A design approach to residual rockfall hazard of drapery systems: example from Clifton Hill, Sumner

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ABSTRACT

Unsecured draperies are routinely used as a rockfall mitigation system. These systems do not completely eliminate the rockfall hazard and are typically classified as passive structures aiming primarily at controlling rockfall motions by constraining them towards the slope. Rockfall hazard is seldom completely eliminated, therefore requiring another line of defence such as a catch ditch or a berm.

This paper presents a new approach that was implemented on Sumner Road at Clifton Hill in Christchurch to quantify the efficiency of the drapery to control the motions of potential rock falls, therefore optimising the design requirements for the catch ditch at the base of the slope. A discrete element model (DEM) was previously developed to specifically simulate the interaction between falling blocks and draperies. Results of 3D rockfall trajectory simulations were used to characterise the influence of block size, shape and fall height on the efficiency of a drapery to reduce the impact kinetic energy and constraint the bottom impact location. Simplified relationships were derived and used to estimate the rebounds at the base of the slope and subsequently design the catch ditch.

1 INTRODUCTION

During the 2010 - 2011 Canterbury Earthquake Sequence, rockfall occurred from a cliff at Clifton Hill, Sumner, affecting the adjacent Main Road. A preliminary assessment indicated an unacceptably high on-going risk of rockfall affecting road users. Shipping containers were placed as a temporary rockfall risk mitigation measure to protect road users. However, Christchurch City Council wishes to remove the shipping containers while introducing effective long term mitigation measures to address the rockfall hazard. Placement of a double twisted wire mesh unsecured drape over the full height of the cliff is proposed as a primary mitigation measure.

Unsecured drapery, i.e. only anchored along the top (Muhunthan et al., 2005), addresses rockfall that originates from the covered area. Although the system can provide some resistance to rockfalls where the mesh is in contact with the slope, it allows for blocks to fall between the slope and the mesh, controlling its descent into a catchment area at the base of the slope. It intends at reducing and confining the risk rather than eliminating it. It is therefore essential for designers to

understand the level of risk reduction that is achieved to ensure that appropriate secondary control measures are implemented wherever necessary.
Based on observed performance of unsecured draperies installed in North America, Muhunthan et al. (2005) developed design guidance providing design and installation recommendations. However, to the authors' knowledge, no guidance is available on catchment requirement at the toe or on the risk reduction achieved by an unsecured drapery.

To this date, few studies have attempted to quantify the performance of draperies. Giacomini et al. (2012) performed a series of rockfall field experiments behind unsecured drapery using stereo paired high speed video cameras to record the trajectories. These tests provided the first insight on the level of energy reduction or confinement that can be achieved; however, they were limited to a single slope with no variation of block shape or size. Muhunthan et al. (2005) developed a finite element model of a drapery to investigate static load distribution across the system but did not perform any rockfall trajectory simulation. Bertrand et al. (2008) proposed a discrete element model (DEM) of a double-twisted hexagonal mesh but the model was intended at modelling the dynamic response of gabion baskets. Subsequently, Thoeni et al. (2013, 2014) enhanced the DEM model to successfully simulate three-dimensional rockfall trajectories behind a drapery therefore providing a promising tool to quantify the efficiency of the system at reducing and confining the rockfall risk.

This papers describes a simplified approach developed to quantify the risk reduction achieved by the proposed drapery at Clifton Hill. The general performance of draperies as observed by Giacomini et al. (2012) is first summarised. Results of a sensitivity analysis performed using the model from Thoeni et al. (2014) are presented. The sensitivity analysis included block shape, block size and surface irregularities. General empirical relations to estimate minimum catchment width and energy reduction were derived for a 30 m high slope. These relations were then used to demonstrate the suitability of the secondary control measures implemented at the toe of the slope.

