

(3) The establishment of multi-factor criteria for vibration hazards and the development and application of multi-factor vibrometer.

Additionally, it discusses the current issues with blasting vibration monitoring technology near ancient buildings and provides corresponding reflections on these problems. The conclusions are intended for discussion purposes only.

(1) Although there is a lot of research work on blasting vibration monitoring near important buildings, the research on monitoring technology and blasting control of tunnel blasting construction near ancient buildings needs to be further carried out.

(2) Relevant experts and practitioners enhance the sensitivity of scientific and technological progress, effectively integrating blasting vibration monitoring technology with advancements in science and technology to enhancing the simplicity and accuracy of monitoring technology.

(3) Practitioners improve the standardization level of blasting vibration intelligent monitoring system and establish a unified measurement standard for vibration measurement, so as to reduce the trouble caused by different instruments and standards. It is also very important to establish new technical standards for vibration monitoring of blasting construction near important structures in advance.

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