Dear editor and reviewer:

We gratefully thank for your constructive remarks and useful suggestions, which has significantly raised the quality of the manuscript and facilitated its improvement. Below the comments of the reviewers are responses point by point and the revisions are indicated.

Reviewer

1. General Comments:

I suggest rewriting the abstract section. The current abstract describes too much experimental process, information, and results. These pieces of information are not what readers most want to see, nor are they the most valuable conclusions drawn in this manuscript. Therefore, I suggest the author rewrite the abstract.

1. Reply:

We gratefully appreciate for your valuable suggestion. A rewritten abstract is as follows:
Abstract: The pile-slab retaining wall has gained widespread utilization in rockfall mitigation engineering, attributed to its excellent impact resistance, substantial interception height, and reliable structural durability. The numerical experiments investigate the dynamic response of a pile-slab retaining wall under the various impact conditions of rockfall. Results reveal that: (1) during the impact process, the stress, strain, and concrete damage of the structure gradually spread from the impact center to entire structure and ultimately result in permanent deformation; (2) the lateral displacement of the pile at the ground surface and the concrete damage under the pile as the impact center is greater than those under the slab as the impact center, implying that the impact location has a significant influence on the stability of the structure; (3) there is a positive correlation between the response indexes (impact force, interaction force, lateral deformation of pile and slab, concrete damage, and the impact velocities; (4) within the discussed impact scenarios, the rockfall peak impact force, the ratio of peak impact force to peak interaction force, and lateral displacement of pile at the ground surface had strong linear relationships with rockfall energy. Utilizing this relationship, the estimated maximum impact energy that the pile-slab retaining wall can withstand is 905 kJ in this study when the structure top is taken as the impact point.

2. **General Comments:**

The manuscript lacks some case studies information and is detached from the case and reality. The numerical simulation results of this manuscript appear to lack basis, greatly reducing their value, and the reliability of the results cannot be verified from real projects.

2. **Reply:**

Thank you for your comment. As illustrated in Fig. 1, pile-slab retaining wall have gained widespread application in various areas. However, there are still challenges in their design and construction, notably regarding the maximum impact energy tolerance of structure and the vulnerability of specific components to damage under impact loads. Therefore, comprehensive research is essential to address these issues. This study utilized a combination of normative modeling and real-world case studies, aiming to capturing the dynamic response characteristics of the structure under specified impact scenarios. The findings serve as a foundation for the future design, implementation, and enhancement of the structural framework.

(a) 10.8 m height PSRW at Kangding county **(b) 4 m height PSRW with tyre cushion at Kangding county**

(c) 4m height PSRW with stone cushion at Kangding county **(d) 5m height PSRW with sand cushion at Kangding county**

(e) 9m height PSRW with stone cushion at Zhangmu port in Tibet

(f) 9m height broken PSRW with no cushion at Zhangmu port in Tibet

Fig. 1 pile-slab rockfall retaining wall has been implemented

3. **General Comments:**

The results obtained from numerical simulation lack in-depth mechanism analysis and in-depth refinement of understanding. The knowledge obtained from the current results and conclusions is similar to that of common sense, and there is no need to carry out this work, as readers can also recognize.

4. **Reply:**

Thank you for your comment. Currently, numerous measures are available for mitigating rockfall disasters. However, adopting different protection structures to suit specific engineering contexts is a pivotal challenge. Rockfall impact energy serves as a key parameter in this regard. This manuscript determines the impact energy of pile-slab rockfall retaining wall, offering a valuable reference for the selection of appropriate rockfall protection structures in the future. Additionally, we have identified a range of structural characteristics under impact loads, offering crucial insights that will inform the future design, enhancement, and implementation of such protective structures. Consequently, we firmly believe that this study possesses considerable significance.

5. **General Comments:**

The discussion section of this manuscript is relatively weak. It is recommended that the author, based on reading and referring to a large number of literature, describe the advantages and limitations of the data, models, methods, results, etc. involved in this manuscript.

6. **Reply:**

We gratefully appreciate for your valuable suggestion. A rewritten discussion is as follows:

4. Discussions

4.1. *Comparison of impact force calculation models*

A comparative analysis compared the elastic theories proposed by Labiouse et al. (1996), Kawahara and Muro (2006), Pichler et al. (2006), and (Hertz, 1881) was conducted to assess the validity of the numerical simulation (Fig. 18). The results reveal a fundamental linear correlation between impact force and velocity. Overall, the computational results are consistent with those of other models in terms of magnitude, thus confirming the validity of the calculations reported here.

