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Published in:
UK Association for Computational Mechanics (UKACM) Conference 2021 proceedings

DOI:
[10.17028/rd.lboro.14595786.v1](https://doi.org/10.17028/rd.lboro.14595786.v1)

Publication date:
2021

Licence:
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Document Version
Peer reviewed version

[Link to publication in Discovery Research Portal](#)

Citation for published version (APA):
Previtali, M., Ciantia, M. O., Spadea, S., Castellanza, R. P., & Crosta, G. B. (2021). Effect of boulder shape on the response of compound meshes subject to dynamic impacts. In *UK Association for Computational Mechanics (UKACM) Conference 2021 proceedings* Loughborough University.
<https://doi.org/10.17028/rd.lboro.14595786.v1>

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Effect of boulder shape on the response of compound meshes subject to dynamic impacts

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Abstract

Rockfall is a type of natural hazard associated with the detachment of one or several boulders in steep slopes. Passive risk mitigation strategies are based on intercepting these blocks during their movement, using rigid barriers, embankments, and flexible protection systems. In recent years, the advancement of remote sensing techniques based on discrete fracture networks allows the characterisation of the shape and size of these boulders even before their detachment [13]. However, physical and numerical modelling of the impact on flexible protection system typically considers spheres [4] and truncated cubes [3] as boulder shape. In this work, the local, i.e. bullet effect [5] and full-scale effect of the aspect ratio of the block is investigated during its impact with a full-scale barrier model. The barrier is characterised by a compound mesh, formed by interweaved double-twisted hexagons and strand ropes stretched between two fence posts. The mesh geometry is reproduced within the Discrete Element framework, using the remote contact interaction approach and the fast mesh generation technique described in [11].

Keywords: *Boulder shape; Impact simulation, Flexible Protection System, Discrete Element Method*

1. Introduction

Rockfall hazard is caused by the detachment of one or several boulders from a slope and the kinetic energy generation associated with the acceleration of mass due to gravity. Risk mitigation procedures are classified as active, preventing the detachment of the block, and passive, that stop its propagation down the slope. Flexible protection systems are the most widespread passive solutions as they are able to withstand significant kinetic energies. These, unlike rigid structures such as walls, spread the boulder deceleration over a significant portion of time, transforming the kinetic energy into deformation energy, and reducing the peak load. The capacity of these barriers is evaluated in the field in terms of the kinetic energy they can withstand, i.e. “critical energy” [3]. However, this is only valid if the barrier can deform as intended, with specific impact positions, boulder shape and size. Since full-scale experimental tests are expensive and non-standard loading conditions can be difficult to implement [15], the investigation of non-standard loading conditions is typically carried out using numerical simulations. It has been observed that, in practice, there is no single value of critical energy for a barrier but rather a range of critical energies corresponding to different block sizes, with the critical energy increasing with the boulder size [5]. This phenomenon, typically referred to as the *bullet effect*, is caused by the fact that smaller blocks have a smaller contact surface. Therefore, the wires undergo highly localised strains, which cause plasticisation and eventually failure before the deformation propagates to the rest of the mesh. Arguably, the same happens when the mesh deformation is inhibited by improper installation and maintenance [7] and under non-standard impact positions [11,17]. The effect of block shape has been investigated numerically by [6] in terms of the contact surface by using slabs of different sizes, while [16] compared the response of the barrier to oblate and prolate spheroids.

Herein the effect of block shape, expressed in terms of aspect ratio, is investigated numerically using a Discrete Element Method (DEM) model. The barrier geometry is discretised by a number of DEM particles, acting as mass points, connected to each other through remote contact bond interactions [8]

that replicate the known behaviour of the steel wires [1,9].

