# A rockfall simulation study for housing development in Gibraltar

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**Abstract:** The city-territory of Gibraltar is dominated by the famous Rock of Gibraltar, which rises some 460 m above sea level. On the eastern side there is a near-vertical face that approaches 200 m in height, whilst on the western side the slope is more gentle. The recent removal of an artificial water catchment area from a 30º steep sand slope between the steep rock cliff and a narrow coastal strip has resulted in opportunities for the expansion of existing housing development on the eastern side of the rock. Development in this area would be susceptible to a significant risk arising from rock falls from the limestone cliff above. A study has been carried out to assess this risk and to investigate options for providing a safe area for development.

This paper describes the study including: the detailed mapping of the slope and the cliff using terrestrial laser scanning; the collection of data to determine the size of the rock blocks that are likely to leave the cliff and arrive at the toe of the slope; and the application of the Rocscience Rocfall program to simulate the rock falls and determine the distance that various modelled rock blocks would travel down the slope, their velocity and impact force at critical collection points. Finally the results of the simulation were used to model different combinations of flexible barriers and/or rock catch areas to protect the proposed housing areas.

**Résumé:** Le territoire de Gibraltar est dominé par le célèbre Rocher de Gibraltar, à 460 m au-dessus du niveau de la mer. Côté Est, un mur vertical s'élève à 200m de haut. La suppression d'un bassin de rétention d'eau situé sur une pente sableuse de 30° encastrée dans une bande étroite entre la falaise rocheuse et le littoral, permet l'extension du développement de la zone résidentielle existante sur le côté Est du Rocher. Ce développement serait sujet à des risques significatifs de chutes de roches des falaises calcaires surplombantes. Une étude a été effectuée pour évaluer ce risque et pour examiner les options assurant la sécurité du développement.

Ce papier décrit cette étude dont : la topographie détaillée de la pente et de la falaise grâce au relevé laser terrestre ; la récolte des données pour déterminer la taille des blocs de roche qui sont susceptibles de tomber en bas de la pente ; et l'application du programme 'Rocscience Rocfall » pour visualiser les chutes des rochers et déterminer la distance parcourue le long de la pente des divers blocs de roche modélisés, leur vitesse et la force d'impact aux points critiques. Par la suite, les résultats du modèle ont été utilisés pour concevoir les différentes combinaisons de barrières flexibles et/ou des zones tampons pour les rochers à fin de protéger les zones résidentielles.

**Keywords:** Engineering geology, site investigation, rock mechanics, geological hazards, mapping.

## INTRODUCTION

Risk of rockfalls from the cliff face of the Rock of Gibraltar is the major constraint affecting a proposed development of two sites at Sandy Bay on the east coast of Gibraltar (Figure 1). The sites are located on the coast either side of a now-abandoned water catchment area. Rockfalls have been recorded along this section of the coastline for many years, some of which have resulted in fatalities. Potential development of this site requires that a rockfall assessment is undertaken. For such a rockfall assessment to be carried out certain key factors need to be determined, the most important of which are the geometry of the slope immediately behind the proposed developments and the size of the rock blocks falling from that slope. Due to the size as well as the steep and irregular nature of the rock slopes immediately upslope behind the proposed developments no accurate topographic maps were in existence, and conventional topographic surveying of suitable accuracy could not be carried out.

Scott Wilson carried out a rock fall assessment for the two proposed developments, involving topographic mapping of the rock slopes immediately above the site using terrestrial LIDAR with a minimum accuracy of 0.1 m, scan-line geological structural surveys of the potential rockfall source areas, and an analysis of the rock block size/frequency distribution of previous rockfall events.

## DESCRIPTION OF THE SITES

The proposed developments are located on the east coast of Gibraltar near the toe of the highest part of the Rock of Gibraltar, which has a maximum elevation of 424 m above ordnance datum (AOD). Refer to Figure 1 for a location map of the two sites. A natural sand slope extends from the base of the rock slope to the sea. This slope once formed the Sandy Bay water catchment area, but the corrugated metal sheeting that was present on the slope has now been removed and the slope has started to re-vegetate. The sand slope starts to pinch out towards the south where the rock slope rises to its highest elevation (424 m AOD) and the toe of the rock slope is much closer to the sea. The rockfall

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analysis has been carried for two (Site Nos. 1 and 2) located on the seaward side of the Sir Herbert Miles Road, immediately to the north and south of the existing Both Worlds residential development.