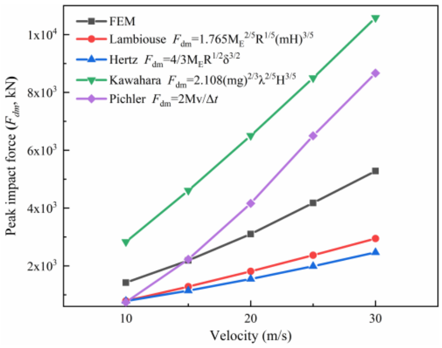

Fig. 18. Relationship between impact velocity and impact force.

4.2. *Relationship between structural evaluation indexes and impact energy*

Table 5 lists the initial kinetic energy of impactor (E), the peak impact force (F_{dm}), the peak interaction force (F_{im}), the ratio of the peak impact force to the peak interaction force (α), the maximum the lateral displacement of pile at the ground surface at t = 650 ms (S_{mpt}), the number of damage failure units (N_d), and the ratio of damage failure units to overall RC structure units (β).

Table 5 Simulation results of various impact cases.

Case	E (kJ)	F_{dm} (kN)	F_{im} (kN)	α (%)	S_{mpt} (mm)	N_d	β (%)
CP-V10	130	1420	2170	65.4	2.25	83	0.0059
CP-V15	292.5	2188	3008	72.7	3.91	817	0.0577
CP-V20	520	3100	3747	82.7	6.17	2179	0.1539
CP-V25	812.5	4175	4422	94.4	8.8	3088	0.2181
CP-V30	1170	5283	5069	104.2	12.03	5040	0.3559
CS-V10	130	1426	2182	65.4	1.76	52	0.0037
CS-V15	292.5	2196	3015	72.7	3.72	321	0.0227
CS-V20	520	3112	3756	82.7	5.77	1062	0.0750
CS-V25	812.5	4182	4433	94.4	8.7	2728	0.1927
CS-V30	1170	5299	5075	104.2	11.2	4880	0.3446

Under the premise of known impact energy, estimating impact force, interaction force, and displacement of pile for the structural design is very important. As shown in Table 5, the variation in peak impact force (F_{dm}) with different impact centers is minimal. Consequently, CP simulation results were chosen for further analysis. The dependence of the peak impact force on the impact energy is shown in Fig. 19a, with a correlation coefficient $R^2 = 0.99$, i.e.,

$$F_{dm} = 3.69(E + 290.33) = 1845(mv^2 + 0.58) \tag{1}$$

where m is the impactor mass (m= 2600 kg herein); v is the initial impact velocity (10 m/s $\leq v \leq$ 30 m/s herein).

The dependence of the ratio of peak impact force to peak interaction force on the impact energy is shown in Fig.19b, with a correlation coefficient of 0.99, i.e.,

$$\alpha = 0.037(E + 1671.89) = 18.5(mv^2 + 3.34) \tag{2}$$

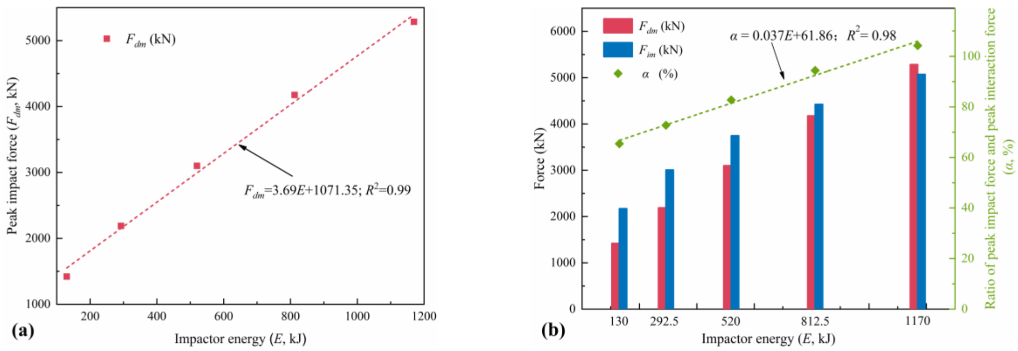

Fig. 19. Dependence of various indexes on impactor energy (a) peak impact force (b) the ratio of peak impact force and peak interaction force.

