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Technical Note

Experimental testing of low-energy rockfall catch fence meshes

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ABSTRACT

Flexible catch fences are widely used to protect infrastructure like railways, roads and buildings from rockfall damage. The wire meshes are the most critical components for catch fences as they dissipate most of the impact energy. Understanding their mechanical response is crucial for a catch fence design. This paper presents a new method for testing the wire meshes under rock impact. Wire meshes with different lengths can be used and the supporting cables can be readily installed in the tests. It is found that a smaller boulder causes more deformation localisation in the mesh. Longer mesh length makes the fence more flexible. Under the same impact condition, the longer mesh deforms more along the impact direction and shrinks more laterally. Supporting cables can reduce the lateral shrinkage of the mesh effectively. Most of the impact energy is dissipated by stretching of the wires. Wire breakage has not been observed.

1. Introduction

Rockfall catch fences are frequently used to protect infrastructure like railways, roads and buildings from rockfall damage (Muraishi et al., 2005; Bertrand et al., 2008; Buzzi et al., 2013). They are classified based on the energy dissipation capacity. A fence which can dissipate impact energy below 100 kJ is classified as low-energy fence (Buzzi et al., 2013). Low-energy catch fences are more widely used than the high-energy ones in most areas of the world. A typical catch fence system consists of a steel wire mesh, supporting cables, posts and ground anchors. The wire mesh is the most critical component because it dissipates most of the impact energy when a fence is hit by a falling rock (Gentilini et al., 2013; Thoeni et al., 2013). It is produced by twisting continuous pairs of steel wires to form different opening shapes with the most common ones being hexagon and diamond (Bertrand et al., 2008; Buzzi et al., 2013). Fig. 1 shows a single cell of a double-twisted hexagonal wire mesh which will be used in the present study.

Mechanical response of the wire mesh has significant influence on energy dissipation capacity and failure modes of rockfall catch fences (Peila et al., 1998; Gerber, 2001; Peila and Ronco, 2009; Tran et al., 2013). Various approaches have been used to study the wire mesh response under different loading conditions. Some methods, such as uniaxial extension tests and punching tests, have focused on the response of the wire meshes under quasi-static loading conditions (Bertrand et al., 2008). In a uniaxial extension test, a wire mesh panel is stretched along its longitudinal direction until wire breakage occurs. In a punching test, a square wire mesh panel is fully constrained at four sides and punched by a spherical mass at the centre of the panel until perforation is observed. In both tests, the loading rate is low and constant. These tests are useful for the design of other rockfall mitigation structures such as gabion structures and rock netting where quasi-static loading conditions are expected (Bertrand et al., 2008). However, the results of these tests cannot be directly used in designing of rockfall catch fences, because these tests cannot reproduce the real loading scenarios under rock impact.

Impact tests on the wire mesh are thus needed for rockfall catch fence design. At present, impact tests are conducted on either a single wire mesh or full-scale catch fences (e.g. Bertolo et al., 2009; Gottardi and Govoni, 2010; Tran et al., 2013; Bertrand et al., 2012; Gentilini et al., 2013; Mentani et al., 2017). Full-scale tests can offer important insight into the dynamic response of a catch fence system. But they are expensive and time-consuming. Moreover, they are more suitable for evaluating the performance of an entire fence structure which includes the wire mesh, posts, cables and all other components, rather than the mechanical response of wire mesh itself, which is crucial for developing preliminary catch fence

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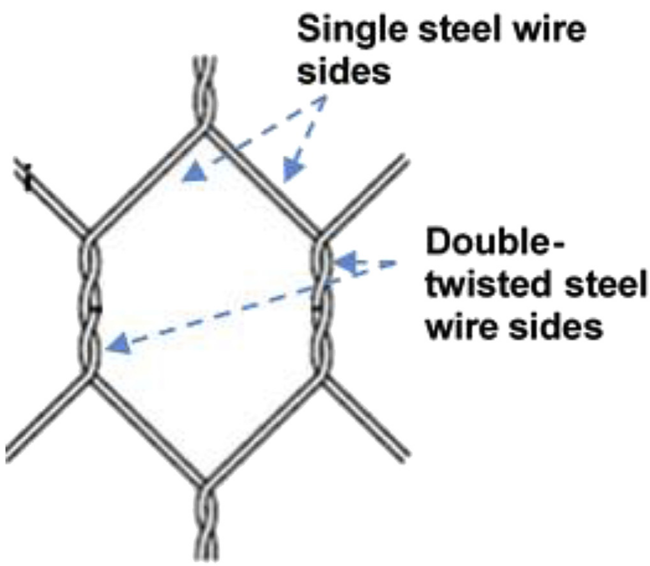

