Type: Journal Article

Title: New light-weight concrete foam to absorb rock fall impact: large-scale pendulum modelling

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Abstract

In this study, the performance of light-weight concrete foam is evaluated. Physical large-scale pendulum impact tests were conducted to study the performance of concrete foam, which was used to shield a reinforced concrete barrier from boulder impact with an energy level of up to 70 kJ. Six successive boulder impacts were carried out. Two different concrete foam thicknesses, 0.4 m and 0.6 m, were investigated. Increasing the cushioning thickness from 0.4 m to 0.6 m can reduce the maximum transmitted load by 48% and 71% for the first and sixth impacts at an impact energy of 70 kJ, respectively. The larger thickness enhances load spreading on the wall and reduces stress concentration. Furthermore, the maximum penetration depth on the 0.4-m thick concrete foam is 0.29 m for the sixth impact, which reaches the 72% of cushion layer thickness of 0.4 m. Based on the existing design guidelines (ASTRA 2010) and the Gibson and Ashby model, the required minimum thickness for up to six successive impacts at an impact energy of 70 kJ is 0.58 m.

Keywords: Boulder impact; cushioning material; concrete foam; rigid barrier; debris flow

Introduction

Flow-type landslides (Hungr *et al.* 2014; Valagussa *et al.* 2014), such as debris flow, are one of the most dangerous geo-hazards in the world. Particle-size segregation enables large boulders to migrate to the head of a flow (Iverson 2007; Chen *et al.* 2014). These boulders often result in high impact forces and pose the greatest threat to downstream facilities (Hu *et al.* 2019; Lee and Winter 2019; Zhang *et al.* 2018). To mitigate flow-entrained boulders, reinforced concrete barriers (Armanini and Scotton 1993; Lo 2000; Canelli *et al.* 2012; Takahashi 2014) are installed along flow paths. Cushioning layers are commonly installed in front of these barriers to shield them from boulder impact and to prevent structural damage (Yoshida 1999; Lambert *et al.* 2009; Heymann *et al.* 2010; Gao *et al.* 2017; Shen *et al.* 2018; 2019).

Rock-filled gabions are the most commonly adopted cushioning layer used by engineers. They are constructed by filling wire baskets with rock fragments. Rock-filled gabions rely on shearing among fragments and crushing of these fragments to dissipate impact energy. However, because of weight and time-consuming mining of rock fragments, it is hard to construct rock-filled gabions cushioning layers in mountain areas. Furthermore, the mechanical response of rock-filled gabions may be variable (Bertrand *et al.* 2008; Breugnot *et al.* 2015) and could depend on the size, angularity, and bulk density of the fragments involved (Lambert *et al.* 2013; 2014; Ng *et al.* 2016; Su *et al.* 2019).

Ng *et al.* (2016) investigated the dynamic response of rock-filled gabions subjected to successive boulder impacts with a series of physical pendulum impact tests. Nine cubic rock-filled gabion cells with a nominal length of 1 m were used to form a cushioning layer in front of the reinforced concrete barrier. The bulk density of each gabion cell was 1500 kg/m^3. Experimental data showed that rock-filled gabions can reduce the boulder impact load with an impact energy of 70 kJ by up to 50% compared to the design impact load on a bare reinforced concrete barrier (Kwan 2012). Moreover, Lambert *et al.* (2007) carried out a series physical experiments and reported at least 15% difference in the measured maximum boulder impact force for rock-filled gabions under the same loading conditions. These findings suggest the variability of cushioning response of rock-filled gabions in reducing boulder impact force. Therefore, a cushioning material with a more consistent and predictable cushioning response in reducing boulder impact force is explored.

In light of the variability in the dynamic response of rock-filled gabions, Schellenberg *et al.* (2006) and Ng *et al.* (2018) investigated the dynamic response of an alternative cushioning material called cellular glass. This type of glass is formed by baking crushed glass with chemical additives. Schellenberg *et al.* (2006) compared the cushioning performances of cellular glass and gravel-filled gabions with a maximum gravel diameter of 32 mm using drop tests with an impact energy of up to 15 kJ. Their experimental data showed that cellular glass can reduce the maximum boulder impact force and transmitted load to a reinforced concrete wall by up to 40% and 50%, respectively, more than gravel-filled gabions. The improved cushioning performance of cellular glass is attributed to its low crushing strength. During impact, cellular glass exhibits large localised and irreversible deformation, which is ideal for extending the contact time of impact, thereby reducing the impact load. Although crushing is ideal for load attenuation, it can lead to excessive deformation, rendering a cushioning layer ineffective for resisting successive boulder impacts. Ng *et al.* (2018) conducted pendulum impact tests on cellular glass. They reported that after two successive impacts at an energy level of 70 kJ, a penetration depth of more than 80% of the cushioning layer's initial thickness was measured. The large penetration exceeded the minimum cushioning layer thickness recommended in international guidelines (ASTRA 2010). Therefore, cellular glass may not be the most suitable cushioning material for resisting boulder fronts because it degrades rapidly under successive loading.