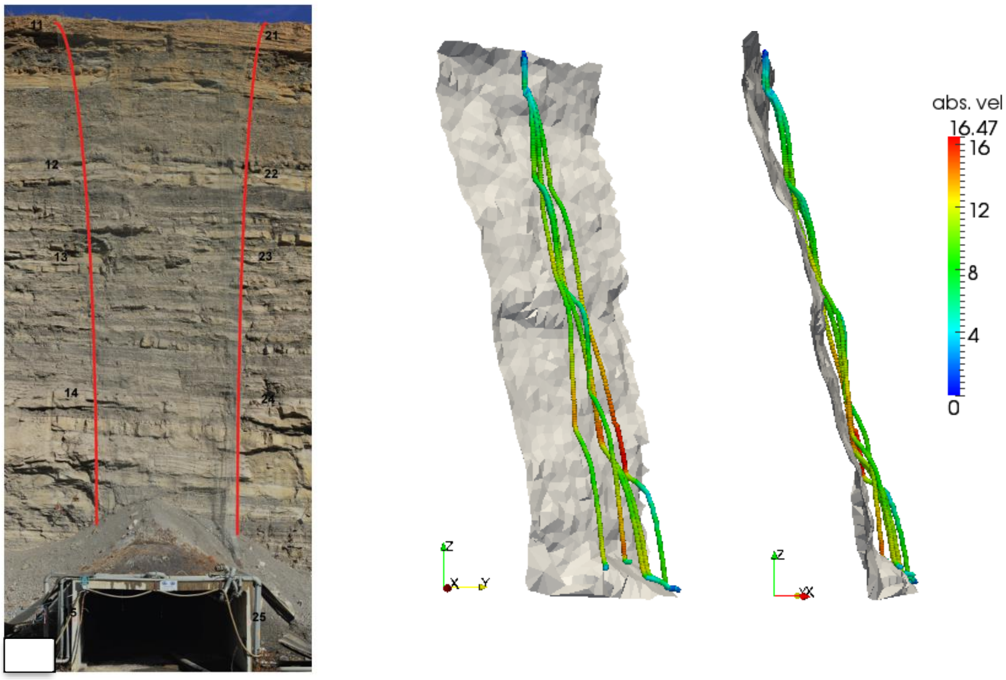
2 PERFORMANCE OF DRAPERIES

2.1 Field experiment

Giacomini et al. (2012) investigated the performance of double-twisted hexagonal wire drapes as a rockfall mitigation system. In situ rockfall experiments were conducted at a mine site to assess the effectiveness of drapery mesh in reducing the rockfall hazard. Two series of tests were carried out by releasing concrete blocks from the top of a highwall, in a meshed and a neighbouring unmeshed area with similar topography and geological characteristics. The blocks falls were recorded and their trajectories were reconstructed via stereo-photogrammetry. These trajectories were then used to infer the motion characteristics of velocity, energy and restitution coefficients (Figure 1).

The comparison between tests with and without drapery clearly highlighted the effect of the protective structure on the block trajectories and impact energies (Table 1). The confining function effect, quantified as the maximum deflection from the slope, was reduced by approximately 70% on average. This confining of the trajectory resulted in an increased number of impacts along the 40 m high slope (2 – 3 impacts without drapery and 4 – 5 with a drapery) and shallower impact angles.

As expected the presence of a drapery tends to reduce the translational velocity of falling blocks. The maximum translational velocity along the fall tends to be reduced to approximately 60% of its counterpart on a similar undraped slope. While the reduction in velocity achieved by the presence of a drape is significant, the maximum velocities observed along a fall largely exceed residual exit velocities sometimes assumed by practitioners (Lambert et al. 2016).



(a) (b)

Figure 1. Rockfall field testing of a drapery system: (a) underground entry portal with a 4 panel wide drapery system and (b) boulder trajectories reconstructed from stereo pairs of high speed video cameras (from Giacomini et al., 2012)

In the presence of a drape, the energy dissipated along the fall can be attributed to two distinct mechanisms: energy dissipated upon impacting the slope, traditionally captured by the use of restitution coefficients and frictional dissipation through block / mesh interaction. The confining of the trajectory results in an increased number of dissipative events. This is however partially overcome by the change in impact angle. Indeed, shallower impact angles results in higher normal restitution coefficient (Wyllie, 2014) and therefore lower energy dissipation upon each impact.

