Large-scale successive boulder impacts on a rigid barrier shielded by gabions

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Abstract: Debris flows occur in multiple surges. Boulders entrained within the flow have been reported to incapacitate structures within its flow path. Single-layer cushions, such as gabions, are often installed to shield debris-resisting barriers from boulder impact. However, most relevant works only focus on single impact and the performance of gabions subjected to successive loading is still not well understood. A new large-scale pendulum facility was established to induce impact energy of up to 70 kJ on an instrumented rigid barrier shielded by 1 m thick gabions. The response of the gabions under six successive impacts was investigated. Results show that the peak boulder impact force given by the Hertz equation is at least four times the measured values. The recommended load-reduction factor ($K_c$) used in practice can be reduced by a factor of two. After six successive impacts at an energy level of 70 kJ, the transmitted force increases by up to 40%. Based on the Swiss guidelines, a 13% increase of gabion thickness is required when successive impacts are concerned. The results presented in this paper will be useful for practitioners designing rigid barriers.

Key words: debris flow, rockfall, impact, gabion, rigid barrier.

Introduction

Debris flows are one of the most dangerous natural hazards that occur in mountainous regions around the world (Hungr et al. 2014). Severe loss of human life and damage to infrastructure resulting from debris flow is reported globally every year (Petley 2014). Severe loss of human life and damage to infrastructure resulting from debris flow is reported globally every year (Petley 2014). Severe loss of human life and damage to infrastructure resulting from debris flow is reported globally every year (Petley 2014). Severe loss of human life and damage to infrastructure resulting from debris flow is reported globally every year (Petley 2014). Debris flows consist of a mixture of poorly sorted sediments, ranging in size from clay particles to boulders, saturated with water (Iverson 1997). They flow in multiple unsteady surges, ranging in size from clay particles to boulders, saturated at the front and free surface of the flow (Hübl et al. 2009). The process of reverse segregation in a debris flow is responsible for boulders accumulating at the front and free surface of the flow (Hübl et al. 2009). Boulders entrained at the flow front carry destructive energy and can incapacitate structures within its flow path (Zhang et al. 1996) reported the destruction of a bridge pier on the Chengdu-Kunning Railroad in China caused by a boulder-entrained debris flow. A train subsequently tried to cross the failed bridge and more than 220 passengers tragically lost their lives.

To intercept debris flows and to protect downstream facilities, structural countermeasures such as rigid barriers (Lo 2000) and baffles (Choi et al. 2014a, 2014b) are often installed along predicted flow paths (Takahashi 2014). Figure 1 shows an array of baffles installed in front of a rigid barrier shielded by gabions in Tung Chung, Hong Kong. The installation of a cushion material in front of rigid debris-resisting structures is necessary to shield them from highly concentrated loads from boulder-entrained debris flow fronts.

Gabions, which are formed by putting rock fragments inside wire baskets, are a cost-effective and easy-to-construct single-layer cushioning system that was firstly investigated for rockfall protection applications (Lambert et al. 2009, 2014). The performance of gabions has since been studied using large-scale drop tests (Lambert et al. 2009) and pendulum impact tests (Heymann et al. 2010a, 2011; Lambert and Bourrier 2013; Lambert et al. 2014).
It is reported that the properties of a cushion layer under the influence of ageing, specifically compaction and consolidation under successive impacts, should be taken into account (ASTRA 2008). However, there is a lack of physical data and field experience to help engineers understand this phenomenon. Lambert et al. (2014) carried out four successive pendulum impact tests with impact energy of up to 2200 kJ. Large deformations occurred under such high impact energy and it was necessary to repair the gabion structure after each impact. Hence, the deformation of the gabion after each successive impact was not investigated. On the contrary, successive impact tests on multi-layered cushioning systems without any repair were carried out by Heymann et al. (2010), Haza-Rozier et al. (2010), and Lambert et al. (2010). Test results show that the maximum transmitted force when using sand as the kernel material is twice as small as when using gabions. Despite the availability of large-scale studies on gabions and multi-layer cushioning systems, there is a lack of scientific guidelines pertinent to the performance and robustness of gabion walls shielding rigid debris-resisting barriers under systematic successive impacts, replicating multiple debris surge impacts.

The purpose of this study is to investigate the performance of gabions shielding a rigid barrier. Successive impacts are carried out to replicate the surge-like nature of debris flows. The mechanical response of the gabion under repeated dynamic loading without repair is interpreted and compared with existing international guidelines.