In this study, concrete foam is proposed as a new cushioning material and evaluated using physical pendulum tests. Concrete foam is produced by mixing cement with chemical additives under high-speed agitation (Ni 2012). This type of foam is easy to manufacture, and the final product is lightweight. Such an innovative material has not yet been evaluated for resisting concentrated impact forces from boulders and it is worthwhile to explore as a new engineering solution.

Hertz contact mechanics

The impact force P and contact mechanics between a sphere and plane based on elastic Hertz contact theory (Johnson 1985) is as follows:

$$P = \frac{4E}{3} R^{\frac{1}{2}} (\delta)^{\frac{3}{2}} \quad (1)$$

where E is the effective moduli of elasticity, which is given as $1/E = (1-\nu_r^2)/E_r + (1-\nu_b^2)/E_b$ (E_r and E_b are the elastic moduli of barrier and concrete boulder, respectively ; ν_r and ν_b are the Poisson's ratios of the reinforced concrete barrier (0.3) and reinforced concrete boulder (0.3), respectively); R is the radii of the boulder; m is the mass of concrete boulder; v is the impact velocity and δ is the deformation (δ), which is given as follows:

$$\delta = \frac{15mv^2}{16ER^{\frac{1}{2}}} \quad (2)$$

Hertz contact theory is normally adopted by engineers to estimate the boulder impact force. However, without the consideration of plastic deformation, the estimated boulder impact force is over-conservative compared to the measured boulder impact force (Hungr *et al.* 1984; Lo 2000). A load-reduction factor K_c of 0.1 is proposed by Kwan (2012) based on the engineering experience in available literature.

Large-scale pendulum impact tests

A large-scale pendulum impact facility constructed in Shenzhen, China, was used to carry out the impact tests in this study. The site has a plan area that is 15 m in length and 6 m in width. Figs. 1a and 1b show front and side views of the pendulum impact setup, respectively. The steel frame occupies a plan area of 5 m by 3 m and has a height of 6 m. A 1.16-m dimeter concrete boulder with a mass of 2000 kg is suspended from the steel frame using two steel strand cables. Three steel loops were installed on the concrete boulder. Two loops were used to connect two steel strand cables from the boulder to the steel frame. The third loop was used to elevate the concrete boulder to the required height. The boulder was lifted using a crane lorry and released to enable the boulder to impact the cushioning material installed in front of the reinforced concrete rigid barrier. The rigid barrier is 3 m in length, 3 m in width and 1.5 m in thickness. The cushioning material was confined using a steel frame to reduce lateral displacement during impact.

The cushioning material was tied to the rigid barrier to prevent it from collapsing after each impact.

Instrumentation

Eight load cells (THD-50K-Y), each with a maximum range of 220 kN, were installed on the rigid barrier to measure the horizontal and vertical loads transferred from the cushioning layer to the rigid barrier (Fig. 2). The acceleration of the concrete boulder was measured by using an accelerometer with a maximum acceleration of 500 g (where g is the acceleration due to earth's gravity). The impact velocity and penetration depth were estimated using a high-speed camera positioned at the side of the pendulum setup (Fig. 2). The high-speed camera records images at a frame rate of 200 frames per second and a resolution of 1376 × 1226 pixels. In addition to the high-speed camera, a video camera with a frame rate of 30 fps and a resolution of 1920×1080 pixels was used to capture the overall impact process from the side of the pendulum setup.

Concrete foam

Concrete foam blocks with a density of 800 kg/m^3 were used in this study. The porosity of the concrete foam is 67%. Each block has dimensions of 0.6 m in length, 0.2 in width and 0.1 m in thickness. A cube of concrete foam block with nominal length of 100 mm was compressed based on the ASTM D1621 (ASTM Standard D1621 2010). The measured crushing resistance and Young's modulus of concrete foam is 2.2 MPa and 423 MPa, respectively. A summary of the properties of concrete foam is given in Table 1.

