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Title: Effects of particle shape on the cushioning mechanics of rock-filled gabions

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Abstract:

Rock-filled gabions are commonly installed in front of reinforced concrete structures to reduce concentrated impact loads induced by rock fall and boulders entrained in debris flows. The cushioning performance of rock-filled gabions is highly variable because of the wide range of rock shapes used to fill the gabion baskets. In this paper, a parametric study was carried out using the Discrete Element Method (DEM) to discern the effects of particle shape on the cushioning performance of rock-filled gabion. Four particle sphericities *S* (ratio of radius of the largest inscribed sphere to the radius of the smallest circumscribed sphere) from 0.5 to 1.0 were adopted to model angular, sub-angular, sub-rounded, and rounded particles. DEM simulations reveal that the boulder penetration depth decreases with particle angularity. For the design of a cushioning layer, a thicker layer should be used if particles are rounded. More importantly, the impact and transmitted forces on a rigid barrier increase with particle angularity. Angular assemblies have more contact points, which enable more stable force chains that can sustain higher loads. The load diffusion angles for rounded particles are up to 20° larger compared to angular particles, suggesting that as particle angularity compromises the load spreading ability of a cushioning layer. In general, rounded rocks should be adopted where possible to reduce transmitted loads and distribute loads more uniformly.

Keywords: rock-filled gabions; particle shape; rockfall; debris flow; rigid barrier; geohazards; discrete element method

Introduction

Debris flow consists of a mixture of poorly-sorted sediments, ranging in size from clay to boulder (Takahashi and Nakagawa 1991; Iverson 1997). The mechanism of particle size segregation enables large boulders to migrate to the front of a flow (Takahashi 2014). These boulders induce high concentrated loads, which may cause significant damage to infrastructure (Zhang 1996; Chen et al. 2014; Valagussa *et al.* 2014; Utili *et al.* 2015; Zhang *et al.* 2018; Hu *et al.* 2019). To arrest these boulders, reinforced concrete barriers are commonly constructed along the predicted flow paths (Shen *et al.* 2018; Lee and Winter 2019). To protect these rigid barriers from damage, rock-filled gabion cushioning layers are commonly installed in front of the rigid barriers.

Large-scale boulder impact tests are commonly used to study the performance of cushioning layers (Lambert 2007; Lambert *et al.* 2009; 2014; Lambert and Bourrier 2013; Lambert *et al.* 2014). Ng *et al.* (2016) modelled a total of six successive boulder impacts at 70 kJ on a rock-filled gabion cushioning layer. They reported that the design boulder impact force on a rock-filled gabion reduces the impact force by a factor of two compared to that of a bare reinforced concrete barrier. More importantly, rock-filled gabion cushioning layers attenuate the impact load by enabling the continuous collapse and formation of force chains among rock fragments. The abovementioned foundation of work sheds light on the importance of force chain strength on the mechanical responses of rock-filled gabions.

Muthuswamy and Tordesillas (2006) and Tordesillas *et al.* (2014) carried out a series of discrete element method simulations to investigate the effects of contact friction and bulk density on the mechanical responses of force chains of granular assemblies. Their findings showed that straighter force chains with higher contact friction can sustain higher loads. Zhang *et al.* (2017) and Su *et al.* (2019a) reported that force chains composed of smaller particle sizes may collapse more easily. However, assemblies with smaller particles have more contact points, which are more effective at spreading load. The aforementioned studies imply that the mechanical responses of granular assemblies are strongly influenced by force chain stability. Granular assemblies become stiffer as force chain load bearing capacity increases.