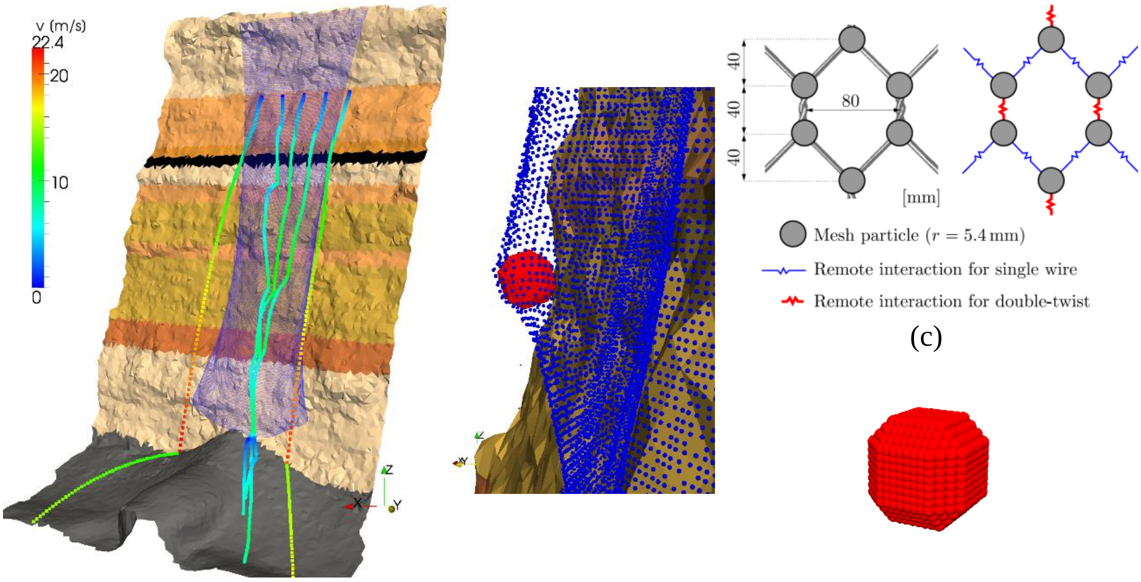
An interesting aspect during a rock fall is the coupling upon impact between tangential velocity and rotational velocity (Preh et al. 2015) resulting in a transfer of kinetic energy from translational to rotational kinetic energy (and vice versa). Experiments by Giacomini et al. (2012) captured this transfer for each impact. It was also observed that the drape was very efficient at dissipating the rotational energy between two successive impacts (between 20% and 80% of the rotational energy dissipated between two consecutive impacts), preventing a gradual increase of the rotational velocity along the fall. Accounting for both translational and rotational kinetic energies, it was observed that overall the block / drape interaction resulted in an average energy dissipation of 0.12 kJ per meter of fall.

Table 1. Comparison of rockfall characteristics between draped and undraped slopes

	Maximum mesh deflection (m)		**Maximum translational velocity (m/s)**	
	Draped	Undraped	Draped	Undraped
Avg	1.6	5.6	15.0	26.5
St dev	0.3	3.4	0.9	1.7
Max	2.1	10.1	16.5	28.4
95th %tile	2.1	9.8	16.2	28.4

2.2 Discrete element model of a double-twisted hexagonal drape system

Thoeni et al. (2013, 2014) proposed a novel approach for the simulation of rockfalls behind drapery systems which can be used to accurately assess the residual rockfall hazard involved with such systems. Based on classical discrete element method, the model offers the ability to account for all the relevant interactions during a rockfall event, i.e. block – slope, block – drapery and slope – drapery (Figure 2). The block is represented by a rigid assembly of spheres. The slope is represented by triangular elements and the drapery is represented by spherical particle which interact remotely. All components of the model are rigorously calibrated and validated against laboratory experiments (Thoeni et al., 2013) and can accurately predict block trajectories and block velocities for rockfall analysis without and with drapery (Thoeni et al., 2014).



(a) (b) (d)

Figure 2. Three dimensional Discrete Element Model for rockfall trajectory analysis behind drapery systems: (a) Full scale model; (b) close-up view of block - drape interaction; (c) DEM model of drape with remote particle interaction; (d) model of ETAG 027 concrete block

2.3 Sensitivity analysis

While site specific modelling should be performed for a quantitative assessment of the residual hazard, such analysis can be time consuming and is not practical at an early stage of a project. In an attempt to derive preliminary design recommendations, a sensitivity analysis was performed. Nine different blocks were considered as a combination of three different shapes (sphere, cube and elongated cube) and three characteristic dimensions (0.2 m, 0.4 m and 0.8 m) resulting in the mass ranging from 10.1 kg (0.2 m sphere) to 2.5 t (0.8 m elongated cube).