In this study, the Gibson and Ashby model is used to characterise the mechanical responses of concrete foam (Gibson and Ashby 1997).

Figure 3 shows a comparison between the measured and theoretical (Gibson and Ashby 1997) compressive stress-strain behaviour of concrete foam. Normally, the theoretical stress-strain behaviour of crushable foam can be characterised by using the Gibson and Ashby model, which has three stages.

In the first stage of the loading process, the mechanical response of concrete foam is governed by the elastic deformation of its cell walls. The compressive stress during loading is given as follows:

$$\sigma = E \times \varepsilon = \left[\varphi^2 (\frac{\rho^*}{\rho_s})^2 + (1-\varphi)\frac{\rho^*}{\rho_s}\right] E_s \times \varepsilon \ (\sigma \le \sigma_c) \quad (3)$$

where E_s is the solid modulus of C30 concrete (3×10^4 MPa); ε is the volumetric strain; and σ_c is the measured foam crushing strength from the lab tests as mentioned above (2.2 MPa); ρ^* is the measured foam density (800 kg/m^3); ρ_s is the solid density of C30 concrete (2400 kg/m^3); φ is the fraction of solid contained in the cell edges (0.8); $1-\varphi$ is the fraction of solid contained in the cell faces (0.2); E is the deduced foam elastic modulus (4.1×10^3 MPa) based on the Eqn. (3). After initial elastic loading, the stress plateaus as the cell walls crush. The crushing stress is given as follows:

$$\sigma = \sigma_c = \left[0.2(\varphi\frac{\rho^*}{\rho_s})^{3/2} + (1-\varphi)(\frac{\rho^*}{\rho_s})\right] \sigma_{fs} \ (\varepsilon_c < \varepsilon < \varepsilon_D) \quad (4)$$

where σ_c is the measured foam crushing strength from the lab tests as mentioned above (2.2 MPa); σ_{fs} is the back-calculated solid fracture strength (24 MPa) based on Eqn. (4); ε_c is the crushing strain; and ε_D is the limiting strain.

In the final stage, when the cell wall entirely collapses, the opposing cell walls come in contact with each other after reaching the limiting strain. Further loading only compresses the cell wall material. Thus, the stress increases rapidly and stiffness is equal to the Young's modulus of the cell material. The limiting strain is described as follows:

$$\varepsilon_D = 1 - 1.4\left(\frac{\rho^*}{\rho_s}\right) = 1 - 1.4R_e \qquad (5)$$

where ρ^* is the measured foam density of 800 kg/m^3; ρ_s is the solid density of 2400 kg/m^3; and R_e is the relative density of 0.33. Compared to the Gibson and Ashby model, the measured loading curve exhibited a stress drop between elastic loading and crushing. After the stress peaked, it decreased rapidly because of a relatively brittle structural failure of the concrete foam block (Fig. 3). Similar observations of rapid softening were also reported by Zhou *et al.* (2010). This rapid reduction in stress was not observed for cellular glass or glass foam (Ng *et al.* 2018). Notwithstanding, by taking the relative density of the concrete foam as 0.33 and by using Eqn. (5), the theoretical limiting strain of concrete foam is 0.54. Furthermore, based on the Gibson and Ashby model, after the limiting strain of 0.54, the cell walls came into contact with each other and the compressive stress increases rapidly. This coincides with the observations that after the strain of 0.60, the measured compressive stress begins increasing significantly. The theoretical limiting strain shows reasonable agreement with measured limiting strain. Even though the Gibson and Ashby model cannot capture the peak stress, it still provides a reasonable prediction of the overall mechanical behaviour of concrete foam.

Test program

Two impact energies were studied, specifically 20 kJ and 70 kJ. In addition, two concrete foam thicknesses of 0.4-m and 0.6-m were investigated at each energy level. Six successive impacts were carried out at the center of each cushioning layer. The test programme for concrete foam and rock-filled gabions is summarized in Table 2.

Test procedure

The concrete boulder was first suspended by a crane lorry and then the concrete boulder was connected to the steel frame using two steel strand cables. The boulder was lifted to target heights of 1.0 m and 3.5 m to achieve impact energies of 20 kJ and 70 kJ, respectively. Finally, the release mechanism is triggered and the concrete boulder is allowed to swing and impact into the cushioning material installed in front of the reinforced concrete barrier. The same procedure was repeated for each successive impact.

