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Managing Asset Resilience in Canyon Terrain using Rockfall Hazard Mapping and Modelling

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Abstract

As part of their "Vision 2030" to transition away from fossil fuels, the Kingdom of Saudi Arabia (KSA) aim to create flagship sustainable tourist destinations. This involves developing tourist resorts and associated assets in AlUla, a region in northwest KSA that boasts unique heritage such as Nabataean tombs and ancient Arabic architecture. The geology of AlUIa includes Cambrian-Ordovician sandstone that has been eroded to form vast canyons. The cliff faces of these canyons are 80-100m high, with canyon widths of 50–300m. Due to the natural beauty of these canyons, resorts will be constructed within them, with assets located adjacent to the cliffs. This is problematic, as the sandstone cliffs are extremely prone to rockfalls. There are two main types of rockfall hazard in these canyons. One, small-scale tafoni weathering induced rockfalls. And two, large-scale topples, slides, and wedge-type rockfalls occurring along high-persistence, sub-vertical joints within the sandstone.

As such, this paper will outline the general methodology for how we undertake rockfall mapping and modelling assessments in critical canyon terrain to manage the resilience of proposed tourism assets to rockfalls. The overall objectives considered within this paper are to 1. Describe how fieldwork is used to obtain critical rockfall data required for modelling. 2. Outline how 2-D modelling is used to quantify rockfall primary impact and runout distances, including descriptions and solutions to specific technical modelling challenges such as unfeasibly high bounces off steep cliffs and long rolls down aeolian sand dunes. 3.Outline how modelling results can be used to develop detailed rockfall hazard maps. And 4. Discuss the overall implications and importance for asset resilience of considering rockfall hazard at an early stage.

Keywords: *Rockfalls, Canyon Terrain, Hazard Mapping, Modelling, and Mitigation, Asset Resilience*

1. Introduction

The Kingdom of Saudi Arabia (KSA) is the largest oil producing country in the world. As part of their "Vision 2030" initiative, the KSA aim to transition away from fossil fuels towards other economic sectors, with an ambitious aim to increase non-oil related GDP from 16% to 50% by 2030. As part of this transition, the KSA aim to construct several flagship sustainable tourist destinations. One of these destinations is AlUla, a region located in the northwest KSA (Figure 1) that boasts unique cultural heritage such as the Nabataean tombs of Hegra.

As outlined in Section 2., the geology and geomorphology of the AlUla region is dominated by steep sandstone cliffs that are highly prone to rockfalls. This is problematic as many of the proposed developments for the AlUla region (such as tourist resorts, hotels, restaurants, entertainment facilities, roads etc.) are expected to be located directly adjacent to rockfall prone cliff faces. To ensure the resilience to rockfalls of any assets located near to cliff faces, it is vital that rockfall hazard is considered from an early stage of design. As such, AECOM have been hired to undertake detailed rockfall hazard assessments at the pre-design stage for a number of assets within the AlUla region.

1.1 Aims and Objectives

Due to confidentiality agreements, this paper cannot name or show specific assets or locations within the wider AlUla region that is shown on Figure 1. As such, the overall aim of this paper is to provide a generalised overview of how we have undertaken detailed rockfall hazard mapping and modelling for assets within AlUla. The specific objectives that fall within this aim are as follows:

1. Describe how fieldwork is used to obtain critical rockfall data required for modelling.
2. Outline how 2-D modelling is used to quantify rockfall primary impact and runout distances, including descriptions and solutions to specific technical modelling challenges associated with steep Canyon and desert terrain (e.g. unfeasibly high bounces off steep cliffs and long rolls down aeolian sand dunes).
3. Outline how modelling results can be used to develop detailed rockfall hazard maps.
4. Discuss the overall implications and importance for asset resilience of considering rockfall hazard at an early stage.