A multitude of studies (Unland and AL-Khasawneh 2009; Ueda *et al.* 2013; Zhou *et al.* 2013; 2017; Falagush *et al.* 2015; Fu *et al.* 2017; Chang *et al.* 2018; Lu *et al.* 2019) have reported that idealising an assembly of angular particles as spheres will give an incorrect mechanical response. The mechanical responses of particle assembly are highly influenced by the various particle shapes (Fig. 1). A simple method used to model particle angularity is by estimating the coefficient of rolling friction based on particle eccentricity (Wensrich and Katterfeld 2012). However, a significant difference in the angle of repose is observed between the idealised spherical particles with prescribed rolling friction and that of real angular particles. Irregular shapes encourage particle rotation as well as resisting it, while prescribed rolling friction only provides rotational resistance. Wang and Song (2019) simulated triaxial compression tests on rockfill materials by using DEM. Their results showed that the particle shape strongly influences the mechanical response of a granular assembly. The peak and residual strength of a granular assembly increases with the aspect ratio of a particle. The effects of particle shape on the mechanical response of granular materials was also reported by other researchers (Jensen *et al.* 2001; Shin and Santamarina 2013; Altuhafi *et al.* 2016; Suh *et al.* 2017). In the aforementioned studies, it was concluded that the friction angle increases with particle angularity because angular particles restrict movement. These findings indicate that particle angularity strongly affects the mechanical response of a granular assembly. Despite the wide body of existing work, the effects of particle shape on the dynamic loading behaviour of cushioning materials has not yet been elucidated.

In this paper, the effects of particle shape on the cushioning mechanism of granular materials will be studied by carrying out a parametric study using the DEM. The influences of particle shape on the attenuation of the boulder impact force and the reduction of the transmitted loads are examined. Findings will be used to provide a basis to potentially optimise the design and performance of rock-filled gabion cushioning layers in the field.

Methodology

In this study, a numerical software called Particle Flow Code PFC^{3D} was used to investigate the mechanical response of rock-filled gabions subjected to boulder impact. The contact mechanics between particles is governed by the Hertz contact model, which is a nonlinear formulation based on the theory of Mindlin (1953). For each timestep, the normal contact force is the product of incremental overlap and the normal contact stiffness for each particle. The equations used to determine the normal and shear contact forces are given as follows (Itasca 1999):

$$dF_n = \frac{3}{2} K_n (u_n)^{0.5} du_n \quad (1)$$

The shear contact force for each particle is the product of incremental overlap and the shear contact stiffness. The shear contact force is governed by Coulomb's law of friction. The equations used to determine the incremental normal and shear contact forces are as follows (Itasca 1999):

$$dF_t = K_t du_t \xi (F_n tan\phi - F_t) \quad (2)$$

where ϕ is the internal friction angle and ξ is the Heaviside function where $\xi(x) = 1$ when $x > 0$ and $\xi(x) = 0$ when $x \leq 0$, K_n and K_t are the normal and shear contact stiffnesses, which are calculated using the following equations:

$$K_\mathrm{n} = \frac{2\sqrt{2R_\mathrm{e}}G}{3(1-v)} \quad (3)$$

$$K_\mathrm{t} = 2\frac{(3G^2(1-v)R_\mathrm{e})^{1/3}}{2-v} {F_n}^{1/3} \quad (4)$$

where R_e is the effective radius, G is the shear modulus, and υ is the Poisson ratio of a grain.

Shape factor

Three characteristics, specifically sphericity, angularity and roughness are investigated (Althhafi *et al.* 2016). In this study, particle sphericity is defined as the ratio of maximum radius of the largest inscribed sphere (R_{max}) to the radius of the smallest circumscribed sphere (R_{min}). Sphericity represents the similarity between particle length, width and height. Sphericity increases as the shape of a particle more closely resembles that of a sphere. A sphericity of unity means the particle is perfectly spherical. By contrast, a sphericity close to zero means the shape of the particle is needle-like.

Field test setup

Large-scale pendulum impact test results reported by Ng *et al.* (2016) on the dynamic response of rock-filled gabions is used to compare with the computed results in this study. Fig. 2 shows a schematic side view of field test setup, which consists of a concrete boulder, a steel frame and rock-filled gabions in front of a rigid reinforced concrete barrier. The concrete boulder has a mass of 2000 kg and is suspended by two strand steel cables. A mechanical latch is installed to release the concrete boulder. A steel frame with a height of 6 m is constructed to suspend the concrete boulder, which swings and impacts the rock-filled gabion cushioning layer. The cushioning layer is constructed using nine separate cubic gabion baskets with a nominal length of 1 m. The size of the rock fragments ranges from 160 mm to 300 mm in diameter (GEO 1993). Steel bolts are installed to prevent gabion cells from toppling during impact process.