Cumulative penetration depth

Fig. 4 shows a comparison of the cumulative penetration depths after the first, fourth and sixth impacts on the concrete foam and rock-filled gabion cushioning layers. Successive boulder impacts at energy levels of 20 kJ and 70 kJ are shown in Figs. 4a and 4b, respectively. The ordinate shows the measured penetration depth (P) and the abscissa shows the horizontal distance of concrete foam in the centreline from 0 to 3 m.

For an impact energy of 20 kJ, the maximum penetration depth (P_{max}) in the 0.4-m thick concrete foam layer after the first impact was 0.04 m. After six successive impacts, the maximum penetration depth increased by 2.4 times to 0.11 m. In contrast, the maximum penetration for the 0.6-m concrete foam cushioning layer was 0.04 m and 0.12 m for the first and sixth impacts, respectively. The large penetration depths are due to cell wall crushing under successive impacts. The differences in maximum penetration between the 0.4-m thick concrete foam and 0.6-m thick concrete foam after the first and the sixth impacts are less than 0.01 m. This implies that the cushioning thickness of concrete foam only has negligible influence on the maximum penetration depth. For rock-filled gabions (1000-mm thickness), at an impact energy of 20 kJ, the maximum penetration depths were 0.29 m, 0.38 m and 0.44 m after the first, fourth and sixth impacts, respectively (Ng *et al.* 2016). The maximum penetration depths in the rock-filled gabion cushioning layer for six successive impacts were at least 3.7 times larger compared to that of the concrete foam cushioning layer.

Figs. 5a and 5b show the localised damage on the 0.4-m and 0.6-m thick concrete foam cushioning layers after the sixth successive impact, respectively. The permanent deformation of the concrete foam is observed to mainly concentrate around the impact area. Post-test investigation of the concrete foam reveals a densified crater where the cell walls have already been compacted (Gibson and Ashby 1997; Ng *et al.* 2018). Some concrete foam fragments were observed to have spalled off on the ground. The horizontal deformation on the 0.4-m thick concrete foam is 0.4 m after the first impact. In contrast with concrete foam, the horizontal deformation for rock-filled gabions is about 4.5 times larger after the first impact. This means that the cushioning mechanism of rock-filled gabions, via shearing among grains and rearrangement of grains, leads to greater transverse deformation compared to that of concrete foam, which relies predominantly on the cushioning mechanism of cell wall crushing.

At an impact energy of 70 kJ (Figs. 4b), the maximum penetration depth after the first impact on the 0.4-m thick concrete foam was 0.09 m. After the fourth and sixth successive impacts, the maximum penetration depth increased by almost 2.8 times and 3.2 times to 0.26 m and 0.29 m, which is 64% and 72% of the original cushion layer thickness of 0.4-m, respectively. According to international design guidelines (ASTRA 2008), the recommended cushioning layer thickness should be at least two times greater than the maximum penetration depth. This means that a cushioning layer thickness of 400 mm is insufficient for resisting up to four successive impacts at an energy level of 70 kJ. Meanwhile, the back-calculated minimum cushioning layer thickness of at least 0.58 m is required based on recommendations by ASTRA (2008). Fig. 6a shows the permanent deformation of the 400-mm thick concrete foam cushioning layer after the sixth successive impact. Post-impact investigation shows larger concrete foam fragments that have spalled off on the ground compared to that for an impact energy of 20 kJ (Fig. 5a). Moreover, deep cracks were observed to have propagated radially from the impact area. Settlement was also observed at the crest of the concrete foam cushioning layer because of the large penetration at the centre of the cushioning layer after the sixth impact.

Based on the Gibson and Ashby model (Gibson and Ashby 1997), the theoretical limiting strain of 0.54 can be calculated by using Eqn. (5). This means that the loading is mostly taken by the cell material and the stress increases rapidly after the limiting strain is reached (Gibson and Ashby 1997). This also implies that cushion mechanism of crushing is less effective in the strain exceeds more than half of the concrete foam thickness. The measured maximum penetration depth for the 0.4-m thick concrete foam was 0.29 m after the sixth impact. The minimum concrete foam cushioning thickness was back-calculated by dividing the maximum penetration depth of 0.29 m by the limiting strain of 0.54. This calculated minimum cushioning thickness of 0.54 m following the Gibson and Ashby model, which shows good agreement with the required cushioning layer thickness calculated by design recommendations by ASTRA (2008), which suggests a thickness of 0.58 m. This implies that concrete foam with a minimum thickness of 0.58 m can attenuate up to six successive impacts at an impact energy of 70 kJ.

