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Mechanics of chain-link wire nets with loose connections

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ABSTRACT

Chain-link wire nets are used for slope stabilization, natural hazard protection systems, mine and tunnel safety and many other important applications. In rockfall protection barriers the nets are designed to withstand dynamic, impulsive loadings. As they are composed of ultra-high strength steel wires with loose three-dimensional connections, the high resistance nets are very flexible and serve to efficiently distribute loads throughout the structure. Rockfall barrier design requires accurate numerical simulations. In this work, a Finite Element model of chain-link nets is developed. To treat the complex contact interactions among chain-link elements and rockfall barrier components we develop a computational scheme relying on a general contact algorithm. The non-linear force displacement response of the net obtained in tensile quasi-static laboratory tests is successfully reproduced by the numerical model. The model parameters are obtained by optimization techniques. The calibrated chain-link model with contact is shown to successfully simulate a full-scale test of a flexible rockfall protection barrier. The computational schemes allow us to accurately model the mechanical behaviour of chain-link wire nets with loose connections.

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1. Introduction

Flexible steel wire nets are essential components of protection systems. Three specific applications in rockfall hazard mitigation are: interception barriers [1–7], drapes [8] and attenuator systems [9], see Figs. 1 and 2. A general feature of these systems is the use of flexible steel wire nets with different geometries (hexagonal, rhomboidal, ring) and connection types (loose, double twisted). Manufactures of wire net systems require accurate numerical simulation techniques to develop new systems and reduce development costs. This is challenging because the range of wire net types demand robust numerical algorithms treating complex contact interactions efficiently and realistically.

Commonly used wire nets include chain-link and double-twisted hexagonal nets. The double-twisted nets are arranged in repeating hexagonal mesh geometries [10]. Loose connection chain link nets are arranged in repeating rhomboidal patterns (Fig. 3), composed of a single wire or a twisted triple wire. The combination of flexibility and high resistance make loose connection chain-link nets ideal for rockfall barriers, slope stabilization, and temporary tunnel support where protection measures must withstand large forces. In loose connection nets, wires are bent to form the chain-to-chain connections. This construction method generates non-linear deformation behaviour thanks to the shape and out-of-plane dimension (eccentricity) of the loose wire connections. It is these properties that make for highly efficient impact interception structures. This work deals with flexible chain-link nets composed of ultra-high strength steel (UHSS) twisted triple wire with loose connections.

Numerical Finite Element (FE) and Discrete Element (DE) models have been developed to simulate rockfall barriers containing double-twisted, hexagonal nets [8,10,11]. Hexagonal nets behave stiffer because the double twisted connections restrict wire-to-wire sliding and thus friction can be neglected. Furthermore, load eccentricities have a negligible effect on their behaviour, because effectively the net lies on a bi-dimensional plane. Therefore, a two-dimensional approximation of the net geometry is sufficient to capture their response to loading. Modelling loose connection chain-link nets on the other hand requires that eccentric connections and contact with sliding friction is modelled. Thus, the three-dimensionality and the true contact interactions of the chain-link net elements need to be taken into account to capture the soft, non-linear response to tensile loading. A first attempt to model such nets was developed by [12] who applied a DE model to reproduce the force–displacement behaviour

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Fig. 1. Rockfall protection barriers: (a) wire-rope chain link net as part of a rockfall barrier impacted by a rock avalanche and (b) double chain-link interception structure as part of a rockfall barrier.

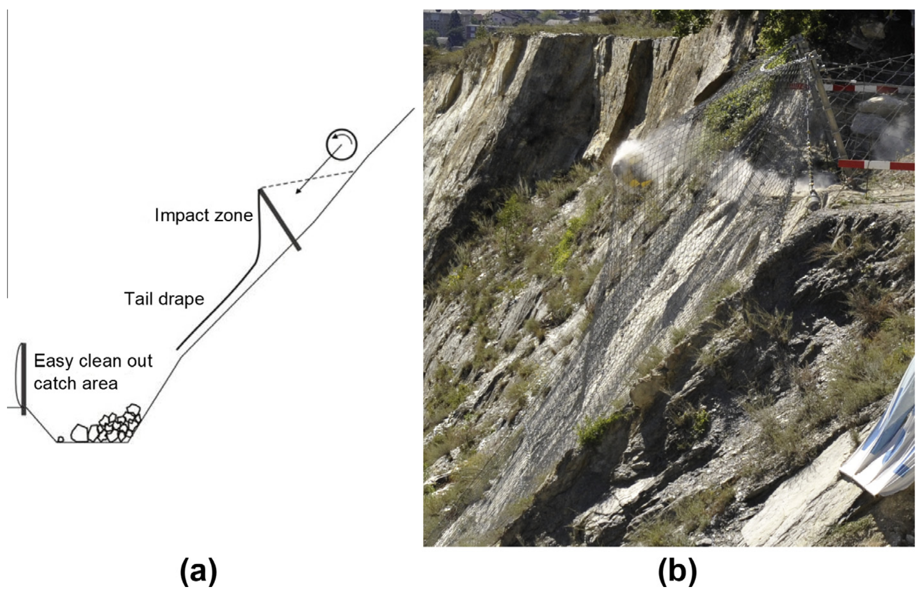

Fig. 2. Rockfall protection attenuators: (a) sketch drawing of a rockfall attenuator system and (b) filmed perspective of rock impact on an attenuator system [17].

obtained from laboratory and field tests. The model was simplified such that the 3D geometry effects were replaced by a 2D geometry in combination with a non-linear material law that could account for the three-dimensional geometric effects. Axial elastic–plastic springs are located at the connections. The spring stiffness and resistance varies according to the mesh opening angle [12]. This is in fact a consequence of the complex mechanical behaviour as a function of the net's three-dimensional geometry. This model was implemented in a DE code for rockfall barrier simulations [2]. This modelling approach is restricted by the large testing requirement to calibrate the angle dependent stiffness and failure load when geometry changes are considered.

This paper deals with the development and improvement of a modelling scheme to treat chain-link contact with sliding friction [6] which models complex mechanical net-connection behaviour respecting the three-dimensional geometric effects. The approach relies on general contact (GC) in which the hard contact behaviour is approximated by a penalty contact method [13]. This method approximates contact enforcement using penalty stiffness. The frictional contact behaviour is considered using a Coulomb-type model. The basic idea behind this scheme is to model the contact interactions between structural components as close as possible to those of real systems. Ring-net rockfall systems have already been modelled with this approach [5,7]. Initial studies on the use of GC to model a single chain-link wire system have been carried out [6]. In this work the modelling of contact interactions includes a number of model extensions. The first is an improved model of the end knot connections that close chain-link elements (Fig. 3). The second models the more complex twisted triple wire strand with an equivalent circular wire including ductile damage. The third addition is the application of optimization techniques to calibrate the model parameters (equivalent wire area and the elastic–plastic constitutive parameters).

A problem addressed in this work is the appropriate element size for the FE discretization. Local FE mesh refinement is required in the area of connections to accurately represent its geometry and mechanical behaviour. However, in the explicit calculations performed herein this local refinement decreased the element-by-element stability limit [7,13]. In this paper a mass-scaling approach [14,15] is proposed to deal with this problem. The scaling is only applied to the elements needed to model the connections. The scaling is small enough that it does not modify the overall dynamic behaviour during impact calculations. Criteria are suggested for an acceptable level of mass scaling for both quasi-static and dynamic analysis.

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