Discrete element modelling

The main purpose of numerical model is to understand the dynamic interaction between the concrete boulder and the rock fragments inside the gabion basket. Therefore, the steel frame and strand cables used to suspend the concrete boulder were not modelled. Fig. 3 shows an oblique view of the numerical model, which includes a spherical boulder and a cell to retain the rock fragments. For each simulation, a sphere with a mass of 2000 kg is given an initial velocity of 8.4 m/s to simulate the concrete boulder with an impact energy of 70 kJ (Ng *et al.* 2016). To simplify the model and save computational time, the constraint provided by the gabion baskets was not simulated. A box with a length of 3 m, height of 3 m, and a width of 1 m was generated to simulate the gabion baskets containing the rock fragments. A total of 776 discrete elements were generated in the box with a target initial porosity of 0.40. The discrete elements were allowed to settle under the influence of gravity to simulate the rocks inside the gabion baskets. The discrete elements were allowed to reach equilibrium, which is defined as the ratio of unbalanced to contact forces of less than $1e^{-5}$. The particle size used in the numerical model was based on that recommended in design guidelines, specifically from 160 mm to 300 mm (GEO 1993). A friction angle of 30° without damping was adopted (Bourrier *et al.* 2008; Zhang *et al.* 2017). This means that energy can only be dissipated by frictional contacts among particles. To monitor the horizontal and vertical load distributions on a rigid barrier, eight measurement regions (2250 m^2 each) were defined on the backside wall (Fig. 4) where the load cells were installed in the field tests reported by Ng *et al.* (2016).

To model the effects of particle shape on the impact dynamics, the clump option was used. A clump is a rigid body composed of series rigid spheres bonded together. The calculation of contacts between each sphere in a clump is ignored in each computational cycle. In this study, a total of 776 spherical particles were firstly generated in the box and then the particles were replaced with clumps with same volume. It is reported by Shin and Santamarina (2013) that the measured sphericities for natural and crushed sand range from 0.5 to 0.9. To compare various particle sphericities, four clumps with particle sphericities of 0.5, 0.6, 0.8 and 1.0, were investigated. A summary of the simulation plan is given in Table 2.

Comparison of boulder impact force between computed and measured results

Fig. 5 shows a comparison between the measured and computed boulder impact forces. The shear modulus used to describe the rocks are adjusted to match the maximum boulder impact force. The difference between the measured and computed maximum boulder impact force is less than 5%, indicating that the input parameters adopted are suitable for predicting the maximum boulder impact force for assemblies with different shapes. Furthermore, large fluctuations were observed in both the measured and computed results. These fluctuations are characteristic of the collapse and formation of force chains as particles rearrange during impact.

The area under the impact force curve is the momentum. The computed momentum is about 30% larger compared to that measured momentum. One possible feature that may contribute to differences between the computed and measured momentum is particle crushing. In the field tests, crushing was observed after each test. However, crushing is not captured in the idealised numerical simulations to study the fundamental grain-scale effects of particle shape. Moreover, without crushing, less energy is absorbed by the granular assembly and more energy is reflected back to the boulder, thereby increasing the rebound velocity of the boulder.

Effects of particle shape

Time histories of boulder penetration depth and velocity

A parametric study was carried out to investigate the effects of particle shape on the cushioning mechanisms of rock-filled gabions. Fig. 6 shows the time histories of the computed boulder displacement (*D*) and boulder velocity (*v*) for angular (*S*=0.5) and rounded particles (*S*=1.0). The initial distance between boulder and particle assembly is 0.24 m. Therefore, the boulder has a displacement of 0.24 m with velocity of 8.4 m/s and impact occurs at 0.03 s, afterwards the boulder decelerates. The boulder displacement reach maximum of 0.51 m and 0.64 m for angular particles and rounded particle, respectively. By subtracting the initial distance of 0.24 m, the maximum calculated boulder penetration depths are 0.27 m and 0.40 m for the angular and rounded particles, respectively. The maximum boulder penetration depth for rounded particles is 1.5 times larger compared to that of angular particles. A larger penetration depth requires more particle rearrangement under the same impact energy. This coincides with that reported by Shin and Santamarina (2013) where angularity restricts particle movement, thereby increasing the shear resistance of a granular assembly. According to international design guidelines (ASTRA 2008), the recommended cushioning layer thickness should be at least the two times the maximum penetration depth. Based on the parametric study on shape effects, the cushioning layer thickness for rounded particles should be designed to be larger compared to that for angular particles. A thickness of 1-m is appropriate for both the rounded and angular particles simulated in this study.