In contrast with the 0.4-m thick concrete foam cushioning layer (Figs. 6a), fewer and shallower cracks were observed on the 0.6-m thick concrete foam cushioning layer after sixth impact (Figs. 6b). Moreover, the maximum penetration depth on the 0.4-m thick concrete foam after the sixth impact was 1.5 times as larger compared to that of the 0.6-m thick concrete foam cushioning layer. The differences between the mechanical response of the 0.4-m and 0.6-m thick concrete foam layers will be discussed later.

Dynamic response of concrete foam

Boulder impact forces

Figure 7 shows the relationship between the measured boulder impact force (F) and the deformation (D) measured for each successive impact on the 0.4-m and 0.6-m thick concrete foam cushioning layers. The abscissa shows the deformation (D), which is calculated from double integration of the measured boulder acceleration. The ordinate shows the boulder impact force (F), which is the product of the measured acceleration and mass of the boulder.

A maximum boulder impact force (F_{max}) of 1177 kN was measured from the 400-mm thick concrete foam after the first impact at an impact energy level of 70 kJ. The maximum penetration depth was 0.11 m. The unloading modulus represented by slope of measured curve is much steeper compared to the loading modulus. This implies that the plastic deformation dominated by cell wall crushing resulted in significant energy absorption (Ng *et al.* 2018). The area under each curve represents the energy absorbed by the concrete foam. The calculated absorption energy is about 70 kJ, indicating that all of the boulder impact energy was transferred from the boulder to the concrete foam cushioning layer. A rebound boulder velocity of 0.4 m/s, which was captured by the high-speed camera, further confirms that almost all of the impact energy was absorbed by the concrete foam. Furthermore, a rebound boulder velocity of 0.8 m/s, also captured by the high-speed camera, for the sixth impact is twice as large compared to that for the first impact. With an increasing number of successive impacts, the incremental increase in rebound velocity was caused by a reduction in cushioning thickness. A thinner cushion, 0.11 m, between the boulder and rigid barrier for the sixth impact generates higher rebound energy. The maximum boulder impact force for the sixth impact on the 0.4-m thick concrete foam is 2.4 times larger compared to that for the first impact. This is because the contact surface between boulder and concrete foam increases under successive impacts. Moreover, the loading modulus caused by densification of the concrete foam with an increasing number of successive impacts also contributes an increase in boulder impact force.

The mechanical response of a 0.6-m thick concrete foam layer for the first, fourth and sixth impacts at an impact energy of 70 kJ were compared. After the first impact, the measured boulder impact force and the maximum deformation were 1348 kN and 0.102 m, respectively. Comparisons between the 0.4-m and 0.6-m concrete foam cushioning layers for an impact energy of 70 kJ shows less than 20% difference in the impact force and penetration depth. This means that the cushioning layer thickness only has minor effects on the mechanical responses of concrete foam for the first impact. However, the maximum boulder impact force on the 0.4-m thick concrete foam is about 44% larger compared to that on the 0.6-m thick concrete foam for the sixth impact, respectively. This may be attributed to that the maximum penetration depth already reaches 64% of the cushion layer thickness after the fourth impact (Figs. 4b). According to the discussion of Gibson and Ashby model above, the plastic deformation for the fourth impact already exceeds the limiting strain of concrete foam. It means that the cell wall entirely collapses, the opposing cell walls come in contact with each other. This also implies that the cushion mechanism of cell wall crushing is less effective in attenuating the concentrated boulder impact load after the fourth impact.

Ng *et al.* (2016) reported experimental data of the cushioning performance of rock-filled gabions subjected to an impact energy level of 70 kJ. To verify the repeatability of cushioning performances for rock-filled gabions, new impact tests at an impact energy level of 70 kJ were carried out. Figure 8 shows the relationship between the boulder impact force and the corresponding penetration depth (Ng *et al.* 2016). Large fluctuations in the impact forces were observed because load transfer depends on the transient formation and destruction of force chains of the rock fragments (Heymann *et al.* 2010a;

2010b; 2011; Lambert *et al.* 2009; 2013; 2014; Su *et al.* 2019). A comparison of the maximum boulder impact force between the rock-filled gabion tests conducted by Ng *et al.* (2016) and those repeated in this study show differences of up to 45% for the first impact. This highlights the variability of the cushioning performance of rock-filled gabions.