**Hertz impact equation**

The design of a rigid barrier for resisting debris flows comprises two components. One component adopts the hydrodynamic approach (Proske et al. 2011) to estimate loading from debris flow and the second component adopts the Hertz equation to estimate boulder impact (Zhang et al. 1996). The superposition of both approaches can then be used to estimate the design impact load (Kwan 2012). The hydrodynamic equation is given as follows:

\[ F = \alpha \rho v^2 \]

where \( F \) is the dynamic impact pressure (Pa), \( \alpha \) is the dynamic pressure coefficient, \( \rho \) is the bulk density (kg/m\(^3\)), and \( v \) is the impact velocity (m/s).

The boulder impact force is calculated based on the Hertz contact theory (Johnson 1985). This theory assumes an elastic impact between a sphere and a plane and is given as follows:

\[ P = \frac{4E_2}{3} \left( \frac{d}{R} \right)^{1/2} \]

where \( P \) is the boulder impact force (in N); the effective modulus of elasticity (\( E \)) is given as \( E = (1 - \nu_1^2)E_1 + (1 - \nu_2^2)E_2 \); \( E_1 \) and \( E_2 \) are the elastic moduli of barrier and concrete boulder, respectively (in Pa); \( \nu_1 \) and \( \nu_2 \) are the Poisson’s ratios of barrier and concrete boulder, respectively; \( R \) is boulder radius (m); \( m \) is the mass of the concrete boulder (kg); \( v \) is the impact velocity (m/s) and the elastic deformation (\( d \)) can be expressed as

\[ d = \frac{15mv^2}{16EKR_{1/2}^{1/5}} \]

Rearranging eq. (2) and defining the kinetic energy as \( I = 0.5mv^2 \) gives the following:

\[ P = 1.9E^{2/5}R^{1/2} \]

It is reported that the Hertz equation predicts an overly conservative boulder impact force because plastic deformation is not considered (Hungr et al. 1984; Lo 2000; Sun et al. 2005). Hence, a load-reduction factor (\( K_c \)) of 0.1 is recommended by Kwan (2012) based on data of case histories documented in available literature.
The weight of the wall was about 32.4 tonnes.

Figures 2 and 2b show front and side views of the pendulum impact setup, respectively. The main components of the test setup comprised a gabion cushion layer, a rigid barrier, and a steel frame used to support and to swing a concrete boulder. The steel frame occupies a plan area of 5 m \( \times \) 3 m and has a height of 6 m. A 1.16 m diameter concrete boulder with a mass of 2000 kg was suspended from the steel frame using two steel strand cables. Three anchors were installed on the concrete boulder. A mechanical latch was used to release the concrete boulder from the crane truck. The gabion cushion layer was installed in front of the rigid barrier. A steel frame was also erected around the peripheral of the wall to confine the cushioning material upon impact. The rigid barrier is 3 m in length, 3 m in width, and 1.5 m in thickness. The weight of the wall was about 32.4 tonnes.

Instrumentation

Eight load cells (model: THD-50K-Y) with a maximum range of 220 kN and a bandwidth of 10 kHz were installed in the rigid barrier to measure the transmitted impact loads on both the horizontal and vertical force directions (Fig. 3). One accelerometer (PCB 350B24) was installed at the back of the concrete boulder to capture the acceleration time history of the concrete boulder. The accelerometer has a measurement range of 5000 g (g is gravitational acceleration) and a bandwidth of 10 kHz. Although the accelerometer measurement range is larger than the effective maximum measurement range (35 g) in this study, the data-acquisition system and accelerometer are still capable of achieving a measurement resolution of 0.2 g. The frame was designed so that the impact orientation is perpendicular to the cushion layer at the first impact. High-speed imagery analysis was carried out to validate the impact orientation. However, after the first impact, a crater forms in the deformed gabion cushion layer and the subsequent points of impact may not be entirely perpendicular to the rigid barrier. The measured acceleration signal includes the actual physical response between the boulder and gabion, and electrical noise. The focus of this study was on the physical response. Hence, a low pass filter was adopted to remove the noise from the signal. To assess the cutoff frequency required to treat the noise, fast Fourier transform (FFT) signal processing was adopted to select a cutoff frequency of 50 Hz. The impact duration is about 0.1 s (10 Hz), which is still five times smaller than the filter frequency adopted (50 Hz). It is acknowledged that piezoelectric sensors may result in measurement bias with prolonged impact duration and may lead to signal reduction in the acceleration data. Hence, piezoresistive sensors are a suitable alternative to reduce this shortcoming (Lambert 2007; Lambert et al. 2014). Laser sensors were used to measure the deformation of the cushion layer at the horizontal centreline at 100 mm intervals. The accuracy of the laser sensor was 1.5 mm. The impact velocity and penetration depth were estimated using a high-speed camera (model: Mikrotron, EoSens mini2), which could capture up to 200 frames per second (fps) at a resolution of 1376 \( \times \) 1226 pixels. In addition to the high-speed camera, a video recorder (model: JVC GX) with a sampling rate of 30 fps at a resolution of 1920 \( \times \) 1080 pixels was also positioned on the side of the setup to capture the impact process. The data-logging system captured data at a rate of up to 10 kHz for up to 50 channels.