Fig. 1. A single cell of double-twisted hexagonal wire mesh.

designs (Gentilini et al., 2013; Thoeni et al., 2013; Al-Budairi et al., 2017). Mentani et al. (2017) has reported impact tests on a single wire mesh, in which a square mesh is fully constrained at all four ends. Such constraint is different from what is used in a real design wherein the longitudinal sides of the wire mesh are either free or attached to a supporting cable (Al-Budairi et al., 2017). Lateral mesh deflection which needs to be properly considered in catch fence design has not been investigated in these tests.

A method for testing the dynamic response of low-energy rockfall catch fence meshes is presented in this note. Boundary conditions which are close to reality can be applied in these tests. Specifically, a testing rig is designed and fabricated to conduct impact tests on a wire mesh panel. Different rock sizes and impact velocities can be used and the length of the wire mesh panel can be adjusted. Supporting cables can also been installed along the edges of the mesh. The equipment, test procedure and test results are presented. The test results can be used for proposing preliminary design of low-energy rock catch fences in which the impact energy is mainly dissipated by mesh stretching (Al-Budairi et al., 2017).

2. Testing rig

A testing rig is designed for impact tests on wire mesh panels at QTS Group Ltd., as shown in Fig. 2. The rig is 6.5 m long, 3.5 m wide and 5 m high. The rig is fixed on the ground by ten vertical posts and safety mesh is installed around it. Two rectangular supporting beams are laterally attached to the rig to hold the wire mesh panels and supporting cables. The distance between these beams is adjustable to fit various panel lengths. In this study, two panel lengths of 2 m and 4 m are considered.

3. Testing procedure

The wire mesh panels are horizontally attached to the rig with the ends being clamped to the supporting beams and the lateral edges being either free or connected to supporting cables. All the meshes are installed manually and there is initial mesh deflection due to gravity. Fig. 3 shows the method for clamping the ends of the panel to the supporting beams. Each end is clamped by bolts and nuts (13 on each beam) between the upper face of the supporting