2. Model description

The barrier model is constituted by two interweaved steel mesh panels (panel size 9.0 x 4.5 m) connected to fence posts (inclined 70 degrees over the horizon) at their edges and two upslope anchor wires at the bottom corners. The mesh panels are constituted by double-twisted (DT) wire hexagons (10 x 6 mm hexagon size, 3 mm wire thickness) and strand rope (SR) squares (250 x 250 mm square side, 10 mm wire thickness). Each segment of the DT mesh wire is discretised using 2 DEM elements, while 5 elements are used for the SR wires, following [9] (Figure 1). Due to the size of the barrier, the quick barrier generation procedure presented in [10] is employed. The SR wires exhibit a pure elastic behaviour [12], while DT interactions employ the plastic hardening model proposed by [14]. This constitutive model is used to extract the internal energy components of the wire: (i) elastic potential energy, (ii) plastic energy (E_{PL}) and (iii) wire-wire frictional sliding energy (E_{WS}). Implementation details are found in [11]. The boulder impacts the centre of the barrier with a velocity of 15 m/s and no spin. The reference boulder geometry is constituted by the truncated cube typically employed for this type of impact tests [3], with a mass of 60 kg and a reference side size of 30 cm. Three boulder shapes, with an aspect ratio of 1.0 (equilateral), 1.25 (slightly prolate), to 2.0 (very prolate), are tested (Figure 1a, b and c, respectively). The boulder size is scaled as such its kinetic energy is constant throughout all the tests.

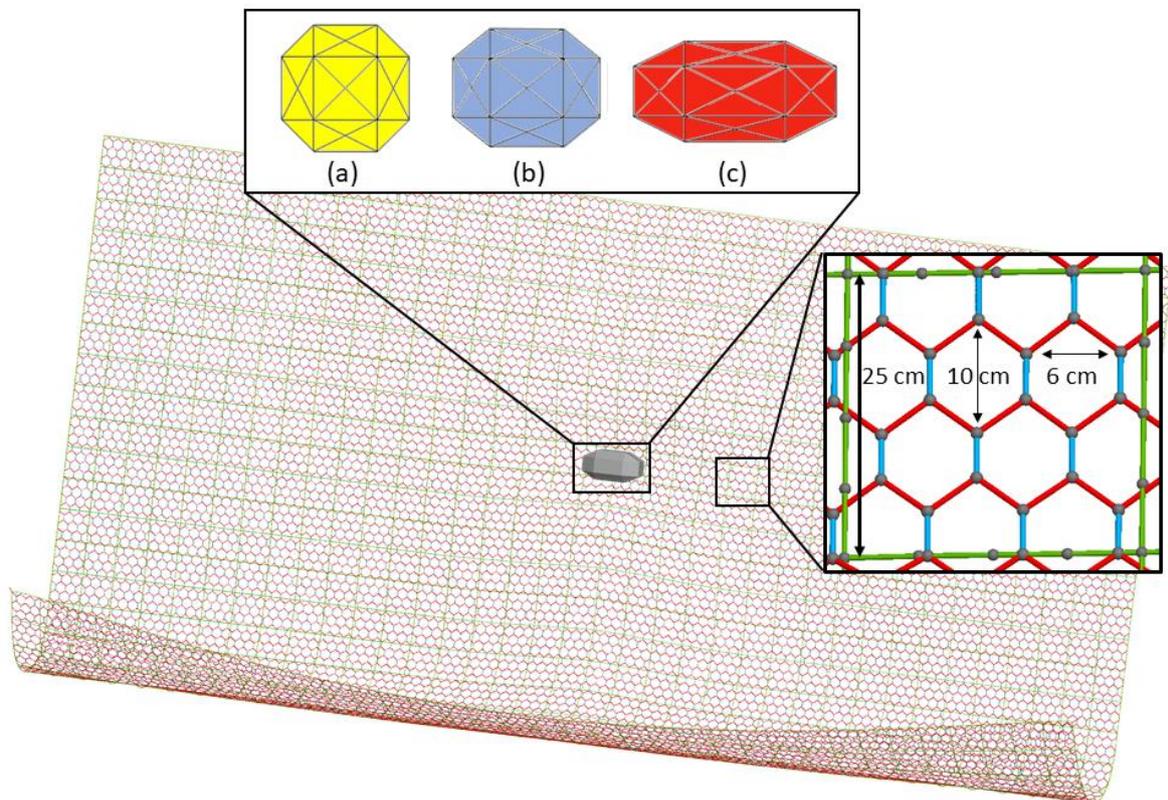


Figure 1: Block impact on the composite mesh.

