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Large-scale rockfall impact experiments on a RC rock-shed with a newly proposed cushion layer composed of sand and EPE

Peng Zhao[a,b], Lingzhi Xie[a,b,c,*], Liangpu Li[d], Quan Liu[d], Song Yuan[d]

[a] Key Laboratory of Deep Underground Science and Engineering, (Sichuan University), Ministry of Education, Chengdu 610065, China
[b] College of Architecture and Environment, Sichuan University, Chengdu 610065, China
[c] Institute of New Energy and Low-Carbon Technology, Sichuan University, Chengdu 610207, China
[d] Sichuan Communication Surveying & Design Institute, Chengdu 610065, China

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ABSTRACT

Rock-sheds are widely used to protect roads in mountainous areas. Generally, a soil cushion is placed on the rock-shed slab to distribute impact forces and absorb energy. However, thicker soil cushions lead to high dead loads and construction costs. This paper proposes a new cushion layer that includes both sand and expandable polyethylene (EPE), with the aim of reducing dead load and improving durability. Several studies are conducted. First, a newly proposed cushion layer composed of a foam material (expanded polystyrene (EPS) or EPE) and granular material (soil or sand) is introduced. The reasons for including EPE are explained. Then, uniaxial compression tests are conducted to elucidate and compare the compression performance of EPS and EPE, particularly the resilience performance. Finally, large-scale rockfall impact experiments are carried out on a reinforced concrete rock-shed with three types of cushion layers: sand, sand-EPS, or sand-EPE. The analysis and comparison of the experimental results suggest that sand-EPE is the optimal cushion layer to resist rockfall impact and protect rock-shed structures.

1. Introduction

Rockfall is one of the most common hazards in mountainous areas and often occurs in a series of damage, especially as a secondary disaster caused by an earthquake. Rockfall can cause roads to become unusable and blocked. Rockfall damage then makes rescuing injured people and rebuilding disaster areas more difficult. Engineers have made considerable progress in the prevention and control of rockfall disaster by combining knowledge gained from their substantial engineering experience. Currently, rock-shed structures have been widely used as one kind of passive protection. To protect roads and other infrastructure, rock-sheds should be able to bear the impact load of rockfalls. Rock-shed structures are commonly constructed from frames with a slab on the top that is covered with cushioning materials [1,2]. Therefore, the impact-resistant system of a rock-shed consists of two parts: the rock-shed structure and the cushioning materials.

To improve rock-shed impact resistance against rockfall, many researchers have carried out relevant experiments. A prototype experiment can exhibit real physical processes, but this type of experiment is uneconomical and requires special techniques [3]. Therefore, prototype experiments are rare. Kishi et al. [4] conducted prototype impact tests by using two types of prestressed concrete (PC) rock-shed frames: inverted L frames and fully rigid frames. They found that the fully rigid frame could effectively disperse the sectional forces over the entire structure and had better resistance to impact loads than that of the inverted L frames. Zineddin and Krauthammer [5] designed rock-slabs with different amounts of steel reinforcement to investigate the dynamic response and behaviour of reinforced concrete (RC) slabs due to applied impact loads. Mougin and Delhomme et al. [6,7] proposed a new rock-shed protection design with the concept of a structurally dissipating rock-shed (SDR), which mainly utilized specially designed supports. These supports were made of steel and absorbed the impact energy through plastic damage deformation. Experiments were conducted on a one-third scale model of an actual SDR. Based on these SDR experiments, Mougin et al. [7] studied the energy absorption effected by this type of RC slab; Delhomme et al. [1] focused on the punching damage of SDR and analysed the experimental values of contact time and percussion load, aiming to develop simplified design methods; Boukria et al. [8] developed an experimental method to identify the impact force on an SDR structure; and Mommessin et al. [6] described the typical behaviours of a horizontal slab and a slanting slab and indicated that certain factors should be considered when designing the

* Corresponding author at: Institute of New Energy and Low-Carbon Technology, Sichuan University, Chengdu 610207, China.
E-mail address: xielingzhi@scu.edu.cn (L. Xie).

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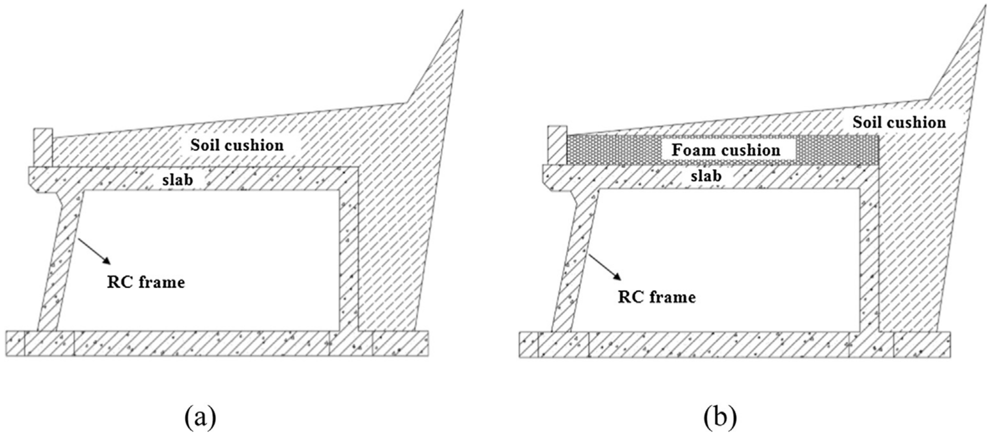

Fig. 1. (a) A conventional RC rock-shed structure with soil cushion; and (b) some soil is replaced with foam material, creating a composite cushion layer.