This equation is based on typical values of Poisson’s ratios and elastic moduli for a spherical boulder and a rigid barrier. The Poisson’s ratios for barrier and concrete boulder are taken as 0.2 and 0.15, respectively.

\[
P = K \cdot 4000v^2
\]

Fig. 2. Large-scale pendulum impact setup: (a) front view; (b) side view. [Colour online.]

(5) \( P = K \cdot 4000v^2 \)
Test programme

The test programme is summarized in Table 1. In total, 18 impact tests were performed using three impact energies, specifically 20, 40, and 70 kJ. For each impact energy level, six successive impacts were carried out. For each energy level, new gabion cells were used. Six impacts were selected to prevent excessive deformation and to allow the effects of successive impact to be studied. Excessive deformation of the gabion cushion layer could potentially damage instrumentation and structural elements of the pendulum setup. At 70 kJ, the maximum deformation for the sixth impact was 0.57 m for a 1 m thick gabion cushion layer.

Modelling setup and test procedure

Gabions were constructed in accordance with GEO (1993). The entire gabion cushion layer comprised nine cubical gabion cells with a nominal length of 1 m. The gabion cells were connected using 3 mm diameter steel wires. The unit weight of each gabion cell was about 15 kN/m³. The gabion baskets are made of hexagonal woven wire mesh. The hexagonal opening of each wire mesh was about 80 by 100 mm. The diameter of wire was 2.7 mm and coated using 0.5 mm thick polyvinyl chloride (PVC) to prevent corrosion. The size of the granitic fragments used to fill gabions ranged from 160 to 300 mm. After filling up each gabion cell, they were anchored to the rigid barrier using steel bolts to prevent toppling during impact. The concrete boulder was lifted using a crane truck and connected to the steel frame using two steel strand cables. Instrumentation and cameras were set up to capture the impact kinematics (Fig. 4). The concrete boulder was lifted to the target height to achieve the correct energy, specifically 1 m for 20 kJ, 2 m for 40 kJ, and 3.5 m for 70 kJ (Fig. 5a). The release mechanism was initiated to allow the concrete boulder to swing into and impact the gabion cushion layer in front of the rigid barrier (Fig. 5b). After each impact, a post-impact investigation was carried out to study the deformation of the gabion cushion layer.

Test results and interpretation

Dynamic response of boulder and gabion

Figure 6 shows the time history of the boulder impact force measured at an energy level of 20 kJ. The impact force is the product of the measured acceleration and boulder mass. The dashed horizontal reference line indicates the estimated boulder impact force using eq. (5), specifically 818 kN. A maximum boulder impact force of 112 kN and impact duration of 0.1 s is measured for the first impact. The estimated force is about seven times larger than the maximum impact force. This is because the effects of a cushion layer and plasticity are not considered. Furthermore, for the sixth impact, the maximum impact force of 400 kN is four times larger than the first impact and the impact duration decreases by a factor of two. This indicates that the gabion cushion layer stiffens with successive impacts. Consequently, a denser gabion cushion leads to a shorter impact duration and larger maximum boulder impact force.

Figures 7a, 7b, and 7c shows the measured maximum boulder impact force, force-reduction percentage, and load-reduction factor (Kc) for successive impacts under different energy levels, respectively. The solid lines in Fig. 7a indicate the measured maximum boulder impact force calculated using the measured peak boulder acceleration. The dashed horizontal reference lines show the estimated impact force using eq. (2), at each energy level. The Hertz equation yields impact forces of 518, 776, and 1081 kN for impact energy levels of 20, 40, and 70 kJ, respectively. It is assumed that the impact plane remains unchanged under successive impacts. An elastic modulus of 16 MPa is adopted from compression tests carried out by Bourrier et al. (2011).

