The Status and Prospect of Research into Protective Structures of Bridge Piers against Rockfall Impact

*GAO Liang1, ZHANG Shan1, ZHANG Junfa1 and WU Xiangnan1
1. School of Civil Engineering and Architecture, Xi’an University of Technology, Xi’an 710048, China

Email: 156820773@qq.com;

Abstract: Rockfall impact on bridge piers threatens severely the mountain bridge structures of lifeline engineering. Intended for mountain bridge pier protection against rockfall impact, the paper conducted comprehensive reviews on the research status of impact effects, anti-collision structure, impact response to rockfall, and protective design at home and abroad, and proposed a new-type protective structure against rockfall impact. In addition, the paper carried out deep studies on such key scientific issues as impact effect calculation, protective materials against rockfall impact, damage mechanism of protective units, and parameter optimization on the system of protective structures against rockfall impact as well, aiming to strength disaster prevention of mountain bridge structures.

1. Introduction
As a common geological disaster in mountainous areas, rockfall is characterized by high unexpectedness, severe destruction, and great harm to lifeline engineering. In recent years, the frequency and scales of rockfall have mounted up rapidly in China. With the implementation of the national strategy of the Silk Road Economic Belt and the 21st-Century Maritime Silk Road, domestic transportation infrastructure has been expanded enormously, and the ratio of bridges to tunnels has been increased as well. In this connection, it has become urgent to protect mountain bridges from rockfall impact. Considering that bridge piers are an important part of bridge engineering, bridge will malfunction once the bridge piers are damaged by rockfall.

To relieve rockfall impact on bridge piers, cushion materials or anti-collision systems are used on bridge piers during engineering design so that the prolonged period of rockfall impact is able to offset the impact effect partly by dissipating impact energy. However, given high randomness and complicated mechanical process of rockfall impact, the existing design of anti-collision system is far from effective. Thus, it has become the basic difficulty to determine rockfall impact effect and to optimize protective performance during the design of bridge pier protection.

2. Analysis of corresponding research status at home and abroad
Here are reviews of relevant research on rockfall impact force, protection of bridge structures against rockfall impact, and protection of bridge piers against rockfall impact as well.

2.1 Rockfall impact effect
As rockfall impact is a kind of pulse [1], the rockfall impact force can hardly be calculated with either Hertz elapse collision theory or Thornton elastic-plastic collision theory. Domestic references are limited to the Code for Design of Highway Subgrades (JTJ13-95) and the Handbook for Design of Railroad Engineering (revised version), in which it is only suggested to use empirical algorithms to
calculate rockfall impact force. Semi-empirical and semi-theoretical algorithms, which are based on in-situ tests of rockfall impact force, are commonly-used in foreign countries, the Japan Highway Public Corporation algorithm [2], for example. In addition, from the perspective of engineering practice, Yang Qixin et al. [3] simulated the impact load for shed-type open cut tunnels with cushion layers of different thicknesses, and also provided the calculation formulas of rockfall impact according to the law of rockfall acceleration change for the duration of impact. Ye Siqiao et al. [4] compared five representative algorithms of rockfall impact force at home and abroad, and concluded that the Chinese algorithm results were much lower than real values while the Japan Highway Public Corporation algorithm that was based on field measurement on rockfall impact conformed to reality better.

Yuan Jinke et al. [5] conducted tests on rockfall impact force, and established the calculation method of maximum impact force which covered various influential factors, such as rock weight, impact velocity, incident angles, and the property and thickness of cushion materials. With the help of impact tests of cone-type rockfall on gravel soil layer, Pichler B et al. [6] proved that the rockfall impact time increased with the increase of rock quality but decreased with the increase of impact velocity. He also considered rockfall impact as an act of collision in a moment, and held it that the calculation of rockfall impact time would affect the calculation results of impact force directly.

To summarize, basic theories of rockfall impact were introduced to China through the above research. By means of theoretical deduction, rockfall impact tests, and numerical simulation, and in view of both theoretical calculation of rockfall impact force and parameter analysis of influential factors on impact force, the aforementioned research expounded calculation formulas of rockfall impact force in aspects of rockfall and impacting objects.

2.2 The protective structure against rockfall impact

Passive protections are mostly used in engineering practice, including rock shed, open cut tunnel, safe net (or wall), protective dyke, and rockfall crater. The following is analysis of research status of existing passive protective structures against rockfall impact.