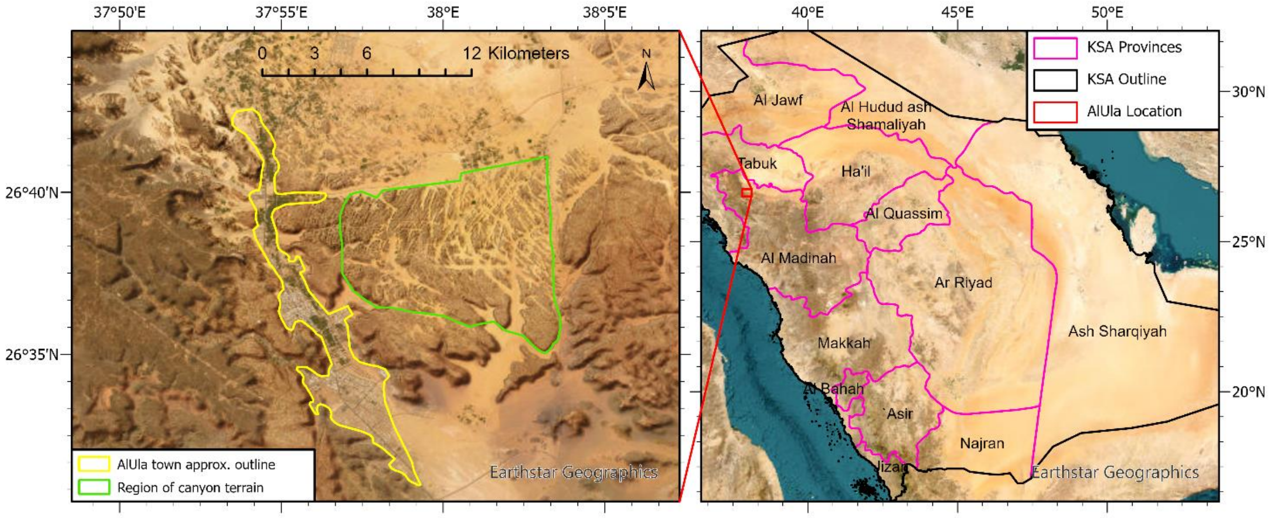


Figure 1: General location maps of AlUla. Note the canyons in the centre of the left map.

The following sections of this paper will now provide an overview of the geology and geomorphology of AlUla, before outlining the critical fieldwork and 2-D modelling methods that AECOM use to assess rockfall hazard, how these are used to obtain detailed hazard maps, and what the overall implications of this work are for ensuring asset resilience to rockfalls.

2. Geological and Geomorphological Setting

Before describing the key field and modelling methodologies used to assess rockfall hazard in this region, it is important to have a good understanding of the geological and geomorphological setting within which these rockfalls are occurring. The following sections will therefore provide a brief overview of the key geology, geomorphology, and geohazards encountered across AlUla.

2.1 Geology, Structural Geology, and Hydrogeology

AlUla is situated within the western Arabian Shield that comprises a Proterozoic basement of igneous and metamorphic rocks of the Arabian craton. This Proterozoic basement was largely overlain by a Palaeozoic succession of sandstones that were deposited during the Cambrian to Ordovician in shallow-marine to fluvial environments. The main sandstone units found across the site are the Quweira, Ram and Uhmm Sahm sandstone formations of the Tayma group (Ministry of Petroleum and Mineral Resources, 1987).

Following this sedimentary deposition, multiple mafic basaltic lava flows occurred during the Neogene in the Late Tertiary. These Basalt lava flows, known locally as Harrats, most commonly erupted from scoria cones and less commonly from shield volcanoes. These flows are thought to have occurred in association with rift-flank extension of the Red Sea Rift divergent tectonics. These flood basalt deposits lie unconformably above the Cambrian to Ordovician sandstone basement. Following and/or during the Late Tertiary was a likely period of erosion that capped the basement deposits with Quaternary superficial aeolian sands, sand dunes, and fluvial/alluvial sheets. This Quaternary erosion is expected to have formed the main Wadi channels that characterises the AlUla region and formed the main sandstone canyons.

2.2 Geomorphology and rockfall hazard

The current geomorphology of AlUla is a fundamental product of the geological history described in section 2.1. To the west, the geomorphology of AlUla is dominated by a flood basalt plateau that is bounded by steep (<45^{o}) scree-covered slopes with elevations of ~1355 m ASL (Above Sea Level). The eastern side comprises flat to undulating wadi and alluvial deposits interspersed with sandstone outcrops, buttes, and canyons. These canyons can have cliff faces up to 100m high with canyons widths of 50 – 300m (e.g. Figure 2, top right and top left). In terms of rockfall hazard, previous AECOM site reconnaissance in this region indicate that rockfalls are common within sandstone outcrops and canyons. The two main types of rockfall hazard expected to occur are:

1) Large-scale discontinuity-controlled rock/block falls (e.g. Figure 2, bottom left). Rock/block falls with sizes >0.5 m^3 that typically form at the intersections of two or more discontinuity sets (e.g., faults, joints, bedding). In the AlUla sandstone, these discontinuities typically have spacings of millimetres to tens of metres.
2) Small-scale tafoni-weathering induced rock falls (e.g. Figure 2, bottom right). Rock/block falls with sizes <0.5 m^3 that are generated via tafoni-weathering. This weathering process typically causes small (up to 0.5 m, average 0.1 – 0.2 m) holes to occur within the rock mass, which eventually merge to form unstable weathered ledges off which small rock blocks can fall/topple.

Furthermore, for both of these types of rockfall hazard, the occurrence of earthquakes and extreme rainfall events could act as a potential rockfall trigger, increasing the likelihood of rockfalls occurring during these events. Given the potentially catastrophic impacts of these rockfall hazard types, both pose significant safety issues for any assets that are to be located in close proximity to a sandstone cliff.

Figure 2: (top right and left). Typical canyon terrain found in the AlUla region; (bottom left) Large-scale discontinuity-controlled rock/block falls; (bottom right) Small-scale tafoni-weathering induced rock falls.

3. Methodology

The generalised methodology used by AECOM for rockfall hazard assessments involves three key stages. One, field mapping (following a typical desk study, that is not described within this paper), two, modelling and data analysis, and three, development of final hazard maps. The following sections will describe the key methodologies used for each stage.

3.1 Rockfall Hazard Field Mapping

The general aim of rockfall hazard field mapping is to identify all rockfall-related hazards across the site and obtain sufficient data on those hazards to understand the underlying causative processes and model their expected future impacts. As outlined in Section 2.2, there are two main types of rockfall hazard expected across the sandstone canyons of AlUla: Large-scale discontinuity-controlled rock/block failures, and small-scale tafoni-weathered induced rock/block failures. To characterise these two types of hazard, various data would be collected during a given site visit. For large-scale rock/block failures, the following data would be obtained:

1. The locations of all potential discontinuity-controlled rock/block failures. These would be located visually by identifying open to partially open discontinuities that were forming large unstable blocks, or loose (previously failed) blocks still resting on discontinuity surfaces.
2. The sizes, shapes, and heights of these potential rock/block failures.
3. Measurements and descriptions of the discontinuity surfaces the blocks were forming on in accordance with BS5930:2015+A1:2020, plus the expected mechanisms of each potential block failure (e.g., slide, wedge, topple).
4. General block and slope condition descriptions (e.g., degree of weathering, degree of discontinuity openness, slope roughness, and morphology of rock face or ledges).
5. The runout distances, sizes, and shapes of historical large-scale blocks, as well as qualitative age estimates (Very old = block was partially buried. Old = block had small build-up of sand on or around its base. Recent = still evidence of a bounce/roll and/or was fresh on the ground surface).

Small-scale tafoni-weathering induced rockfalls typically occur continuously at all locations across a rockface, typically originating from highly weathered ledges in the upper two thirds of a cliff. As these ledges are often not accessible, to fully characterise this hazard, field data collection would be focused on obtaining data from historical examples of similar small-scale rock/block failures that remained on the ground surface. As such, the following data would be collected for observed small-scale historical runouts:

1. Rock/block size and shape.
2. Runouts (horizontal distance from base of slope); and
3. Estimated age of runout (as classified above for larger historical past events).

Finally, general descriptions of material types and landscape geomorphology would be recorded for each portion of a site. This would include lithological descriptions of the key rock and soil units (e.g., sandstone, sand dunes) in accordance with BS 5930:2015+A1:2020, and descriptions of general landscape morphology (e.g., dune heights and slope angles, canyon cliff face heights and morphology, presence of vegetation).

3.2 Primary Impact and Runout Distance 2-D Modelling

The aim of runout and primary impact distance modelling is to use 2D modelling to quantify the expected primary impact and runout distances of specific field-identified large-scale potential failures and general small-scale tafoni weathering-induced failures.