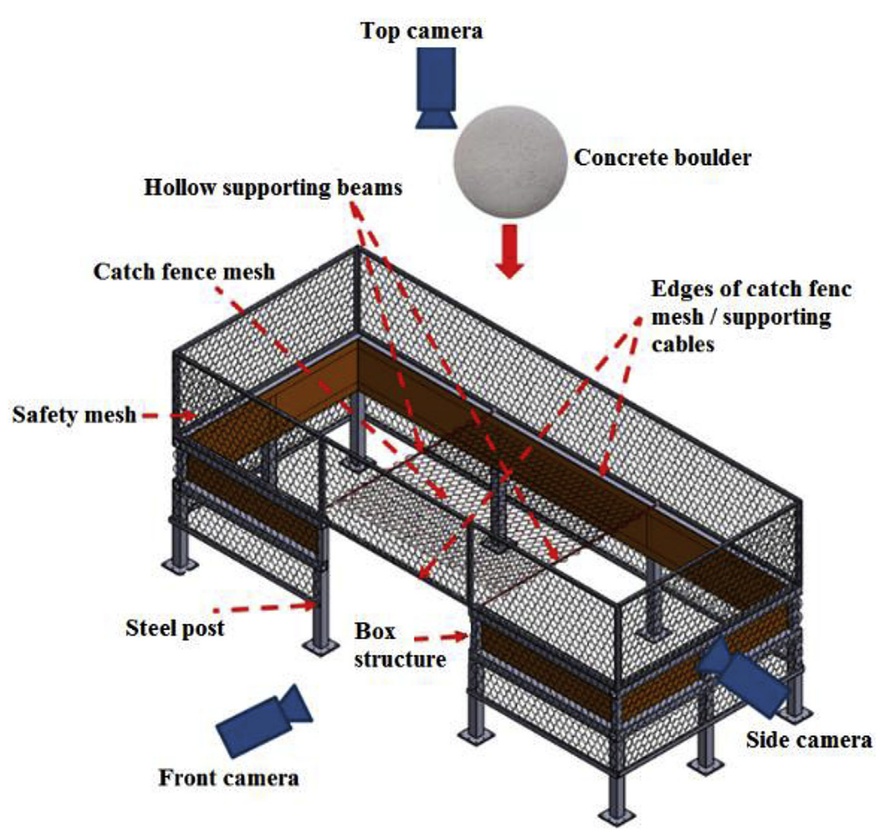

Fig. 2. Illustration of the test rig and testing setup.

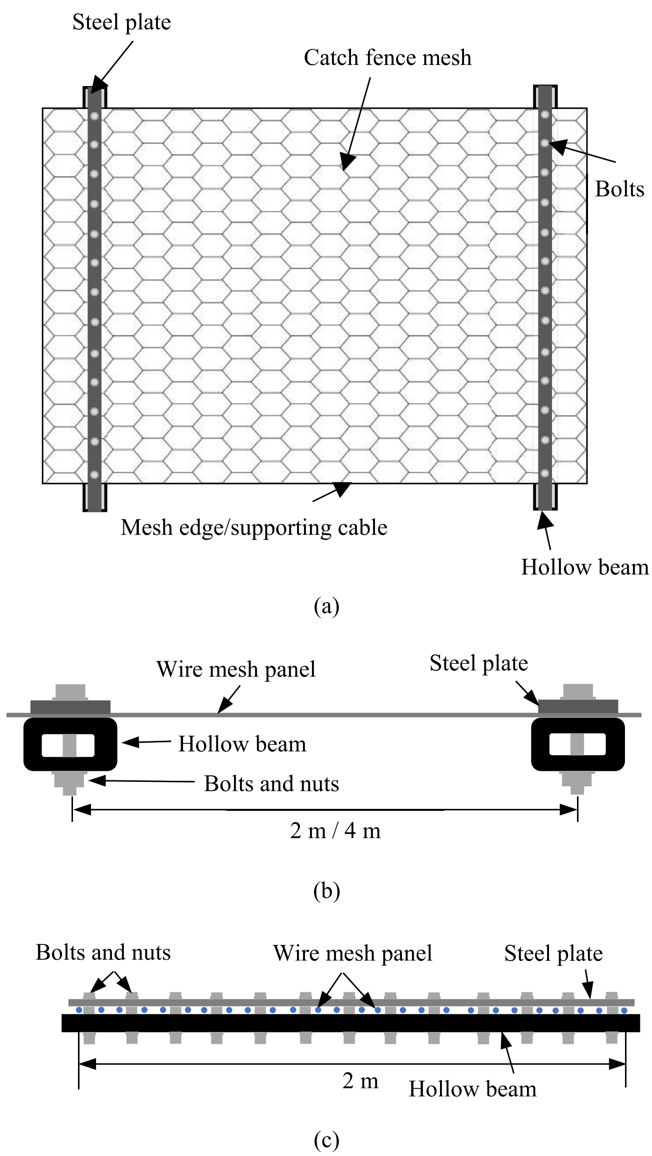

Fig. 3. Illustration of the constraint for wire mesh panels in impact tests without supporting cables: (a) Top view, (b) Front view, and (c) Side view.

beam and a steel panel. When supporting cables are used, the first line of cells on each long side of the wire mesh panel is wrapped around the cable and clamped by steel C-rings. The terminal ends of these cables are then wrapped around the 2nd and 12th bolts and clamped using suitable cable grips (Fig. 4).

In order to capture the wire mesh deflection, three digital cameras are used in the tests (Fig. 2). A high-speed camera (500 frames per second) is used at the front of the testing rig to capture the mesh deformation and the boulder trajectory. The captured videos are used to calculate the boulder velocity and its kinetic energy using a video analysis and modelling tool Tracker (http://physlets.org/tracker/). The location of the boulder is determined using the scale on the rulers attached on the testing rig (Fig. 5). A second camera is attached above the test rig to capture the top view of the wire mesh and a side camera is used to capture the deformation in the supporting beams during the tests.