A standard slope geometry used in the parameter study was based on the highwall section presented in Thoeni et al. (2014) with a total slope height of 45 m and an average slope angle of approximately 75°. Some modifications to the slope morphology were introduced to investigate a range of slope surface irregularities that may locally reduce the efficiency of the drapery due to a reduced slope mesh contact. Ledges at different heights (15 m and 30 m) with different depths (0.5m to 2.0 m) were introduced to generate different slope scenarios (Figure 3). Three of each blocks were then released from three positions at the same elevation on the slope. Block trajectories during the fall were recorded, from which kinetic energy, and bouncing distance from the slope, were derived. The energy and block deflection after a 30 m fall were analysed.

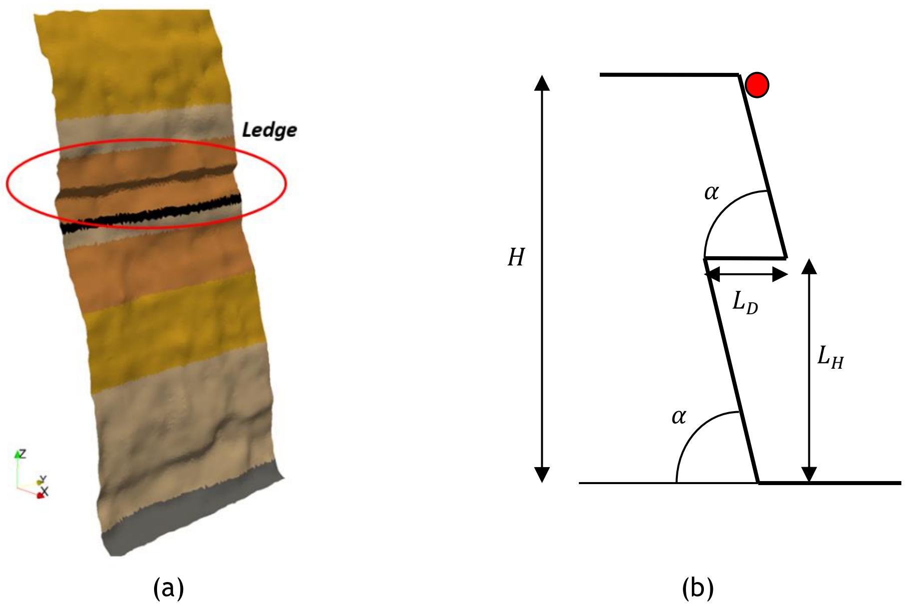


Figure 3. (a) Example of artificially modified geometry for rockfall trajectory study; (b) surface irregularity scenario considered in the analysis

Translational kinetic energy is presented as a function of block mass in
Figure **4**a. Results suggest block mass is the primary controlling factor and that block shape and slope morphology only have a secondary influence. Conservation of energy implies that the maximum energy that can be achieved by a falling block is equal to its initial potential energy (m×g×30). The efficiency of the drapery can be expressed as the ratio of impact energy to initial potential energy (E_{kin}/E_{pot}), i.e. a high ratio correspond to a low efficiency (i.e. a high proportion of the potential energy is transferred into kinetic energy).
Figure **4**b suggests that the efficiency as energy reduction can be minimal for large blocks (500 kg or above).

An upper bound bottom impact energy trend line can be estimated as:

$$E_{kin} = C_k \times m^{\alpha} \quad (2)$$

where C_k = 125, α = 1.15 and the mass is expressed in kg.