The primary impact distance of a rockfall is defined as the horizontal distance between the hillslope toe/base and the location where a rockfall first impacts the ground surface after being detached from a rockmass (Figure 3A). The runout distance is defined as the horizontal distance between the hillslope toe/base and the final stopping position of a rockfall (Figure 3). These quantified runout distances can then be used to define hazard maps demarking the areas of a site that are most likely to be affected by both types of future rockfall. In this case, primary impact and runout distances for both observed types of rockfall hazard are modelled using RocFall software developed by RocScience®. This is a statistical programme that can be used to model rockfall trajectories along specific trajectories, whilst accounting for both the geometry and material properties of the hillslope a rock fall is travelling down, and the size, shape, initial height, and triggering conditions of the rock block itself.

The following bullet points outline the general methodology that is followed for using RocFall-2D software to obtain primary impact and runout distances for both large-scale potential failures and general small-scale tafoni weathering-induced failures.

1. For each identified large-scale failure, a slope profile representing the most likely runout trajectory was extracted from an appropriate DEM using ArcGIS spatial analyst tools.
2. Based on field mapping, each slope profile was assigned materials along its length (e.g., sand, talus unweathered sandstone etc.). Each material type is assigned parameters for the normal and tangential restitution, roughness, and friction. Talus and tafoni weathered materials are modelled as “rough” surfaces to better reflect the depressions and protrusions within the surface that can influence a rockfalls behaviour. These parameters and associated standard deviations are selected based on the RocScience library values, which are derived from a variety of published sources including Azzoni *et al.,* (1992; 1995) and Chau (2002).
3. A “rigid body” (i.e., the rockfall to be modelled) was then defined within the slope profile for each model. For the potential future large-scale failures, the rigid body (often called the “seeder”) was placed at the exact position along the slope that it was observed in the field. The sizes and shapes of these are based on the field observations for the relevant block.
4. To model the small-scale tafoni-weathering induced rockfall hazard, on each slope profile extracted for the specific large-scale failures, additional “small-scale” seeders are placed at the top of the modelled slope and assigned shapes and sizes based on the field observations from the relevant site location.
5. The seeders for the large potential failures were then assigned starting velocity and rotation parameters depending on the expected failure mechanism identified in the field. These parameters were not used for the smaller scale tafoni-weathering cases, as their triggering mechanism is less prone to building inertia prior to transitioning into a rockfall. Both the large-scale and small-scale seeders were assigned density values of 2463 kg/m^3, which is typical for sandstone.
6. At this stage, models were now defined at the locations of all large-scale failures. The models were then run using an iterative process, whereby 50 model runs were used for each seeder, where each run uses different variations of material and seeder properties based on the standard deviations.
7. From the 50 models runs, the worst-case primary impact distance and runout distance were extracted for both the specific large-scale failure seeder, and the general small-scale tafoni-weathering failure seeder.

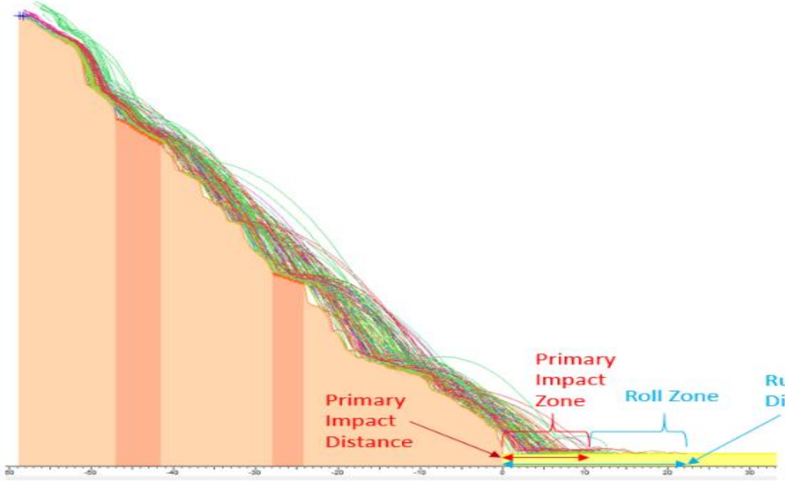
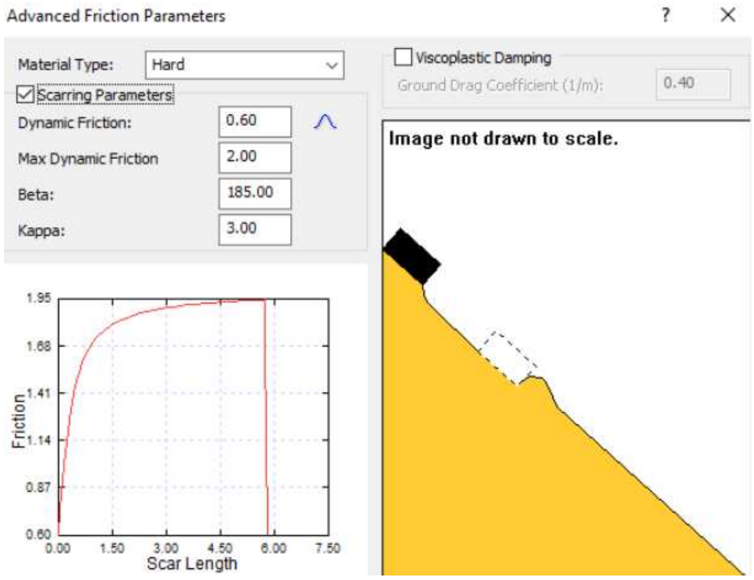