Four impact tests on double-twisted wire mesh panels are reported in this note (Table 1), where three of these tests are conducted without supporting cables and one with supporting cables. In these tests, two spherical concrete boulders (100 kg and 200 kg) are used. Spherical boulders are used because they are easy to make. The boulders are lifted 2.5 m above the centre of the panels (distance between the bottom of the boulder and wire mesh) which produces an impact velocity of 7 m/s (Fig. 5). The Maccaferri double-twisted hexagonal wire mesh P8/2.7 is used in these tests where the single wire diameter is 2.7 mm and the hexagonal cell dimension is 80 mm × 100 mm. The supporting cables are 10 mm diameter galvanised wire ropes.

4. Test results and discussion

The test results are presented in Figs. 6–12. In these figures, the time $t = 0$ s corresponds to the time when the boulder first hits the mesh (Fig. 6) and the negative value of vertical position indicates that the boulder is beneath the initial mesh elevation. The kinetic energy is calculated using the vertical velocity of boulders where the negative velocity value corresponds to downward movement of the boulders.

Fig. 6 shows the effect of boulder size on dynamic response of the wire mesh. For Tests 1 and 2, the impact energy is different because of different boulder weights, but the maximum vertical deflection at the middle of the mesh panels (maximum absolute value of the vertical boulder location) is almost the same. This could be attributable to the size of impact area which is proportional to

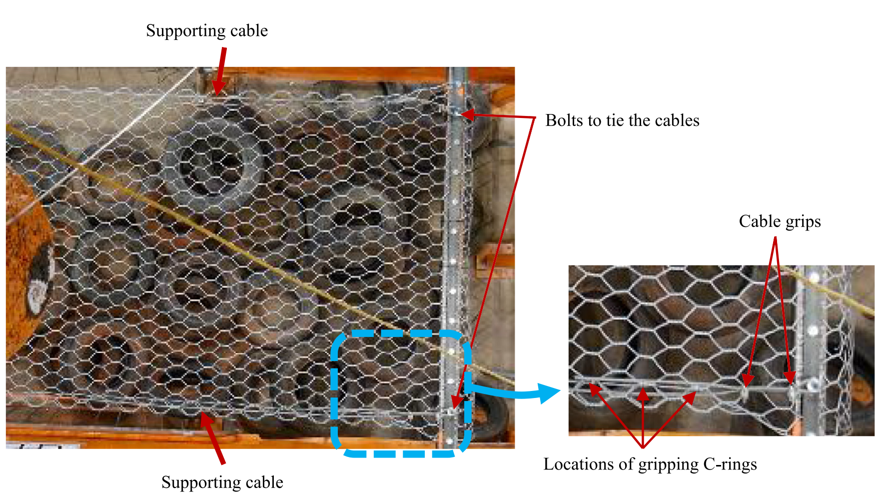

Fig. 4. Method for fixing supporting cables in the tests.