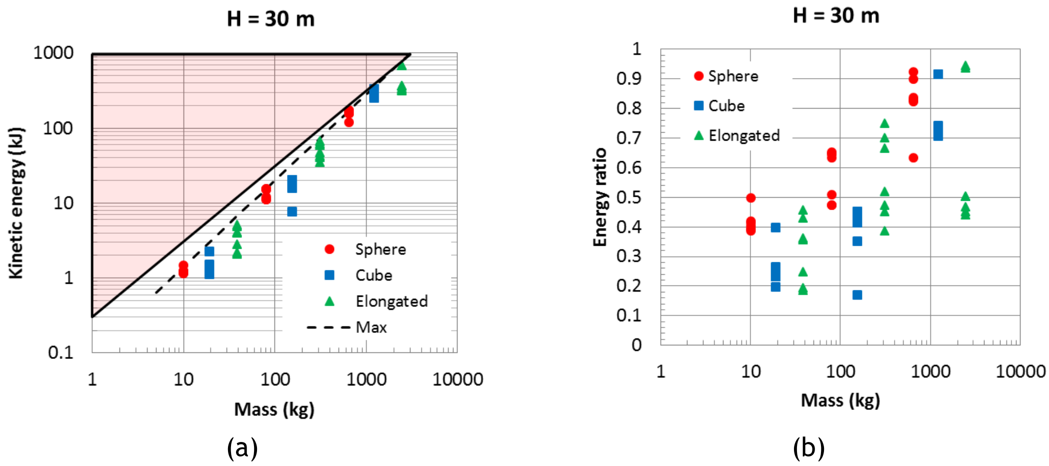


Figure 4. (a) Translational kinetic energy as a function of mass for all combinations of block shapes, sizes and slope morphologies; (b) energy dissipation ratio

As discussed previously, a key aspect in the performance of a drapery lies in its ability to confine trajectories and therefore bottom impact locations close to the toe of the slope. The requirement for a minimum bottom catch width was therefore assessed from the observed deflection (Figure 5). While deflection appears generally greater when a ledge is present on the slope, no obvious trend can be derived with the location or the depth of ledge. However, results suggest again block mass is broadly the primary controlling factor, above block shape or slope irregularities. The catch width tends to increase with mass. An upper bound envelope for the minimum catch width can be expressed with the following equation:

$$d_{max} = C_d + \beta \cdot \log m \qquad (3)$$

where: $C_d = 0.5$ and $\beta = 1.6$

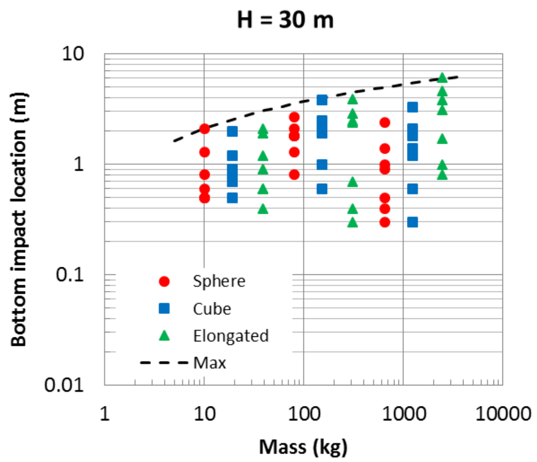


Figure 5. Horizontal bounce as a function of mass for all combinations of block sizes, shapes and slope morphologies

3 ROCKFALL PROTECTION AT CLIFTON HILL

3.1 Clifton Hill

The cliff at Clifton Hill comprises a 20 m to 30 m high steep rock slope exposing interlayered basalt lava flows and volcanic breccia with rare thin epiclastic horizons (
Figure **6**). The crest of the cliff exposes a layer of loess in the order of two metres thickness.

Rock blocks up to about 1 m in maximum dimension fell from the slope during the earthquakes and while most of the debris did not land on the road, some blocks in the area where the separation between the road and the toe of the cliff is at a minimum, landed on the city-bound lane.

Analysis of the cliff as part of the detailed design concluded that the likelihood of large scale cliff collapse failure of the cliff at this location is acceptably low and that the main geo-hazard to road users is the rockfall of discrete blocks of rock. Therefore, as part of the long term mitigation measures to address the rockfall hazard after removal of the shipping containers, it was proposed to install a double twist mesh drape over a length of about 100 m of cliff face extending the full height of the cliff (
Figure **6**).