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Impact energy (kJ)</th>
<th>Impact velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-20</td>
<td>20</td>
<td>4.5</td>
</tr>
<tr>
<td>G-40</td>
<td>40</td>
<td>6.3</td>
</tr>
<tr>
<td>G-70</td>
<td>70</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Table 1. Test programme.
Fig. 4. Schematic plan view of camera setup. [Colour online.]

Fig. 5. Impact test procedure: (a) concrete boulder lifted to the required height; (b) boulder impacting the gabion cushion layer. [Colour online.]

Fig. 6. Variation of boulder impact force with time for the first and sixth impacts at 20 kJ. [Colour online.]
It is noted, however, that the mechanical response of gabions filled with coarse material is highly variable from one test to another (Bertrand et al. 2008; Breugnot et al. 2016). Lambert (2007) reports at least 15% difference in measured peak impact forces on single gabion cells under the same testing condition. Many experiments are often required to obtain an average mechanical response of a gabion. Thus, it is important to place a greater emphasis on observed trends rather than focusing on a single impact test.

At an energy level of 20 kJ, a maximum measured boulder impact force of 112 kN is generated at first impact. This measured impact force is almost five times less than the predicted impact force using the Hertz equation. After the second impact, the boulder impact force exhibits a large incremental increase of 119%. The fourth, fifth, and sixth successive impacts result in incremental increases in maximum boulder impact forces of about 23%, 15%, and 16%, respectively. The increment of maximum boulder impact force did not cease with successive impacts at 20 kJ and indicates that progressive stone rearrangement, stone lateral displacement, and stone crushing mechanisms will likely continue to occur under successive loading.

After the first impact at 40 kJ, a maximum boulder impact force of 139 kN is measured. The predicted boulder impact force using the Hertz equation is about 5.5 times greater than the measured load. After the second, third, and fourth impacts, incremental increases in maximum boulder impact forces of 124%, 10%, and 22% are measured. Between the fourth and sixth impacts, results show a decrease in maximum boulder impact force of about 15%. Again, the overall trend indicates that the rock fragments in the basket have further potential to reach a denser arrangement.

For successive impacts carried out at an energy level of 70 kJ, a maximum impact load of 289 kN is measured after the first impact. The boulder impact force predicted using the Hertz equation is about four times larger than the measured force after the first impact. The second and third impacts result in incremental changes in maximum boulder impact forces of about 60% and 28%, respectively. After the third impact, a slight decrease in impact force is measured. The maximum change in impact force between the third and sixth impacts is less than 8%. Furthermore, the maximum boulder impact force increases by a factor of two between the first and sixth impacts.

The increase in boulder impact force with successive impacts under the same kinetic energy before impact can be explained using eq. (4), where the boulder radius and impact energy remain constant for each of the six successive impacts at the same initial energy level. With increasing successive impacts, the gabion cushion layer densifies and the elastic modulus increases. Assuming that the elastic model remains applicable despite large plastic deformation, the increase in impact force is attributed to an increasing elastic modulus of the gabion cushion layer under successive impacts. The measured maximum impact force between the first and final impacts at an energy level of 70 kJ increases by a factor of four. However, it is acknowledged that the transfer of force through a coarse granular medium only involves a limited number of force chains. This will inevitably lead to some degree of variability in measurements. After three successive impacts, the rock fragment arrangement densified and was almost stable. Hence, only a slight change of impact force is observed during the last three impacts.

Figure 7b shows a comparison of the force reduction, in percentage, with successive impacts at energy levels of 20, 40, and 70 kJ. The percentage was calculated using the following equation:

\[ P_r = 1 - \frac{F_g}{F_b} \]

where \( P_r \) is the force-reduction percentage, \( F_g \) is the measured maximum force with gabions, and \( F_b \) is the calculated force for a wall without cushioning. The boulder force is calculated using eq. (5) and the load-reduction factor is assumed as 0.1. For the first impact, the force-reduction percentages were 86%, 89%, and 83% for energy levels of 20, 40, and 70 kJ, respectively. After the third impact, the force reduction percentages decrease to 70%, 72%, and 65% for energy levels of 20, 40, and 70 kJ, respectively. All three curves show similar trends after the first three impacts. A decrement of force-reduction percentage of about 19% and 11% is ob-
served between the third impact and fourth impacts under energy levels of 20 and 40 kJ, respectively.