The lateral displacement of pile at the ground surface is an important index to judge the failure of pile foundation under lateral load. As shown in Table 5, the maximum lateral displacement of pile at the ground surface under pile as impact center is greater than that under slab as impact center. Therefore, the situation where the pile is the center of impact is the more dangerous. As shown in Fig. 20, with the increase of impact energy, the displacement value and number of damage failure units enlarges, which means the structure suffers more damage under CP. Furthermore, the maximum lateral displacement of pile at the ground surface when t = 650 ms, can be calculated by the following aquation:

$$S_{mpt} = 0.00934\left(E + 164.88\right) = 4.67\left(mv^2 + 0.33\right) \tag{3}$$

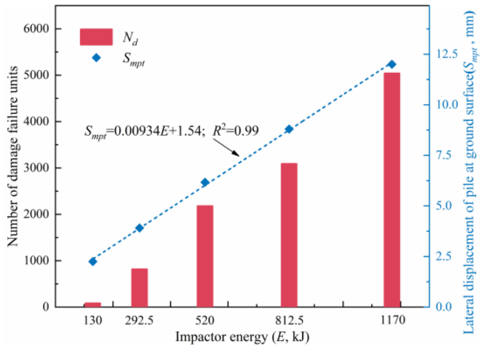

Fig. 20. Dependence of the lateral displacement of 3# pile at the ground surface on impactor energy

According to the Chinese Specification for the Design of Rock Retaining Wall Engineering in Geological Hazards (CAGHP, 2019), the lateral displacement of the resistant sliding pile at the ground surface must not exceed 10 mm. Substituting this value into Formula 3, the maximum impact energy that the PSRW can withstand in this study is 905 kJ.

4.3. Comparison with other concrete rockfall retaining walls

Table 6 presents crucial data on an improved cast-in-place rockfall concrete barrier developed by the US Department of Transportation (Patnaik et al., 2015). This barrier exhibits relatively low resistance to impact energy, which restricts its applicability to situations where high-impact energy rockfalls are likely to occur. Integrating a specialized buffering layer on the concrete retaining wall, the barrier's impact resistance can be effectively enhanced (Kurihashi et al., 2020). According to Maegawa et al. (2011), concrete rockfall barriers with a buffering layer offer a maximum impact resistance ranging from approximately 120 to 490 kJ. Addressing the resistance limitations of traditional concrete rockfall barriers, Furet et al. (2022) proposed the articulated concrete block rockfall protection structures. These innovative structures allow concrete blocks hingedly connected to one another, enabling greater impact energy absorption.

Table 6 Comparison of different concrete rockfall protection structures

Structure name	**The maximum impact energy that structure can withstand (kJ)**	**Energy dissipation ratio (%)**	**Interception altitude (m)**
Cast-in-place rockfall concrete barriers (Patnaik et al., 2015)	127	/	0.81
Concrete retaining wall with buffering system (Kurihashi et al., 2020)	273	100	2.5

Concrete rock – wall (Maegawa et al., 2011)	490	/	/
Articulated concrete blocks rockfall protection structure (Furet et al., 2022)	1020	100	3.2
Pile-slab retaining wall	905	100	6

Note: Energy dissipation ratio denotes the ratio of dissipated energy to input energy.

In terms of energy dissipation, structure damage and friction are responsible for 74% of the impact energy dissipation, with the remaining 26% attributed to other phenomena such as deformation of structural elements, elastic wave propagation, viscous damping, and fracturing. Compared to conventional concrete rockfall barriers, PSRW exhibit significantly higher impact resistance (905 kJ) and interception height (6 m). Similarly, these structures absorb all the impact energy, preventing the impactor from rebounding.

For traditional RC retaining walls subjected to a 16 kJ impact energy, shear cracks develop diagonally from the impact point, with wider spreading observed on the rear face compared to the collision surface (Kurihashi et al., 2020). Fig. 21 illustrates the concrete damage nephogram of PSRW under the impact load of 1170 kN. It is evident that concrete damage primarily concentrated around the impact point and at the junction between the pile and slab. Importantly, there is no evidence of crack penetration into the structure itself, indicating that the PSRW maintains its structural integrity.