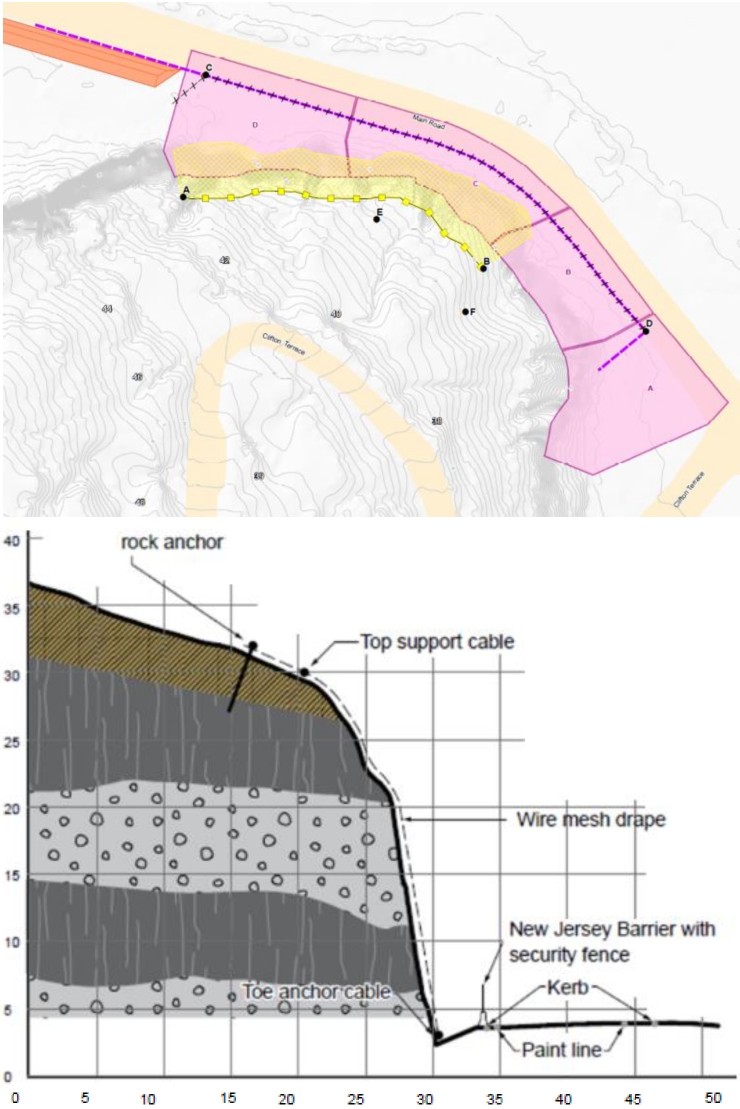


Figure 6. Clifton Hill rockfall mitigation: (top) Site plan with approximate extend of double twist wire mesh; (bottom) Typical cross section with proposed rockfall protection

3.2 Residual hazard

Due to the geometrical similarities (slope angle, height and irregularities) between Clifton Hill and the slope profiles used Section 2.3, impact energy and catchment width requirement were derived using equation (2) and (3) respectively. A design rock block for the rockfall hazard assessment of 500 kg was considered, corresponding to the maximum size of potentially unstable block. Indeed, larger blocks were either bolted to the slope or scaled prior to the installation of the drape. For the 500 kg design block, bottom impact energy is expected to be in the order of 160 kN whereas a minimum catch width of 4.8 m is required.

A minimum 5 m wide catchment area was therefore designed with a 1V:6H back slope covered with a loose granular cushioning material to absorb the kinetic energy of blocks potentially falling between the drape and the slope. Assuming normal and tangential restitution coefficients of 0.15 and 0.6 respectively (Giacomini et al., 2012), the maximum subsequent bounce height and resulting kinetic energy at the base of the slope are expected to be in the order of 0.7 m and 7 kJ. A 0.9 m high segmental concrete barrier was therefore installed adjacent to the road to provide additional rockfall protection.

4 CONCLUSIONS

This paper provides some insights on the performance of unsecured drapery systems. Based on field experiments and numerical analysis, the efficiency is discussed both in terms of kinetic energy reduction and trajectory confinement. The influence of block shape, block mass and slope irregularities was investigated using a DEM model. Results show that boulder mass is the most important aspect to consider when assessing the efficiency of a drapery and the residual hazard at the bottom both in terms of magnitude and areal extent.

Unsecured drapery systems are more efficient at reducing impact energy for smaller blocks than larger blocks. It was found that a 10 kg boulder may have its kinetic energy reduced to less than 50% its potential energy. Energy dissipation was observed to be minimal for blocks larger 500 kg. In addition, it was found that, as mass increases, the confining effect is reduced, from 2 m or less for a 10 kg boulder to up to 6 m for a 2,500 kg boulder. Two empirical relationships were derived to provide estimates the residual impact energy at the base of the slope and the minimum catch width requirement. An example of application is presented to illustrate how these relationships can be used to verify the suitability of additional measures to mitigate the residual hazard.

Ideally, site specific modelling should be performed to analyse the residual hazard associated with the installation of a drape, especially if slope characteristics differ from those presented in this study, i.e. 75° slope angle and a 30 m vertical drop or if the surface irregularities present on the slope fall outside of the range of scenarios covered in the sensitivity analysis.

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