The force-reduction percentage of the single-layer gabion cushion layer in this study is further compared with a single impact on a 2 m thick sandwich wall with two layers at 210 kJ (Lambert et al. 2014). The sandwich wall comprises a 1 m thick gabion layer and a 1 m thick sand–tire mixture. Although Lambert et al. (2014) adopted a higher energy level in their tests, the force-reduction percentage, specifically 78%, does not differ substantially from the results of this study. A force-reduction percentage of 71% was measured in a similar pendulum impact test conducted on a 1 m thick cushion layer under an impact energy of 2 kJ (Heymann et al. 2010).

Figure 7c shows a comparison of the deduced load-reduction factors ($K_c$) for successive impacts at 20, 40, and 70 kJ. The dashed horizontal line shows a load-reduction factor of 0.1 as recommended for boulder impact on a bare rigid barrier (Kwan 2012). For the first impact, the back-calculated $K_c$ values are 0.01 for both energy levels of 20 and 40 kJ, and 0.02 for an energy level of 70 kJ. The incremental change in $K_c$ values exhibits a similar trend as the maximum boulder impact force (Fig. 7a). This implies that the $K_c$ factor should not be considered as a constant for successive impacts. The back-calculated $K_c$ values for the sixth successive impacts at energy levels of 20, 40, and 70 kJ are 0.05, 0.04, and 0.04, respectively. These back-calculated $K_c$ values are considerably less than the current suggested value of 0.1 for bare rigid barriers (Kwan 2012).

**Load transmitted to rigid barrier**

For the first impact, the maximum transmitted force is 6.4 kN and the impact duration is 0.05 s. The magnitude of the maximum transmitted force increases while the impact duration decreases from the first to the fourth impacts. For the fourth impact, the maximum transmitted force is 10.5 kN and the impact duration reduces by a factor of two compared to the first impact duration. This is because the deformation of the gabion cushions increases with successive impacts. As the cushion layer deforms under successive loading, a nonperpendicular impact orientation with the rigid barrier influences the transmitted forces. Hence, the maximum transmitted forces appear to decrease at the fifth and sixth impacts. It is acknowledged that abnormal measurements are likely caused by the coarse granular nature and limited force chains in gabions. Bugnon et al. (2012) report that the size of the load cell can influence the measurements attained.

**Figure 8** shows the transmitted forces measured using the load cells installed on the rigid barrier for an impact energy of 20 kJ. For the first impact, the maximum transmitted force is 6.4 kN and the impact duration is 0.05 s. The magnitude of the maximum transmitted force increases while the impact duration decreases from the first to the fourth impacts. For the fourth impact, the maximum transmitted force is 10.5 kN and the impact duration reduces by a factor of two compared to the first impact duration. This is because the deformation of the gabion cushions increases with successive impacts. As the cushion layer deforms under successive loading, a nonperpendicular impact orientation with the rigid barrier influences the transmitted forces. Hence, the maximum transmitted forces appear to decrease at the fifth and sixth impacts. It is acknowledged that abnormal measurements are likely caused by the coarse granular nature and limited force chains in gabions. Bugnon et al. (2012) report that the size of the load cell can influence the measurements attained. The load cell surface used in this study was 150 mm in length and 150 mm in width. However, the size of rock fragments ranges from 160 to 300 mm. A larger load cell surface may therefore influence the results of the load measurements.

**Figure 9** shows the maximum measured force along the vertical centreline of the rigid barrier at 20 kJ, specifically load cell number 1, 3, 4, and 5 (Fig. 3). The vertical depth is normalized by the boulder radius (580 mm). Load cell No. 2 incurred damage, hence measurements were not available. For the first impact, the maximum load is captured at the mid-height of the barrier, normalized vertical depth of 2.6. The maximum transmitted force from the first impact is about 6.4 kN. The uppermost load cell, at a normalized vertical depth of 4.3, did not register any load. However, at an equal distance downwards, specifically a normalized depth of about 0.9, a force of about 1.2 kN is measured. The force transfer appears to be more effective downwards with a higher confining stress leading to closer rock fragment contacts. The higher stress is a surrogate of overburden from gabion baskets resting above. Similar effects also were observed by Haza-Rozier et al. (2010). The higher force transmissivity near the bottom will need to be considered in the design of gabion cushion layers in practice.

After the second, third, fourth, and fifth impacts, the location of the maximum vertical transmitted force remains at the same vertical depth, specifically at the mid-height of the barrier. However, after the sixth impact, the point of maximum loading appears to shift upwards to a normalized depth of 3.3. The change in vertical position of maximum loading is because of the changing contact point between the concrete boulder and cushion layer. As a crater forms in the deformed cushion layer, the contact point between the concrete boulder and cushion layer no longer remains perpendicular. Based on the boulder kinematics captured from the high
speed camera, the maximum deviation angle from the perpendicular orientation is less than 5°.