Maximum boulder impact force

Fig. 7 shows a comparison of the time histories of the computed boulder impact force among the four particle shapes simulated, specifically angular (*S*=0.5), sub-angular (*S*=0.6), sub-rounded (*S*=0.8) and rounded (*S*=1.0). This maximum boulder impact force increases with particle angularity. The maximum boulder impact force of 451 kN for angular particles (*S*=0.5) is about 1.6 times larger compared to that of rounded particles. This means that the maximum boulder impact force increases with particles angularity. This is because angularity restricts particle rotations during impact, thereby enabling the force chains to sustain higher loads. Likewise, Althhafi *et al.* (2016) reported that by increasing particle angularity, grain rotations are restricted, which give rise to stiffer granular assemblies.

Figs. 8a and 8b show side views of the force chain distributions when the maximum impact force occurs for angular and rounded particles, respectively. The thickness of the force chains is scaled. The force chains at the bottom of cushioning layer, under higher confining stress, are denser and thicker compared to that at the top because of the influence of gravity. Similarly, Ng *et al.* (2016) and Su *et al.* (2019b) also reported that higher loads are transmitted downwards due to the overburden provided by the overlying gabion cells. Furthermore, the load diffusion angles, which provide an indication of the load spreading capability, are 30° and 50° for angular and rounded particles, respectively. Evidently, the effect of particle shape strongly influences the load diffusion angle, which decreases with the particle angularity.

Fig. 9 shows the average contact force carried by the force chains when the cushioning layer is impacted. The maximum average contact force for angular particles is about 1.8 times larger compared to that for rounded particles, corroborating that more loads can be supported by the force chains comprising particles with increasing angularity. Furthermore, the loading and unloading slopes, representing the average contact force, for angular particles are much steeper compared to that of rounded particles. This also highlights that angularity enhances the stiffness of an assembly.

The maximum number of force chains for rounded particles is about 1.4 times larger compared to that of angular particles. This means more force chains are required to resist the boulder impact force with rounded particles compared to that with angular particles. Evidently, force chains composed of angular particles are more stable compared to that of rounded particles.

Fig. 10 shows a comparison of the average coordination number (*Z*) between angular and rounded particles. The average coordination number is calculated as follows (Thornton 2000):

$$Z = \frac{2C - N_1}{N - N_0 - N_1} \quad (6)$$

where C is the number of contacts among particles, N is the number of particles, N_0 and N_1 represent the number of particles with no contacts and one contact, respectively. The average coordination number provides the average number of contacts that contribute to the mechanical stability of a granular assembly.

The rounded particles exhibit a relatively constant average coordination number of five during the impact process. However, the average coordination number for angular particles reaches a maximum of 31, which is six times larger compared to that of the rounded particles. The maximum coordination number for angular particles is about six times larger compared to that of rounded particles. Similar observations were reported by Wang and Song (2019), indicating that more contacts are formed for particles with increasing angularity. More contacts in an assembly enable higher sustained loads in the force chains during impact (Fig. 8). Moreover, this observation is consistent with that reported by Muthuswamy and Tordesillas (2006). By examine the coordination number, it can be seen that rounded particles with less constraints collapse more easily to attenuate the boulder impact force.

Transmitted loads to rigid barrier

Figs. 11 shows the time histories of the total transmitted loads (L) on the backside wall for the four different particle shapes simulated, specifically angular (S=0.5), sub-angular (S=0.6), sub-rounded (S=0.8) and rounded (S=1.0). The maximum total transmitted load (L) for angular particles occurs at 0.045 s, which is 0.010 s before rounded particles, suggesting that the time it takes to transmits load decrease with particle angularity. The same trend is supported by Figs. 8a and 8b, which also shows angular particles with smaller load diffusion angles. The smaller angles enable a shorter load transmission distance. Moreover, the maximum total transmitted load for angular particles is 1.9 times larger compared to that of rounded particles.

Fig. 12 shows a comparison of the maximum boulder impact force and the total transmitted load among particles with different shapes. To minimise the effects of the spatial variation of the initial packing arrangement of the particles, a total of 10 simulations were repeated at different impact locations of the cushioning layer for each particle shape. The spacing between each impact location was 50 mm. The dashed horizontal reference line indicates the estimated boulder impact force without consideration of cushion layer by using eq. (5), specifically 1730 kN.

$$F = K_c 4000 v^{1.2} r^2 \quad (5)$$

where F is the boulder impact force (N); K_c of 0.1 is recommended by Kwan (2012) based on the case histories, v is the boulder velocity (m/s) and r is the boulder radius (m).