SDR. In addition, Yang et al. [9], Zhao et al. [10], and Wang et al. [11] presented a new flexible rock-shed design. They conducted experiments to study the transfer mechanism and failure modes of a safety netting system. In addition to prototype experimentation, numerical analysis is also applied to study rock-sheds since this method can more efficiently consider multiple engineering conditions. Zhang et al. [12] established five kinds of rock-sheds to study rockfall impact properties of different structures. The analysis showed that different shed structure types exhibited different dynamic responses under the same impact load. Delhomme et al. [13] reanalysed the structural response of SDR by using a 3D numerical model and compared the numerical results to those of several experimental tests. Yang et al. [14] simulated the dynamic response in a rock-shed structure due to rockfall impact at different speeds and incident angles. Specifically, they analysed the contact force, displacement, damage, and energy of a structure due to an impact load. Yang et al. [9], Wang et al. [15], and Zhao et al. [10] performed a numerical simulation to evaluate the performance of a flexible rock-shed.

The studies mentioned above mainly focused on the rock-shed structure, the relatively stiff component of the impact-resistant system. When a rock-shed bears high impact energy, the structure will be significantly damaged. Moreover, repairing structure damage is difficult, and the cost of maintenance is high. Because a cushion layer can dissipate impact energy, distribute contact stresses, and increase impact time [16], the ability of a cushion layer to resist rockfall impact is worth exploiting. Traditional practice is to place thick granular material (i.e., sand and soil) on the slab as a shock absorber. Schellenberg et al. [17] carried out a series of impact tests and optimized the design of RC rock-sheds. In their tests, special cushion systems consisting of high-tensile steel wire mesh and cellular glass were adopted. Kawahara and Muro [18] discussed the influence of sand density and cushion thickness on rockfall based on laboratory tests. Labiouse et al. [19] also conducted an experimental study to gain a better understanding of the damping abilities of a soil cushion and to estimate the impact. Pei [20] adopted a numerical method to analyse the dynamic response and energy dissipation mechanism of different combinations of sand cushion. Utilizing conventional cushion to resist high impact energy requires a thicker soil layer. According to the Guidelines for Design of Highway Tunnel in China [21], to resist rockfall, the soil cushion thickness should be greater than 1.5 m. In addition, thicker soil cushions are needed in the areas where rockfalls frequently occur. However, thicker soil cushions lead to higher dead loads due to the weight of the soil; therefore, they decrease the design efficiency of rock-sheds. Accordingly, Kishi et al. [22] proposed a three-layered absorbing system. The system was composed of three materials: a 50–100 cm thick layer of expanded polystyrene (EPS) as the bottom layer, a 20–30 cm thick RC core slab, and a 50 cm thick sand cushion as the top layer. By applying this absorbing system, they found that the maximum transmitted impact force onto the upper flange could be 1/3–1/4 of that using a 90 cm thick sand cushion. Although this three-layered absorbing system can reduce the impact force, EPS is unable to protect the RC core slab from damage, and repair work is also difficult. In conclusion, the cushioning material selected to act as an energy absorber should possess the following requirements: (1) have a low density; (2) be able to relieve an impact load and dissipate impact energy; (3) be resilient; (4) have a reasonable cost; and (5) be convenient to construct. In recent years, EPS has been used to absorb energy in some designs, and researchers have performed studies on the dissipating effects of EPS under impact loads by using numerical methods [23,24]. However, studies on unconventional cushioning material used to resist rockfall impacts are rare, especially relevant large-scale rock-shed experiments.

Therefore, in this paper, we suggest replacing part of the soil cushion with foam material, with the aim of reducing the dead load and improving the resistant performance. Moreover, large-scale impact experiments on RC rock-shed are also carried out considering various cushion layers that consist of different combinations of sand, EPS and expandable polyethylene (EPE). Through a series of comparative analyses, the cushioning performance of EPE is highlighted. The paper is organized as follows. First, a newly proposed cushion layer created by combining foam material (EPS or EPE) and granular material (soil or sand) is introduced. Second, uniaxial compression tests are conducted to obtain the mechanical properties of EPS and EPE, and the influence of density, loading rate, and thickness on the compression performance are analysed. A series of large-scale rockfall impact experiments are carried out on RC rock-shed with three types of cushion layers: sand, a combination of sand and EPS, and a combination of sand and EPE. Finally, the experimental results of the resisting behaviours of the different cushion layers to rockfall impact are studied and discussed.

2. The newly proposed rock-shed cushion layer

A conventional reinforced concrete rock-shed structure consists of two parts: the RC frame and the soil cushion on top of the slab (Fig. 1a). Theoretically, the soil cushion is designed to effectively distribute impact force and absorb energy, relieving the impact load on the RC frame. With respect to a designed rock-shed, when the impact resistance must be improved, thicker soil can help to achieve this goal. However, a thicker soil cushion leads to a larger dead load, which weakens the structural performance. Redesigning the rock-shed based on thicker soil will result in high construction costs. Conversely, a relatively thin cushion layer is insufficient to mitigate the impact load and does not facilitate effective rock-shed protection. Therefore, this limitation of soil cushion directly restricts its application.

To increase cushioning performance, we suggested that a part of the