The incremental increase in measured maximum force from the first to third impacts are 7%, 11%, and 28%, respectively. The increasing load transfer to the rigid barrier with successive impacts is attributed to the rearrangement of the rock fragments. Rock fragment rearrangement leads to a denser and stiffer gabion cushion layer that cannot dissipate impact energy as efficiently. Furthermore, the distance between front face and rigid barrier face decreases with successive impacts due to the deformation. These factors lead to a greater maximum transmitted force. After the fifth impact, results show the maximum force at a normalized vertical depth of 3.3 decreases by about 46%. Furthermore, the upward shift in the maximum force is likely attributed to a non-perpendicular impact orientation resulting from deformation of the cushion layer. After six impacts at 20 kJ, it is clear that without consideration of successive impacts, the transmitted impact force can be underestimated by at least 40%.

Figure 10 shows the maximum transmitted force distribution along the horizontal direction using load cells numbered 3, 6, 7, and 8 (Fig. 3). The horizontal direction is normalized by the boulder radius. Upon the first impact, the maximum transmitted force (6.4 kN) develops at the centre of the wall with the load attenuating with increasing horizontal distance. The location of maximum loading shifts slightly along the horizontal direction from the centre of the barrier to a normalized horizontal distance of 0.7. The change in position of maximum loading may be attributed to rock fragment rearrangement. Results reveal an influence zone of about 2.1 times the boulder radius for six successive impacts. A small load of up to 1.15 kN was registered at a normalized horizontal distance of 1.4. The load spreading is confined by the boundary conditions of the setup because the displacement of the
 gabion is constrained by the peripheral steel frame, rigid barrier, and wire mesh. Given a lack of load measurements between normalized distances of 0.7 and 1.4, and between 1.4 and 2.1, a precise load-spread angle cannot be established. However, if one assumes that the load-cell measurement at a normalized distance of 1.4 is sufficient to capture the maximum load spreading extent in this study, then the diffusion angle can be taken as the radius of the contact surface. The calculated diffusion angle for the given boundary condition is 17°. It appears that gabions cannot effectively spread the impact load. However, it is important to note that the cushion layer is bound by a peripheral frame, the rigid barrier, and the steel mesh. These boundary conditions are expected to restrict load spreading.

The force transfer appears to be more effective downwards because of the higher confining stress and more effective rock fragment contacts. This implies that a gabion cushion layer should be thicker near the bottom if a similar degree of load reduction is desired.

Deformation of gabion cushion layer under successive impacts

Figures 11a, 11b, and 11c show a comparison of the normalized penetration depth along the normalized horizontal distance for successive impacts at energy levels of 20, 40, and 70 kJ, respectively. The penetration depth is normalized by the 1 m thickness of the gabion cushion layer. The horizontal length of the gabion cushion layer is normalized by the boulder radius (580 mm). The horizontal dashed line shows the normalized maximum elastic deformation calculated by eq. (3). For impact energy levels of 20, 40, and 70 kJ, the predicted elastic deformations are 0.10 (100 mm), 0.13 (130 mm), and 0.16 (160 mm), respectively.

A maximum normalized penetration depth of 0.29, equivalent to half of the boulder radius, is observed after the first impact at 20 kJ (Fig. 11a). The gabion deformation spreads to a normalized horizontal distance of up to 1.5 times the boulder radius from the centre of the rigid barrier. The second impact led to an additional maximum penetration depth of about 20%. The third and fourth impacts led to incremental increases in maximum penetration depth by 8% and 10%, respectively. However, there is no clear incremental increase in penetration between the third and fourth impacts. The fifth impact reveals an incremental increase in maximum penetration depth by 11% compared to the fourth impact. The sixth impact exhibits an incremental increase of less than 5% in normalized maximum penetration depth compared to the fifth impact. By comparing the estimated elastic deformation, it is clear that plastic deformation of the cushion layer is substantial and cannot be overlooked. The predicted maximum deformation is about three times smaller than the measured penetration depth after the first impact.

Figures 12a and 12b show the deformation of gabion cushion layer after the first and sixth impact under 20 kJ, respectively. At the first impact, only a slight rearrangement of rock fragments occurred. However, after the sixth impact, a large surface deformation, significant degree of rock fragments crushing, and damage to the wire meshes were observed. This implies that during the sixth impact, energy is likely to also be dissipated by particle crushing rather than solely rock fragment rearrangement. It is noted that fragmentation also occurred for 40 and 70 kJ impacts.