Figure 3: Schematic diagram demonstrating the primary impact and runout distances that can be obtained from RocFall 2D outputs.

The above methodology is used for the majority of all modelling cases. However, it has been found that there are more technically challenging cases that occasionally require additional modelling parameters. First, are cases where rockfalls originating from particularly high and steep cliff faces develop very high velocities (and therefore kinetic energies) and therefore unrealistically high bounces for rockfalls. These bounces occur because high energies are not always sufficiently dampened on impact with the ground to account for increased fracturing of the rock block and/ or cratering of impact surface (i.e. inelastic conditions). To rectify this, a scaling velocity factor of 9.144 m/s (Pfeiffer, 1989) was introduced to reduce the unrealistic bounce heights. This factor is designed to account for the increased energy loss that a higher kinetic energy impact would have on initial impact with the ground. Second, is that some models have unfeasibly long slides where a block falls onto a long steep sand dunes, as the model cannot always account for the build-up of sand that would occur at the front of a block as it travelled. To rectify this, lower tangential restitution values within the accepted range for a given material type were used (Gkouvailas, 2014), and a "scarring parameter" was used to simulate sand build-up in front of a block (Figure 4), and. The scarring parameter effectively models the build-up of a scar (depression) in front of a block as it slides, where the friction along that scar increases exponentially from the initial dynamic friction value to a pre-determined maximum.


Advanced Friction Parameters

Material Type: Hard

☑ Scarring Parameters

Dynamic Friction: 0.60

Max Dynamic Friction 2.00

Beta: 185.00

Kappa: 3.00

☐ Viscoplastic Damping

Ground Drag Coefficient (1/m): 0.40

Image not drawn to scale.

Figure 4: Graphical Representation of Scarring Parameters used within the RocFall 2 software to account for sand build up in front of a sliding block.

3.3 Developing Rockfall Hazard Maps

The final stage of this methodology is to convert the final primary impact and runout distances for both hazard types into graphical hazard zones that could be used by planners to define site boundaries, asset locations, and key areas requiring further mitigation. For the specific large-scale potential blocks, the worst-case primary impact and runout distances were extracted from the models and plotted as solid lines along the 2D modelled section that represents the most likely failure trajectory. A cone is then applied around that line to indicate the potential variability in the actual trajectory that could occur. The radius and position of these cones was determined on a case-by-case basis using expert judgement of the local slope morphology. For the general small-scale tafoni-weathering induced rock/blocks, the worst-case maximum and 85th percentile primary impact and runout distances were extracted from the 50 simulations of the worst-case model for each site. These were then plotted across the entirety of each site to show an estimation of the likely areas affected by the primary impacts and runouts for both the most conservative worst case (100% percentile), and the more physically reasonable worst case (85th percentile).