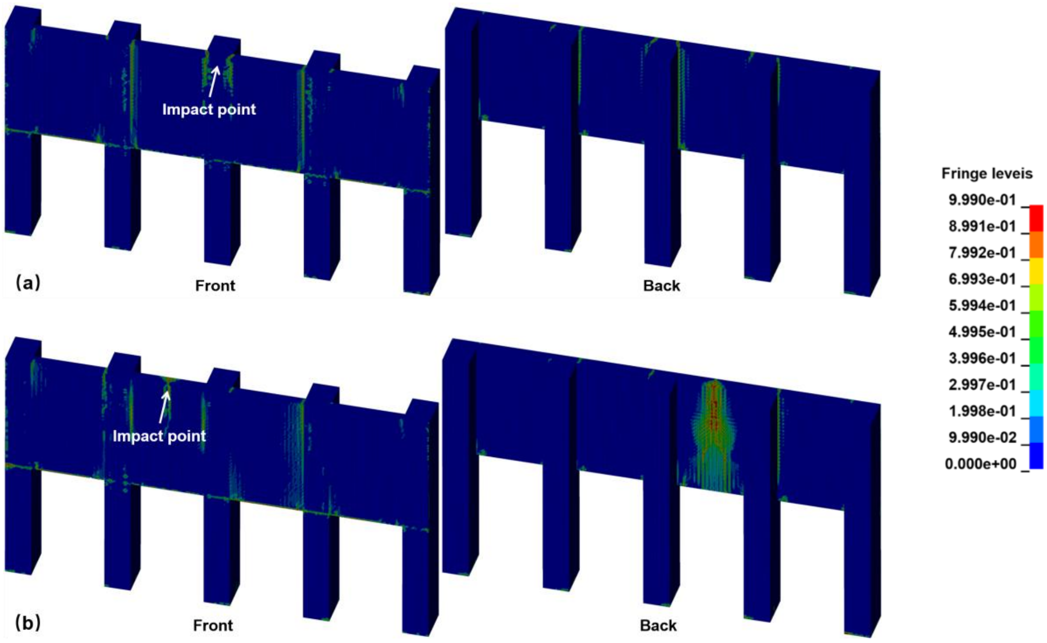

Fig. 21. Damage nephogram of concrete at t = 650 ms (a) CP-V30 (b) CS-V30.

Although the lateral displacement of the pile exceeds the stipulated limit, reaching 12mm as indicated in Table 5 and Figure 21, it is essential to recognize that the specified ultimate lateral displacement is often a conservative estimate. Concurrently, the maximum lateral displacement at the crown of the cantilever section is 35 mm, which is substantially less than the lateral displacement threshold for the cantilever section of the anti-slide pile. This threshold is defined as 1% of the cantilever section's length, according to CAGHP (2019). As a result, the impact load does not compromise the integrity of the structure.

In summary, the PSRW is an innovative rockfall protection structure, providing an enhanced level of impact resistance, increased interception height, and reduced concrete damage. Additionally, the minimal lateral displacement observed after impact further ensures the structural integrity and safety in challenging terrain areas.

4.4. Discussion on Engineering Practicality

The data presented in Table 7 reveal the distribution of rockfall energy levels across four regions that experience frequent rockfalls. It is evident from the table that substantial rockfalls with an impact energy of less than 1000 kJ occur in the Alps region. Schneider et al. (2023) utilized Doppler radar technology to monitor rockfall activity in Brienz/Brinzals, Switzerland. Their research indicated that although the rockfalls' volume ranged from 1 to 100 m^3, smaller events (1 m^3) were significantly more prevalent. As previously mentioned, the PSRW demonstrates resistance against rockfalls with an impact energy of approximately 1000 kJ, thereby rendering it an appropriate choice for numerous small alpine rockfall scenarios. Additionally, its compact size and robust structural stability enhance its suitability for mountainous construction.

Table 7 Rockfall events in different areas

Study area	Total number of rockfall events	Rockfall energy < 1000 kJ	Percentage
French Alps (Le Roy et al., 2019)	18	9	50%
Swiss Alps (Dietze et al., 2017)	37	37	100%
Along the railway in Japan (Muraishi et al., 2005)	173	158	91%
New South Wales, Australia (Spadari et al., 2013)	211	200	94%

Editor

1. General Comments:

In addition, more generalisation would be welcome, namely on how this research would apply in other geographic areas with similar hazards, namely the Alps where rockfall is probable.

1. Reply:

We gratefully appreciate for your valuable suggestion. We have added a practical discussion of the structure to the discussion section. The specific contents are as follows.

4.5. Discussion on Engineering Practicality

The statistical table presented in Table 6 illustrates the rockfall energy levels across four regions globally prone to frequent rockfall disasters. Evidently, from Table 6, it is apparent that a significant proportion of rockfall incidents consist of small alpine rockfalls possessing an impact energy below 1000 kJ. Schneider et al. (2023) employed Doppler radar to observe rockfall occurrences within the active rockfall complex situated in Brienz/Brinzals, Switzerland. Their findings revealed that while the rockfall events encompassed volumes spanning from 1 to 100 m^3, smaller events (1 m^3) proved to be significantly more prevalent. As aforementioned, the PSRW exhibits resilience against rockfalls exerting an impact energy of approximately 1000kJ, thereby rendering it an apt choice for numerous small alpine rockfall situations. Furthermore, its compact size and robust structural stability bolster its suitability for mountainous construction endeavors.

Table 1 Survey results of rockfall events in different areas

Study area	**Total number of rockfall evens**	**Rockfall energy < 1000 kJ**	**Percentage**
French Alps (Le Roy et al., 2019)	18	9	50%
Swiss Alps (Dietze et al., 2017)	37	37	100%
Along the railway in Japan (Muraishi et al., 2005)	173	158	91%
New South Wales, Australia (Spadari et al., 2013)	211	200	94%

Reference

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