Results show a maximum normalized penetration depth of 0.36 after the first impact at an energy level of 40 kJ (Fig. 11b). The second, third, fourth, fifth, and sixth impacts lead to additional increases in maximum normalized penetration depths by 13%, 13%, 8%, 3%, and 6%, respectively. For an energy level of 40 kJ, it is also clear that the measured penetration depth at the first impact is about three times greater than the predicted elastic maximum deformation. Successive impacts at 70 kJ (Fig. 11c) result in a maximum normalized penetration depth of about 0.41 after the first impact, the second and third impacts result in incremental increases in maximum penetration depth of about 13% and 17%, respectively. The fourth, fifth, and sixth impacts do not exhibit substantial incremental change in maximum penetration depth. The measured maximum penetration depth after the first impact for an energy level of 70 kJ is more than 2.5 times larger compared to that estimated using the Hertz equation.

A comparison of the estimated elastic deformation and measured maximum penetration clearly shows that the limitation of Hertz contact theory lies in the fact that it does not capture plastic deformation. After the first impact, the maximum penetration is at least twice the elastic deformation for energy levels of 20, 40, and 70 kJ. It can be observed that at impact energy levels of 20, 40,
and 70 kJ that the maximum penetration depth increases with successive impacts, but at a decreasing rate. This implies that plastic deformation decreases with successive impacts as the gabion rock fragments reached a denser configuration and the boulder impact force (Fig. 6a) will eventually tend towards the elastic solution.

Figure 13 shows the bulk densities of gabion cells in the centre of cushion layer under successive impact for energy levels of 20, 40, and 70 kJ. The bulk density is calculated using the following equations:

\[ V = \pi \delta^3 \left( R - \frac{\delta}{3} \right) \]  

where \( \rho = m/V \) is the bulk density of the gabion cell in the centre (in kg/m\(^3\)), \( V \) is the volume of gabion cell (in m\(^3\)), and \( \delta \) is the penetration depth (in m). The deformed gabions under successive impacts characterize the volume of the spherical cap. To approximate the change in density of the gabion cushion layer, the gabion cells are assumed to be a homogenous material and the lateral deformation of the cells is not considered. Caution should be taken when adopting the calculated values for engineering purposes.

The dashed horizontal line represents the initial measured bulk density of 1560 kg/m\(^3\). At an energy level of 20 kJ, a 10% increase in bulk density was estimated, specifically 1718 kg/m\(^3\). The incremental percentage increases were 6%, 3%, 1%, 5%, and 3% after the second, third, fourth, fifth, and sixth impacts, respectively. An increasing trend is observed, specifically about 5% change in bulk density, which implies that the gabion has potential for further rock fragment rearrangement and densification at an energy level of 20 kJ. At an energy level of 40 kJ, a similar progressive increase in bulk density is observed as an energy level of 20 kJ. After the third impact, about 6% change in bulk density is estimated at an energy level of 40 kJ. Measurements show a 30% increment at an energy level of 70 kJ after the first impact. Furthermore, incremental changes of 7% and 13% are exhibited after the second and third impacts. Between the third and sixth impacts, less than 2% change was observed. This implies that at a higher energy level, i.e., 70 kJ, the gabion cushion layer exhibits a denser rock fragment arrangement.

Figure 12. Deformation of gabion cushion layer in the 20 kJ test: (a) first impact; (b) sixth impact. [Colour online.]

Figure 13. Change in bulk density of the central gabion cell with successive impacts. [Colour online.]

The minimum thickness of the cushioning materials is recommended as follows (ASTRA 2008):

\[ e \geq \frac{1}{2} \delta \]

where \( e \) is the required thickness of the cushioning material (in m); and \( \delta_{\text{max}} \) is the maximum grain diameter of the cushioning material (in m). The thickness of the first and second impacts are sufficient in accordance to these design recommendations. However, after the fifth and sixth impacts at 40 kJ, the recommended thickness guidelines are not fulfilled. Furthermore, under an energy level of 70 kJ, the penetrations of the third, fourth, fifth, and sixth impacts exceed the recommended cushion layer thickness requirements. A comparison of the test results from this study with cushion layer thickness guidelines show that it is important for practitioners to consider the deformation resulting from successive impacts, instead of only considering just a single impact.
scenario. Without considering successive impacts, the deformation of the cushion layer can be underestimated by at least 13%.