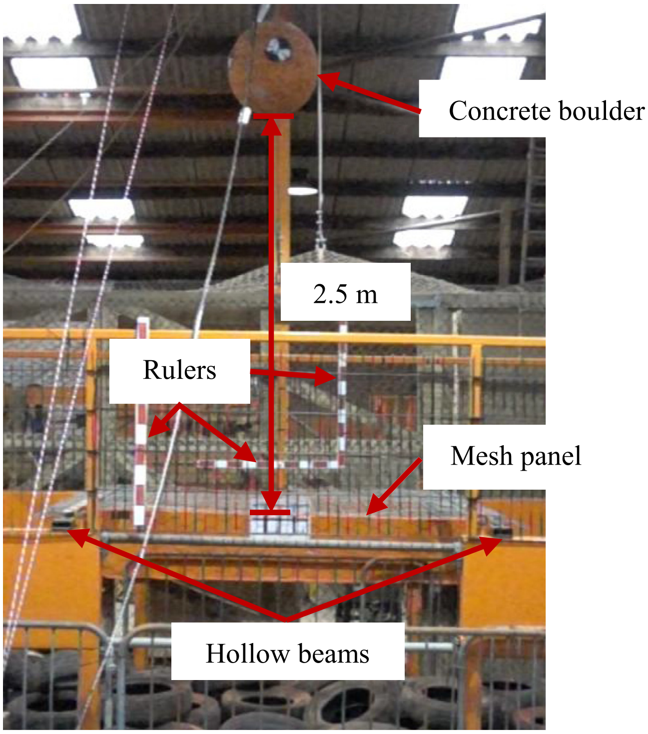

Fig. 5. Front view of Test 2.

Table 1
Summary of the impact tests.

Test number	Boulder mass (kg)	Boulder height (m)	Impact velocity (m/s)	Mesh size (m × m) (width × length)	Supporting cables
1	100	2.5	7	2 × 2	No
2	200	2.5	7	2 × 2	No
3	200	2.5	7	2 × 4	No
4	200	2.5	7	2 × 4	Yes

the size of the boulders. Since the impact area is smaller in Test 1 due to smaller boulder size, the mesh deformation is more localised in the centre. Therefore, the same maximum mesh deflection can be caused by smaller impact energy (Mentani et al., 2016).

Figs. 7 and 8 show the lateral deflection of the wire mesh panels of Tests 1 and 2. It can be seen that the lateral deflection in Test 2 is much larger due to higher impact energy. Fig. 7 shows that the

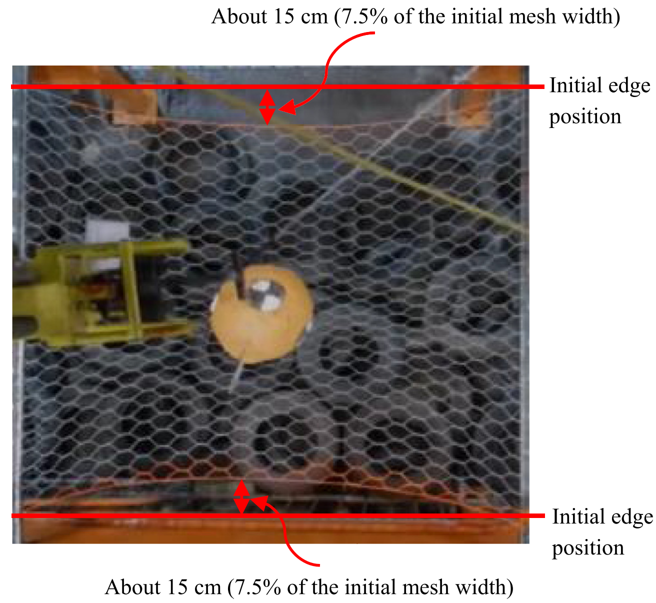

Fig. 7. Lateral deflection of the wire mesh of Test 1 (top view).

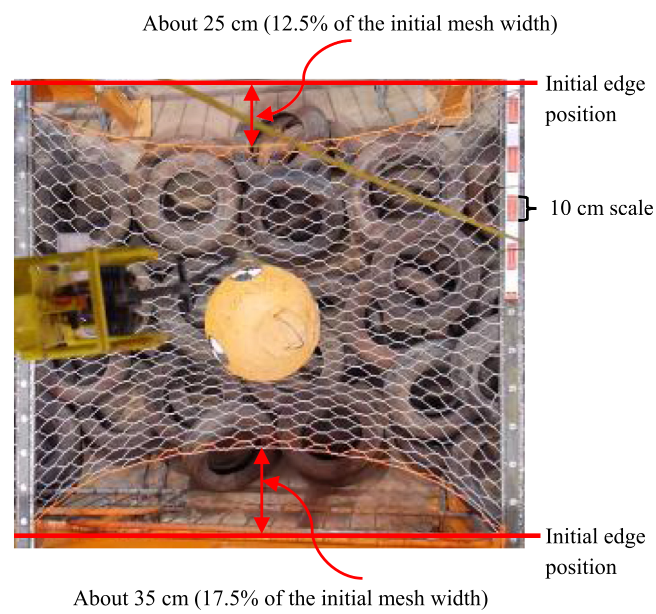

Fig. 8. Lateral deflection of the wire mesh of Test 2 (top view).