The boulder orientation is also constant: it is assumed to always impact the mesh with the maximum possible contact surface. This is done because experimental field data shows that the blocks stabilise around their largest moment of inertia [2]. Additionally, this assumption is used to avoid spurious dynamic effects in the results: a prolate boulder impacting normal to its longer axis has roughly the same kinetic energy and contact surface ratio of a smaller boulder with higher velocity, causing the bullet effect.

3. Numerical results

The boulder deceleration profile, obtained from linear velocity derivation in the time domain, is shown in Figure 2. The peak deceleration is close in all the tests, and it does not appear to be directly dependent on the boulder shape, which is in opposition with the results shown in [6]. The block with an aspect ratio 1.25 appears to have a lower initial deceleration, which it is assumed to be since its relative contact area with DT wires is higher than in the reference test. This effect is not present in the test with an aspect ratio 2.0, as multiple SR wires are in contact with the boulder itself.

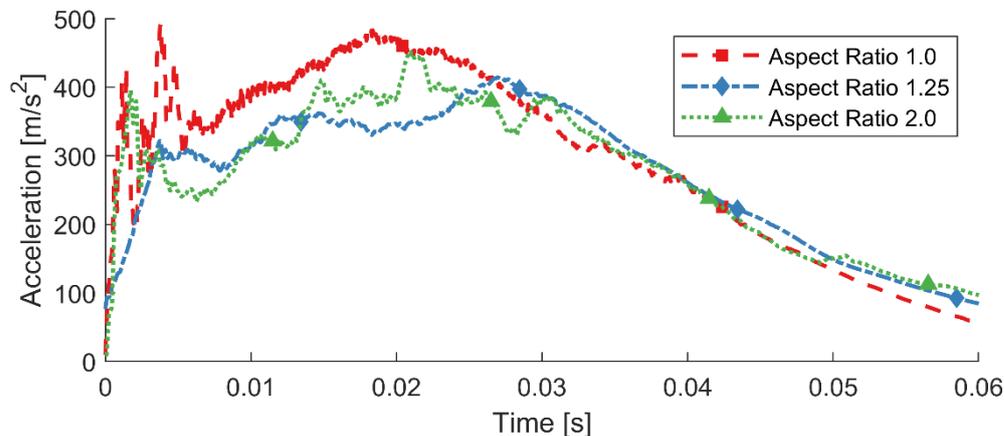


Figure 2: Acceleration profiles in time for the three boulders.

The maximum mesh deformation, obtained from the DEM particles displacement, appears to increase slightly with the aspect ratio (Table 1), which is consistent with that reported by [16], although the tests carried out in said paper do not employ a constant boulder orientation, as done herein. The bending moment (M) and shear force (F_S) applied to the fence posts also increases with the aspect ratio, although it is not a significant change. The energy dissipated by plasticity and wire strain is also maximum in the second test, which is consistent with the assumption of a larger contact area with the double-twisted mesh.

Table 1: Simulation results

Aspect ratio	Fence posts		Mesh			Boulder
	M [$kN \cdot m$]	F_S [kN]	Displacement [m]	E_{PL} [kJ]	E_{WS} [kJ]	Deceleration [m/s^2]
1	117.74	66.09	0.29	2.36	2.10	480
1.25	121.43	66.34	0.31	2.69	2.24	410
2	123.73	67.13	0.33	2.60	2.20	445

4. Conclusions

Herein a shape sensitivity analysis has been carried out using a remote-interaction approach in DEM. The tests were carried out trying to minimise the effect of parameters not directly related to the particle shape, such as boulder mass, kinetic energy, and contact area, which are investigated in previous papers. Despite these changes, some of the results exhibit similar trends to those found in the literature. Subsequent studies should integrate the effect of boulder angularity and symmetry, as well as considering the effect of spin on the boulder-mesh contact.

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