Fig. 9a shows a comparison of the maximum impact force (F_{max}) measured for the 0.4-m and 0.6-m thick concrete foam layers subjected to successive impacts at energy levels of 20 kJ and 70 kJ. The measured F_{max} increases with successive impacts because of increase in contact surface and loading modulus under successive impacts. However, a decrease in measured F_{max} is observed for the fourth impact on the 0.4-m thick concrete foam at an impact energy of 20 kJ. Similar decreases in measured F_{max} are also observed on the 0.4-m thick and 0.6-m thick concrete foam layers for the fifth and sixth successive impacts at an impact energy of 70 kJ, respectively. This decrease may be attributed to difference in the boulder impact point between each successive impact. The maximum boulder impact force on the 0.4-m thick concrete foam is 30% larger compared to that on the 0.6-m thick concrete foam for the first impact at an impact energy of 20 kJ. This may be caused by the gap that formed between the cushioning layer and the rigid barrier will prolong the impact duration, thereby reducing the impact force. It is interesting to note that the observed differences in the maximum boulder impact force between the 0.4-m thick and 0.6-m thick concrete foam layers from the second impact to the sixth impact are less than 20%. Furthermore, at an impact energy of 70 kJ, observed differences in the maximum boulder impact force up to the fourth impact, were all less than 15%. As mentioned above, the maximum penetration depth is less than the limiting strain of concrete foam up to fourth impact at an impact energy of 70 kJ (Figs. 4b). This means that the effects of cushioning layer thickness on the mechanical responses of concrete foam are small if the plastic deformation is less than the limiting strain.

However, the difference on maximum boulder impact force between 0.4-m thick and 0.6-m thick concrete foam increases to 24% and 77% for the fifth and sixth impact, respectively. The large differences observed between the two cushioning thickness is because the penetration depth of the 0.4-m thick concrete foam for the fourth impact reaches the 64% of the cushion thickness, which already exceeds the theoretical limiting strain of 0.54 calculated by using Eqn. (5). This implies that the cell wall has entirely collapsed and the cushion is no longer effective in attenuating the load. Evidently, concrete foam only provides consistent cushion performances as long as the normalized penetration depth is less than the theoretical limiting strain.

Figs. 9b shows the back-calculated load-reduction factors (K_c) after each impact. The load-reduction factor K_c increases with successive impacts. This means that the cushion efficiency of concrete foam diminishes with successive impacts. It can be found that the $\mathrm{K_c}$ value of 0.4-m thick concrete at an impact energy 20 kJ are all larger than that at 70 kJ except for the fourth impact. Similar findings on load-reduction factors (K_c) are also observed on the 0.6-m thick concrete foam. The penetration depth for 70 kJ is much larger compared to that for 20 kJ. Larger penetration depths result in smaller load-reduction factors. This observation is consistent with that reported by Ng *et al.* (2018).

Effects of cushion thickness on transmitted loads

Figs. 10a and 10b show the measured maximum transmitted loads (T_{max}) along the vertical and horizontal centrelines of the reinforced concrete barrier, respectively. In Fig.10a, the abscissa shows the measured maximum transmitted load. The mid-height of the barrier is at a barrier height of 1.5 m. The measured load distributions behind the 0.4-m and 0.6-m thick concrete foam layers and a 1-m thick rock-filled gabion layer are compared for the first and sixth impacts.

For the 0.4-m thick concrete foam, a maximum transmitted force T_{max} of 98kN was measured after the first impact at the mid-height of the barrier. No load was registered near the top or the bottom of the reinforced concrete barrier, implying that the transmitted load was concentrated around the centre of the rigid barrier. At the centre of the rigid barrier, the maximum transmitted force from the 0.4-m thick concrete foam layer is about 1.9 times greater than that measured for the 0.6-m thick concrete foam cushioning layer for the first impact. Findings show that the transmitted load can be reduced by 71% for the sixth impact if the concrete foam thickness is increased from 0.4 m to 0.6 m. The difference in transmitted load between different thicknesses is due to a larger load spreading area, which induces minimizes stress concentration at the middle of the rigid barrier. Furthermore, the residual cushion layer thickness on the 0.6-m thick concrete foam is 41% thicker that on the 0.4-m thick concrete foam (Figs. 4b). This also leads more energy dissipation with a thicker cushioning layer, which decreases the transmitted load on the rigid barrier.