Compared with the estimated boulder impact force without consideration of cushion layer, it can be found that at least 75% is reduced when considering the cushion effects. Furthermore, both the maximum boulder impact force (F_{max}) and maximum total transmitted load (L_{max}) decreases with increasing particle angularity. The average maximum boulder impact force and maximum total transmitted load for angular particles (S=0.5) are about 1.8 times larger compared to that for rounded particles (S=1.0), respectively. The difference in impact and transmitted loads is because the force chains are most stable for angular particles. Correspondingly, rounded rock fragments should be adopted in the rock-filled gabions in field to promote less stable force chains to enhance energy dissipation.

Figs. 13a and 13b show comparisons of the computed maximum load distributions along vertical and horizontal centrelines of the rigid barrier, respectively. In Fig, 13a, the horizontal axis shows the maximum transmitted load (L_{max}) and vertical axis shows the vertical depth (h / H) along the wall normalised by the barrier height. The transmitted loads are monitored from the backside wall, at heights of h_1 to h_5, specifically 0.13 m, 0.88 m, 1.63 m, 2.13 m and 2.88 m.

Small transmitted loads were observed at the top and bottom of the barrier at normalised heights of 0.04 and 0.96 for all four shapes of particles. The diminishing loads show that the particle shape does not have an obvious effect on transmitted load which is at the edge of backside wall. For an assembly of rounded particles, the maximum transmitted load at the mid-height of wall is two to four times larger compared to that at a normalised height of 0.29 and 0.71, respectively. Furthermore, for sub-angular particles (S=0.6) the maximum transmitted loads at the wall centre are about three and 21 times larger compared to that at a normalised height of 0.29 and 0.71, respectively. It is perhaps not surprising that transmitted loads become more concentrated at the centre of rigid barrier with increasing particle angularity because force chains become more stable (Fig. 9). The load diffusion angle decreases with the increasing particle angularity. Such an effect also contributes to load concentration at the centre of rigid barrier. The purpose of the cushioning materials is to reduce the concentrated loads on the rigid barrier. Therefore, this further supports that rounded particles should be adopted in field to promise the transmitted loads distributed on rigid barrier more uniformly.

Figs. 13b shows the transmitted load distributions along the horizontal centreline of rigid barrier. For rounded particles (S=1.0), the maximum transmitted load at centre of wall is 1.5 times larger compared to that at the normalised horizontal distance of 0.17. This means the transmitted loads decreases with distance from the centre of backside wall. This is because more energy has dissipated over longer transmission distances (Su *et al.* 2019a). Longer force chains consist of a larger number of particles, which collapse more easily (Muthuswamy and Tordesillas 2006). Furthermore, for angular particles (S=0.5), the maximum transmitted load at centre of wall is about 2 and 10 times larger compared to that at the normalised horizontal distance of 0.17 and 0.33, respectively. To reduce the effects of load concentration, rounded rock fragments should be adopted in gabion baskets to ensure a more uniform load distribution.

Conclusions

A parametric study was conducted to investigate effects of particle shape on the cushioning performance of rock-filled gabions. Key findings from this study can be drawn as follows:

a) Boulder penetration depth decreases with particle angularity. Assemblies of angular grains generally have a larger number of grain contacts, which promote more stable force chains, which can sustain higher loads. From the view point of rock-filled gabion cushioning design, perhaps a thicker cushioning layer may be adopted when rounded fragments are used in a gabion basket. A thickness of 1 m for an impact energy of 70 kJ was suitable in this study.

b) The maximum boulder impact force and total transmitted load increases by up to 180% with increasing particle angularity. This observation was directly attributed to more stable force chains. This observation further corroborates that more rounded rock fragments should be used where possible to reduce the load transmission to a structure under protection.

c) Transmitted loads are more uniformly distributed along the cushioning layer as particle angularity decreases. The load diffusion angle of rounded particles is up to 20° larger compared to the angular particles. If a more uniform cushioning effect is desired, rounded particles should be adopted.

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