Translational kinetic energy rate

Figure 14 shows the variation of translational energy percentage for the first and sixth impacts at energies of 20, 40, and 70 kJ. The translational kinetic energy, as a percentage, is represented as follows:

\[
P_d = \frac{I_r}{I_t} \times 100\%
\]

where \(P_d\) is the translational kinetic energy percentage, \(I_r\) is the translational kinetic energy calculated using \(0.5mv^2\), and \(I_t\) is the boulder kinetic energy before impact. The measured acceleration is used to calculate the boulder velocity using successive time integration. Given the initial velocities of 4.5 m/s (20 kJ) and 7.8 m/s (70 kJ), the variation of boulder velocity with time is deduced.

The variable \(P_d\) provides an indication on the rate of energy transferred and stored in the cushion layer. The energy stored in the cushion layer is a combination of kinetic and strain energy. The stored energy changes with time. Energy dissipation occurs in the gabion in the form of crushing and shearing, and is strongly dependent on the stress and deformation in the stone matrix. Furthermore, part of the energy can transfer to the reinforced rigid barrier as an elastic compression wave.

For the first impact, the rates of translational kinetic energy at energy levels of 20, 40, and 70 kJ exhibit differences of less than 12%. The difference may be attributed to larger penetration from higher impact energies. Larger penetration will result in greater contact area, which consequently results in more rapid kinetic energy decrease.

For the sixth impact, the impact duration is almost half of that captured for the first impact. Results show differences of less than 10% between the rates of translational kinetic energy under the three different initial energy levels. A comparison of translational kinetic energy shows that the rate is not strongly dependent on the impact energy levels tested, but it is more strongly influenced by the number of successive impacts. It is apparent that the energy levels adopted were too close in magnitude for the first impact to result in significant rock fragment rearrangement in the gabions. A more rapid translational kinetic energy rate is observed for the sixth impact. This is attributed to the larger densification of the rock fragments in the gabion. Moreover, energy dissipation during an impact is attributed to a combination of several mechanisms including particle crushing, shearing between particles (predominately during the first impact), deformation of the wire mesh, and elastic compression. This observation is in line with the large amount of crushed materials after the sixth impact (Fig. 10b).

Conclusions

A series of large-scale pendulum impact tests was carried out to study the effect of successive impacts with increasing energy on gabions shielding a rigid barrier, replicating multiple boulder-entrained debris surges. Results for the energy levels tested in this study reveal the following:
1. The limitation of the commonly adopted Hertz equation in predicting boulder impact on cushioning material lies in its inability to consider plasticity. For a boulder impacting on a gabion cushion layer for the first time, the measured impact forces are only about one-quarter of the theoretical values given by the Hertz equation. Concurrently, the measured maximum penetration depths are at least 2.5 times larger than the elastic maximum deformation predicted from the Hertz impact equation.

2. The load-reduction factor ($K_L$) of 0.1 suggested by Kwan (2012) does not consider the effect of cushion layers. For a 1 m thick gabion cushion layer subjected to six successive impacts at an energy level of up to 70 kJ, the back-calculated $K_L$ was found to be no more than 0.05 for repeated impacts. This indicates a possibility of reducing the design impact load by half when a gabion cushion layer is used.

3. The load-transmission mechanism of a gabion cushion layer under initial successive impact relies on increasing stiffness predominantly through rearrangement of the rock fragments. Following a larger number of successive impacts at a higher energy level, densified gabion relies primarily on rock fragment breakage to dissipate energy. After six successive impacts, the transmitted forces increased by about 40%. The maximum boulder impact force approximately doubled between the first and sixth impacts. The gabion cushion layer changed less than 2% in density after the third impact at 70 kJ.

4. The transfer of impact force through the gabion layer appears to be more effective near the bottom due to the higher confining stress and closer rock fragment contacts, which is a surrogate of overburden from gabion baskets resting above. This implies that a gabion cushion layer should be thicker near the bottom of a rigid barrier if a similar degree of load reduction is desired.

5. When considering the design cushion layer thickness in accordance with Swiss guidelines (ASTRA 2008), the gabion thickness can be underestimated by at least 13% at an energy level of 70 kJ if successive impacts are concerned. Translational kinetic energy rate of a gabion cushion layer is more strongly influenced by the number of successive impacts rather than the impact energy (up to 70 kJ in this study). The impact durations are twice as long for the sixth impact compared to the first impact. This implies that practitioners may need to place greater emphasis on the effects of the multiple-surge-like nature of debris flows and successive impacts in the design of gabion cushion layers if impact at the same location is pertinent to the design.

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