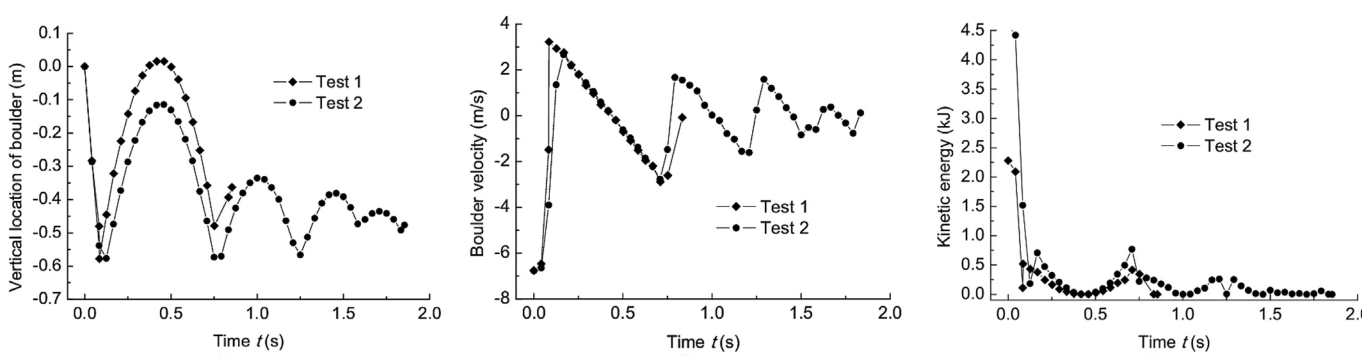

Fig. 6. Effect of the boulder size on mesh response: (a) Vertical trajectory, (b) Vertical velocity, and (c) Kinematic energy of the boulder in Tests 1 and 2.

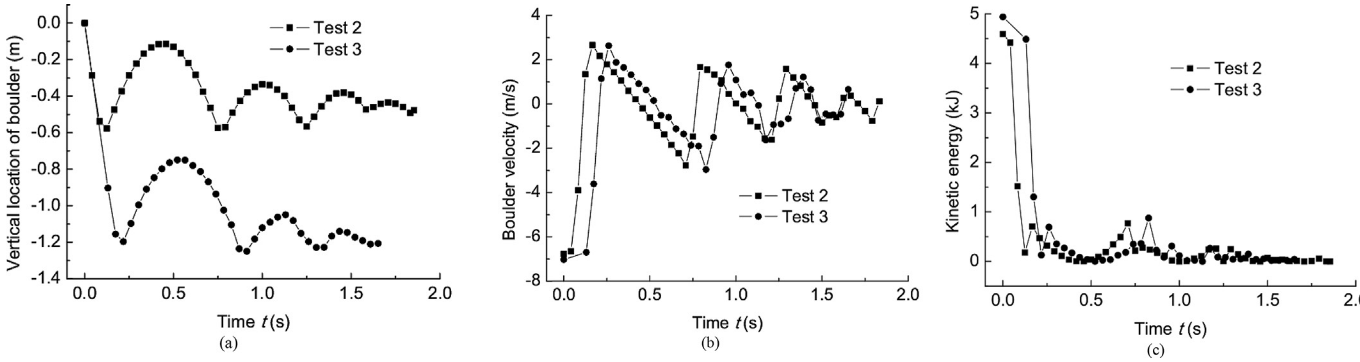

Fig. 9. Effect of the mesh length on mesh response: (a) Vertical trajectory, (b) Vertical velocity, and (c) Kinematic energy of the boulder in Tests 2 and 3.