Wang Min, Shi Shaoqing, Yang Youkui et al. [7] conducted research on energy consumption of the rockfall SNS flexible safety net system with steel rope net as the main component, and established the calculation model of ring network with two forms of composition. What’s more, by applying the above research results to rock sheds, they [8] proposed the flexible structure for rock sheds, and also conducted corresponding computed analysis on full-scale experiments, dynamic response, and energy absorption characteristics. Shi Shaoqing et al. [9] applied waste tires to new-type flexible safety wall structures. By researching on the energy consumption characteristics of materials for each part of waste tires, he pointed out that the use of waste tire could improve significantly the protective capacity of new-type flexible safety walls due to its obvious ability of energy consumption and buffer function. He Siming et al. [10] proposed a new energy dissipation-seismic reduction shed. By installing energy dissipation-seismic reduction apparatus on the shed base, he built up a nonlinear mass-spring system model to simulate dynamic response of shed structures under the rockfall impact load. He also used the energy method to analyze the protective mechanism against rockfall impact for the new energy dissipation-seismic reduction shed. Moreover, He Siming et al. introduced the energy dissipation-seismic reduction materials of EPS slates [11], foam aluminum [12], and modified concrete to the protective structure against rockfall impact for the new shed. With static loading tests and dynamic finite elements, they analyzed dynamic response of the protective structure against rockfall impact, and further revealed the energy dissipation-seismic reduction mechanism for the new shed.

All in all, with the emergence of new structural materials and the flexible application of various protective apparatus in engineering practice, engineering technicians have developed multiple new protective systems against rockfall impact, and discuss relative technical problems concerning material selection for protection use and improvements on protective apparatus.

2.3 Impact response and protective design for bridge piers

Researchers have done a great deal of research work on rockfall impact on bridge piers from different perspectives. Luo Songnan et al. [13] simplified the constraints of upper parts and lower parts of high bridge piers, respectively, and established the basic nonlinear dynamic equation for high bridge piers under
the action of impact load. Through numerical simulation, they also compared the displacement response under the action of triangular impact load and that under the action of rectangular impact load. Pei Xiangjun et al. [14] used the non-continuum theory to analyze the impact of peripheral unstable hill stones on bridge piers in meizoseismal areas, and found that under the impact and extrusion of rockfall, the maximum permanent displacement occurred on collar beams and bridge tops. With the help of HJC damage mechanism, Yuan Jinke, Pei Xiangjun [15] established a numerical model to analyze kinetically the rockfall impact on bridge piers, obtaining the bridge piers’ change of stress fields and displacement fields. They denoted that rockfall impact force presented an obviously nonlinear trend, and that for passive anti-collision structures, the maximum impact force should be referred to when determining corresponding indices. Based on LS-DYNA software and explicit nonlinear analysis, Yu Zhixiang et al. [16] used HJC constitutive relations to simulate reinforced concrete. From the perspectives of volume damage ratio and pier stud displacement, they researched on how different impacting factors helped damage pier studs, and concluded that rock diameters and impact velocity contributed more to pier stud damage. The above studies on dynamic response, deformation laws, and volume damage ratios under impact load are of great significance to anti-collision of bridge piers.

Research on rockfall impact prevention has been conducted successively since Chediguan bridge was destroyed by rockfall during the 5·12 Wenchuan Earthquake. He Siming et al. proposed a protective structure for bridge piers against rockfall impact, and used the dynamic finite elements to compare the dynamic response before and after the bridge pier was intensified. In this regard, they revealed the energy dissipation-seismic reduction mechanism, based on which they designed a protective structure for Chediguan bridge pier against rockfall impact. Moreover, He Zilu and He Siming invented a tiled compound pier protective apparatus, with protective units that were fixed firmly onto the external pier wall. The units contained several protective components of the same structure, each of which was composed of internal fillings, external reinforcing ribs, and filled airtight cavities that were separated by the reinforcing ribs. With explicit nonlinear dynamic analysis, and in combination with model test results, Yu Zhixiang et al. [17] conducted numerical simulation on two protective materials of steel sleeves and thickened plain concrete, and proposed an improved type of separable steel sleeves to cover the shortage of bonded steel sleeves as well. The above computed research on energy consumption buffer laws, crashworthiness, and design parameters with respect to anti-collision bridge piers against rockfall impact is of great significance to the establishment of anti-collision systems for bridge piers.

All in all, theoretic analysis and the finite element method have been used for exploratory study on rockfall impact prevention in terms of rockfall impact, protective structures against rockfall impact, and structural response of bridge piers to rockfall impact together with corresponding protective design.