The transmitted load for the 0.4-m thick concrete foam cushioning layer increases at a higher rate compared to the 0.6-m thick concrete foam cushioning layer under successive impacts. This is because the residual thickness for the 0.4-m thick concrete foam cushioning layer after the sixth impact is only 27% of the 0.6-m thick concrete foam. A smaller thickness leads to reduced load spreading on the wall, thus inducing higher stress concentration along the impact axis. A comparison of the maximum transmitted loads in the impact axis shows reductions of 91% and 83% when the 0.4-m thick and 0.6-m thick concrete foam is replaced with 1-m rock-filled gabion, respectively. This may be attributed to the high bulk density of rock-filled gabion, which is almost two times that compared with concrete foam. The greater inertia of the rock-filled gabion extends the impact duration and further decreases transmitted loads. Furthermore, the thicker cushioning layer of rock-filled gabion enhances load spreading on the rigid barrier, thereby minimizing stress concentration on the rigid barrier.

Figs. 10b shows the loads measured by the four load cells installed along the horizontal centreline of rigid barrier at an impact energy of 70 kJ. The horizontal distances of four load cells from the centre of rigid barrier are 0.0 m, 0.4 m, 0.8 m and 1.2 m. No load was measured at horizontal distances of 0.8 m and 1.2 m for both the 400-mm and 600-mm concrete foam cushioning layers, respectively, after the first impact. The maximum extent of load distributed horizontally on the rigid barrier is at the horizontal distance of 0.4 m. As illustrated in Fig. 11, the load diffusion angle α of 17° can be deduced based on the cushioning layer thickness and the assumed maximum load distribution extent minus the boulder radius of 0.58 m. For the rock-filled gabion cushioning layers, at horizontal distances of 0.8 m and 1.2 m, transmitted loads of 3.5 kN and 1.0 kN were measured, respectively. A larger diffusion angle of 32° was measured for rock-filled gabions. This angle is about three times larger than that of concrete foam. Moreover, the slope of the curve for concrete foam, which represents the load distribution, is much steeper compared to that of the rock-filled gabion cushioning layers. This indicates that the transmitted loads are more uniformly distributed on the 1-m thick rock-filled gabion cushioning layers compared to the 0.4-m thick and 0.6-m thick concrete foam layers. This is because the collapse and generation of force chains induced by rock fragments rearrangements increases load spreading during the impact process (Muthuswamy and Todesillas 2006; Su *et al.* 2019). Furthermore, a thicker rock-filled gabion layer will also contribute to more uniformly distributing the load on the rigid barrier.

Conclusions

The dynamics response of a new cushioning material, concrete foam, was evaluated using a physical pendulum impact model. Impact energies of up to 70 kJ was investigated for up to six successive impacts. Based on the experimental results, some key findings are summarized as follows:

1. If the concrete foam thickness is increased from 0.4 m to 0.6 m the maximum transmitted loads in the impact direction can be reduced by 48% and 71% for the first and sixth impacts at an impact energy of 70 kJ, respectively. This is because of a thicker cushioning layer enhances load spreading, thereby minimizing stress concentration along the axis of impact.

2. The differences in maximum penetration depth and boulder impact force between 0.4-m thick and 0.6-m concrete foam are all less than 20% at an impact energy of 20 kJ. Furthermore, at an impact energy of 70 kJ, the differences in maximum

penetration depth and boulder impact force are less than 20% from the first impact to the third impact. This indicates that the concrete foam only provides consistent cushion performances as long as the normalized penetration depth is less than the theoretical limiting strain.

3. Based on the existing design guidelines (ASTRA 2010) and Gibson and Ashby model, the required minimum thickness for up to six successive impacts at an impact energy of 70 kJ is 0.58 m.

Acknowledgements

The authors are grateful for the financial support from the National Natural Science Foundation of China (51709052). The authors would like to gratefully acknowledge the support from the Fundamental Research Funds for the Central Universities (2019B07714). The authors are also grateful for financial support from the Research Grants Council of the Government of Hong Kong SAR, China (AoE/E-603/18; T22-603/15N; 16209717; 16212618). This paper is published with the permission of the Head of the Geotechnical Engineering Office and the Director of Civil Engineering and Development, the Government of Hong Kong SAR, China.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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