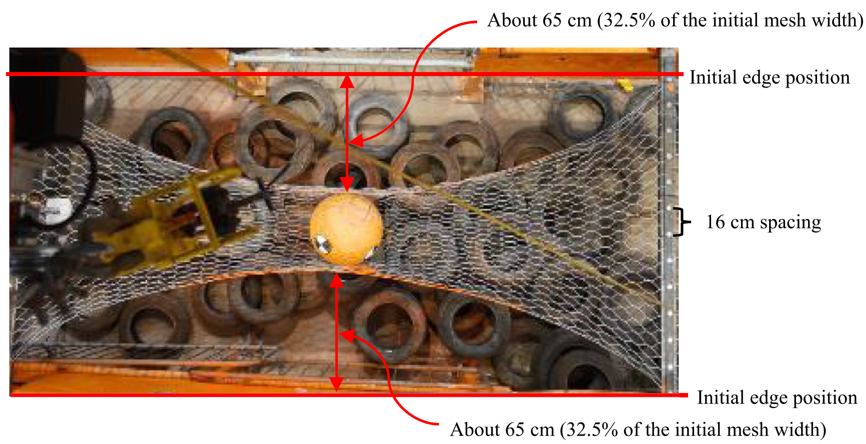

Fig. 10. Lateral deflection of the wire mesh of Test 3 (top view).

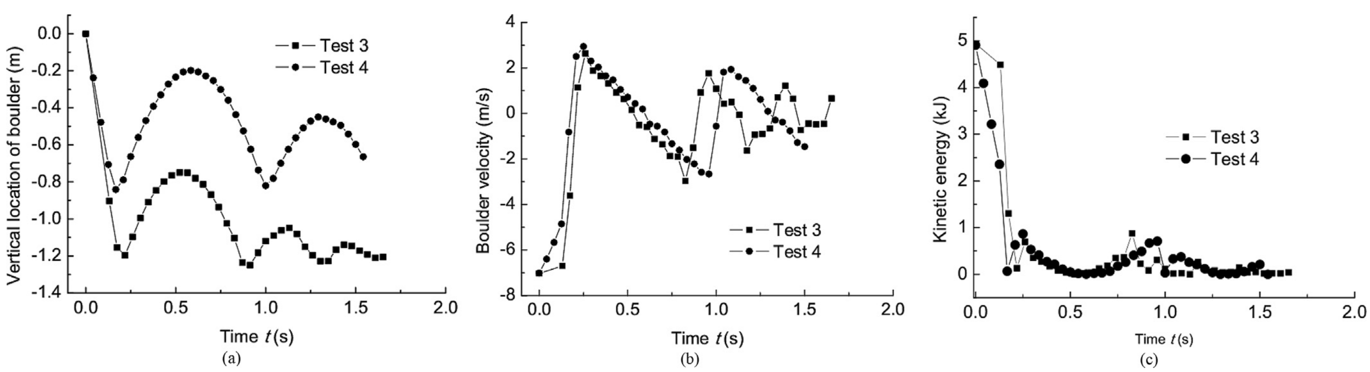

Fig. 11. Effect of the supporting cable on mesh response: (a) Vertical trajectory, (b) Vertical velocity, and (c) Kinematic energy of the boulder in Tests 3 and 4.

mesh deflection is not symmetric in Test 2, because the boulder has missed the centre of the panel at the impact.

The effect of the mesh panel length is studied in Tests 2 and 3. As shown in Fig. 9, the maximum vertical deformation of the longer wire mesh in Test 3 is twice of that observed in Test 2. After the first impact, the boulder bounces back by 85% of the maximum mesh deformation in Test 2 whereas only 58% bouncing back is observed in Test 3. This indicates that the shorter wire mesh behaves much stiffer than the longer one does. Fig. 10 shows the lateral deformation of wire mesh in Test 3. The maximum lateral deflection is more than twice of that in Test 2. The mesh setup in Test 3 should not be used in a real design, as it could fail to capture a falling rock due to the significant mesh shrinkage. In order to enhance the mesh performance, supporting cables should be used to prevent this severe lateral shrinkage (e.g. Buzzi et al., 2013; Tran et al., 2013). This is further investigated in Test 4 wherein two supporting cables are installed along the two long sides.

Figs. 11 and 12 show the results of Test 4. The maximum mesh deflection is smaller while the bounder bouncing back is higher in Test 4 (Fig. 11), because the supporting cables have reduced the flexibility of the wire mesh. Meanwhile, Fig. 12 shows that the maximum lateral deflection of the wire mesh in Test 4 is less than half of that in Test 3, which indicates that the supporting cables can effectively reduce the lateral shrinkage of the wire mesh. In a real design where the mesh length between two neighbouring posts is large, supporting cables must be used to reduce the lateral deflection of wire meshes (Al-Budairi et al., 2017).