2.4 Scientific issues to be further studied
Certain research achievements have been attained on rockfall impact, and design and improvements of the protective system. However, with respect to the fundamental scientific issue of rockfall impact prevention of bridges, the following aspects still await studies:

2.4.1 Calculation methods of rockfall impact effect. Existing calculation formulas of rockfall impact force are mainly based on structural response backstepping and static equivalence. The process of rockfall impact is regarded as a typical inelastic collision, because it involves elastic-plastic deformation, impact energy conversion, and determination of impact force.

2.4.2 Damage mechanism of protective materials and protective units under rockfall impact. The dynamic analysis of protective structures and their materials under rockfall impact contains material deformation, structural deformation, structural dynamic characteristics, and structural dynamic response. The relation remains unclear between the damage law of protective systems for bridge piers and rockfall impact force.

2.4.3 Parameter optimization of the rockfall impact prevention system for bridge piers. The ability of protective system mainly depends on the cushion materials and protective performance of the structure, and the protective units of the protective structure is the key of the design, and therefore it’s must be based on dynamic analysis of the structure under rockfall impact, and based on the multi-level
protective goal to study the cushioning property, and then carry on its parameter optimization analysis.

3. The rockfall impact prevention system for bridge piers
According to engineering practice, the tiled compound pier protective structure helps relieve the impact force on bridge piers to a certain degree. Specifically, this structure was applied to Chediguan bridge that was destroyed by rockfall during the 5·12 Wenchuan Earthquake and proved to be effectively protective. This structure gives prior consideration to material buffer and multi-level protection. However, this paper proposed a new-type rockfall impact prevention system for bridge piers (Figure 1) as an improvement to it in lights of rockfall impact dynamic effect, damage modes of rockfall prevention material and component, protective structure, and connecting structure of bridge piers. For this new system, rockfall impact tests were mainly carried out as a way to improve the protective performance and to unveil the operating mechanism as well. This system has realized design optimization for both protective parameters and protective units, thus further upgrading performance of the protective system for bridge piers.

Figure 1. A new-type rockfall impact prevention system for bridge piers
Specific significances are summarized as follows:

3.1 Lay theoretical foundation for rockfall impact dynamic computation
The foundation of rockfall impact research includes rockfall impact force computation, motion curves analysis, and impact effect forecast. Relevant design theories are mostly experience-based or formula-based, whose formulas target mainly at soil cushion or sand cushion. Thus, the paper conducted dynamic analysis on rockfall impact from the aspects of rockfall itself and the stuff being impacted.

3.2 Provide means for parameter optimization of rockfall impact prevention structures for bridge piers
Existing protective structures for bridge piers are mainly against vessel collision and vehicle collision, whose methods and effects of collision are greatly different from those by rockfall impact. Therefore, the paper carried out dynamic buffer performance tests to research into the deformation and damage laws of the protective structures of bridge piers under rockfall impact. By analyzing changes of impact force, the paper analyzed the protective mechanism of both cushion materials and the protective components.

3.3 Provide reference for design of rockfall impact prevention systems for bridge piers
Based on cushion performance, the paper dynamically analyzed anti-collision performance of the protective structure against rockfall impact, and also introduced the multi-level prevention idea. The dynamic model for bridge piers under rockfall impact was established to obtain the operating principle of the protective structure against rockfall impact, which helped improve the protective performance for bridge piers.

4. Conclusion
In terms of protective structures for mountain bridge piers against rockfall impact, the paper reviews comprehensively relevant research status at home and abroad, and proposes a new-type rockfall
impact prevention system for bridge piers. Through impact test and finite element numerical, this paper shows the conclusions as follows:

1. Due to the flexible cushion layer under the rolling impact, the impact contact belongs to the point contact, limited by the thickness of cushion layer, the cushioning property of protective cushion structure is difficult to give full play. So, in order to improve the performance of buffer on the protective cushion structure, we can increase stiffness protective layer on the outside of flexible cushion layer, so as to make the point contact into surface contact, effectively improve the utilization rate of buffer material.

2. Project team in the study of impact protective measures for roof boarding in early, and found that the foam sandwich reinforced concrete plate has good shock resistance, applied to pier impact protective structure, from the change or block the shock wave propagation path and deformation energy dissipation, namely using the flexible buffering inner core and rigid surface layer protective measures, and draw lessons from the construction method of shield tunneling segment, the tube-plate type hard-soft laminated protection system for bridge piers against rockfall impact is put forward.

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