4. Results and Discussion

The main result from this methodology are hazard maps (e.g. Figure 5) showing the hazard zones that could be impacted by the primary impacts and runouts of both large-scale discontinuity controlled and small-scale tafoni-weathering induced rockfalls. The final aim of this paper is to assess the importance and implications for asset resilience of assessing rockfall hazard at an early stage in project design. In the AlUla cases worked on so far, AECOM have been involved at the pre-concept design stage. This is important, as it means we are able to communicate to the clients and architects via hazard maps such as those shown in Figure 5 which areas of a given site should be avoided for locating assets. I.e. removing as much risk as possible to the asset before it is even constructed thereby increasing its initial and ongoing resilience. Furthermore, if it is not possible to completely disassociate the asset from the hazard, these maps also serve to quantify which assets will need mitigation and what mitigation might be needed. For example, considering Figure 5, if an asset had to be located within the runout/impact cone of Rockfall R167, then the field data already exist to define the specific geological hazard (e.g. likely failure mechanism, location, fall height etc.) and therefore appropriate mitigation (e.g. berms, ditches, catchment fences etc.) can be modelled and designed into the asset from outset. This is clearly much more efficient than attempting to add design mitigation considerations after asset designs have already been finalised, and ensures that asset resilience is fundamentally built into the asset.

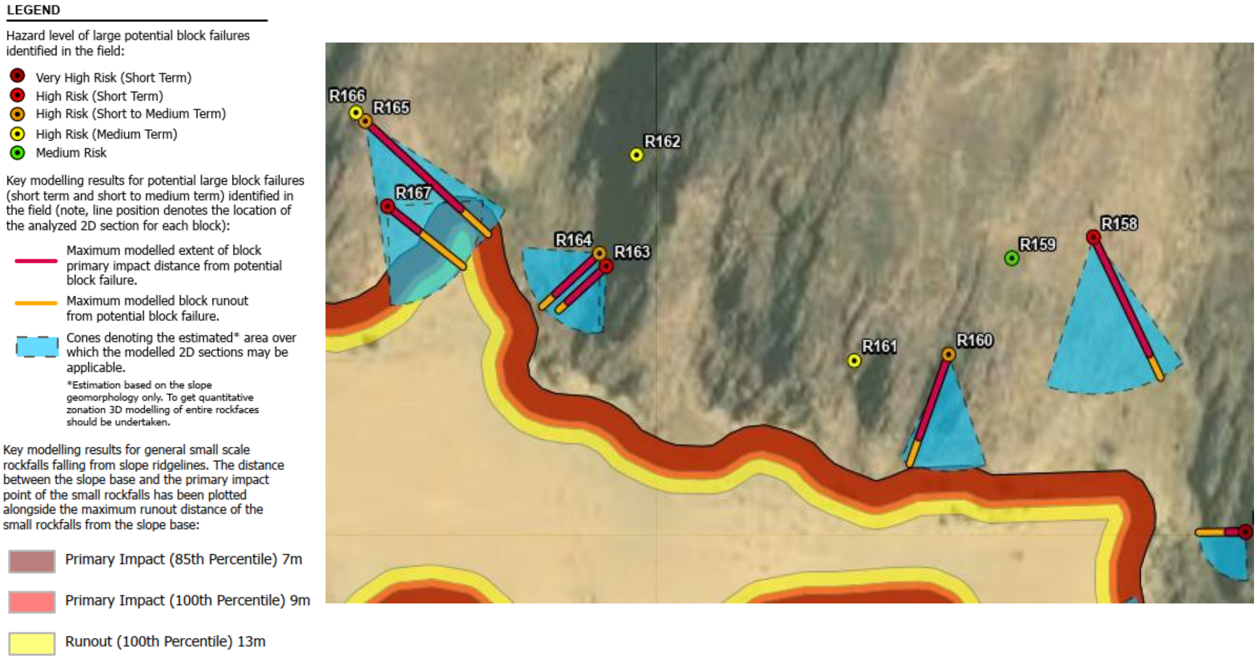


Figure 5: Example hazard map obtained from the presented rockfall mapping and modelling methodology. Note that grid references, coordinates, and scales have been purposefully removed to maintain the anonymity of the site location.

5.Conclusions

In conclusion, this paper demonstrates the general methodology used by AECOM to assess rockfall hazard at an early stage of asset design using a combination of fieldwork and 2-D rockfall runout modelling. From a technical perspective, we present specific solutions to rockfall runout modelling challenges such as unfeasibly high and long rockfall bouncing and rolling, which should be a useful reference point for others who engage with similar modelling work. We also present examples of the final hazard map outputs that stem from our rockfall hazard assessments. Based on our experience, we conclude that when used at an early design stage, these maps allow for efficient master planning to be undertaken which reduces the initial risk posed by rockfalls to assets. Furthermore, this information gathered via the field mapping and modelling process allows potential design mitigation solutions to be considered and designed from the onset, thus ensuring ongoing asset resilience to rockfalls.

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