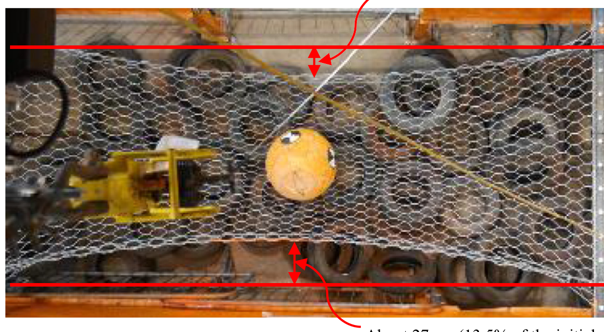

Fig. 12. Lateral deflection of the wire mesh of test 4 (top view).

The energy dissipation capacity is used as the primarily design measure of rockfall catch fences (Gerber, 2001; Peila and Ronco, 2009). Thus, it is important to understand the mechanism of energy dissipation in the fences (Mentani et al., 2016). In the tests presented here, the impact energy is defined as the kinematic energy of boulders when they first hit the mesh. Figs. 6, 9 and 11 show that, in all four tests, about 80%–90% of the impact energy is dissipated after the first impact. This is because most of the mesh plastic deformation occurs at that point. When the boulders are removed from the mesh after the tests, the shape of the deformed wire mesh does not change significantly, which shows that most of the deformation is plastic in the steel wires. No wire breakage has been observed in these tests and insignificant plastic deformation has been noticed in the supporting beams and cables. Thus, most of the impact energy is dissipated by plastic deformation of the wire mesh.

5. Conclusions

A method of testing mechanical response of the wire mesh under rock impact is presented. This approach offers the possibility to conduct tests with various loading conditions. Different boulder sizes, impact velocities, impact locations and mesh sizes can be used. Supporting cables can also be installed along the long mesh edges. This method has been used to investigate the response of the Maccaferri double-twisted wire mesh and four tests are presented. The major findings are shown below:

(1) Smaller boulder causes more stress and strain localisation in the middle of the mesh. Therefore, smaller boulder can cause more mesh deflection at the same impact energy. This means that a proper catch fence design should consider not only the impact energy but also the boulder size. In an extreme case, the catch fence can be penetrated by a small boulder due to the bullet effect (Mentani et al., 2016).

(2) The construction costs for catch fences can be significantly reduced by increasing the post spacing, because it is generally expensive to build the foundations for the posts in either rocks or soils (Al-Budairi et al., 2017). However, wider mesh has much higher flexibility. Tests in this note show that the catch fence may fail to capture the falling rock because of large lateral deflection of long meshes. Supporting cables can help reduce the lateral deflection of meshes effectively.

(3) The impact energy is mainly dissipated by wire stretching in the first impact. No mesh rupture is observed in these tests. Indeed, for low-energy rockfall catch fences, mesh stretching is the main mechanism for energy dissipation (Buzzi et al., 2013).

It should be mentioned that the results presented here are affected by the boundary conditions in the tests. In all the tests, the two short sides of the meshes are fixed on the hollow beams while the two long sides are either free or attached to the supporting cables. Such constraints are different from those in a real catch fence, especially those for the short sides. Therefore, these test results cannot be directly used to predict the mesh response in a real catch fence. It should only be used to develop preliminary design of rock catch fences, which can then be improved using numerical modelling and full-scale tests (e.g. Bertolo et al., 2009; Gentilini et al., 2013; Al-Budairi et al., 2017). In addition, the tests are carried out using spherical boulders while rocks with various shapes can be encountered in the field. A boulder with shape edges could cause more localised deformation around the edges, which should be properly considered in a real design. In interpreting the results in this note, the test rig is assumed to be rigid. This assumption is acceptable as the impact energy level is low in these tests. The stiffness of the rig must be properly considered when the impact energy is higher.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication.

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