### Site No. 1

In the area above Site 1 the former water catchment slopes are predominantly formed of sand with a gradient of approximately 30°. The sand slopes extend from 16 m AOD at the Sir Herbert Miles Road to 240 m AOD at the toe of the rock cliff. The rock slopes are formed of limestone and extend to a maximum elevation of some 380 m AOD. Three rock fall fences have been constructed on the disused water catchment slope, the most recent of which is a Geobrugg fence with a capacity of 750 kJ. The two older fences were not formally designed but were installed in the early 1970s as a precautionary measure against rockfalls impacting the existing coastal development. Rockfalls have resulted in several holes and impact marks on these two fences.

### Site No. 2

At Site No. 2 the road is located along the toe of a vegetated cemented scree slope, which rises in elevation from approximately 20 m AOD (at the road) to 120 m AOD at the toe of the rock slope. The angle of the scree slope ranges from 30° to 38° and the surface is very irregular in shape as the cemented scree is composed predominantly of boulders. The rock slope, which extends from the top of the cemented scree slope, is approximately 320 m in height. The base of the rock cliff is much closer to the road (approximately 130 m plan distance) than at Site No. 1.

Two rock fall fences, (constructed in the early 1970s) have been installed on the scree slope immediately above (to the west of) Site No. 2. Several holes and impact marks were apparent in these fences, indicating that rock falls had impacted the fences. It was also apparent that several relict and more recent landslides have occurred on the scree slope. Several boulders were noted along the toe of the scree slope on the western side of the road indicating that recent rockfalls from the rock slope had taken place.


**Figure 1.** General view of the site

## INPUTS REQUIRED FOR THE ROCK FALL ANALYSIS

Engineering geological mapping of the entire disused water catchment slope and adjacent slopes (Figure 2) was undertaken as an input to the rockfall analysis. The mapping concentrated on:

- Accurately mapping the morphology and profiles of the slope immediately upslope of the proposed developments;
- Determining the geology of the slopes;
- Establishing the likely sizes of the rock blocks sourcing from these slopes;
- Characterizing the likely frequency of the different sizes of rock blocks that had fallen from the slopes.

### Slope Profile

Due to the steepness and irregular nature of the rock slopes in the Sandy Bay area no suitable maps were available that could be used to generate accurate slope profiles, as required for the rockfall analyses. Scott Wilson therefore employed the Department of Geography at Durham University to survey the slopes using a terrestrial-based laser scanner. The instrument used was a Measurement Devices Limited Laser Ace 600, which uses a 905 nm eye-safe laser to collect about 250 points per second at a range of up to 700 m. Accuracy is ±0.1 m at 700 m and directional precision is 0.01 degrees. The data was analysed using Archaeoptics Demon 1.5.0 software. Several scans of the rock slope were carried out from different locations so that full coverage of the slope could be achieved. The scans were then meshed together to produce a 3-dimensional surface of the slope. Slope profiles were generated from this 3-D surface for input to the rockfall analyses. The laser scanner data was also used to produce an accurate topographic base map for the field mapping.

## *Geology of the Slopes*

There are three main materials that compose the slopes around the proposed developments (Figure 2):

- Cemented aeolian sand;
- Cemented scree breccia;
- Limestone

### *Cemented Aeolian Sand*

Cemented aeolian sand overlies the cemented scree breccia in the area immediately up slope (west) from the Both Worlds development, and forms the majority of the water catchment slope above Site No. 1. The Cemented Aeolian Sand predominantly comprises medium grained, well-rounded mainly quartz sand grains and exhibits large scale cross bedding. The material has also been cemented as result of calcium carbonate washing into the sand. The naturally formed slopes within the sand are notably regular with slope angles of approximately 30°, reflecting the natural angle of repose for sand. However, as a result of cementation the sand can be seen to stand at angles of 80º to 90º in cut slopes.

### *Cemented Scree Breccia*

Cemented scree breccia forms the slopes south of the Both Worlds development in the location of Site No. 2. In this area these deposits extend from the toe of the limestone rock slope to the sea. Cemented scree breccia also partly forms the toe of the disused water catchment immediately upslope (west) from Sir Herbert Miles Road. The cemented scree breccia starts to pinch out towards Site No. 1 (Figure 2).

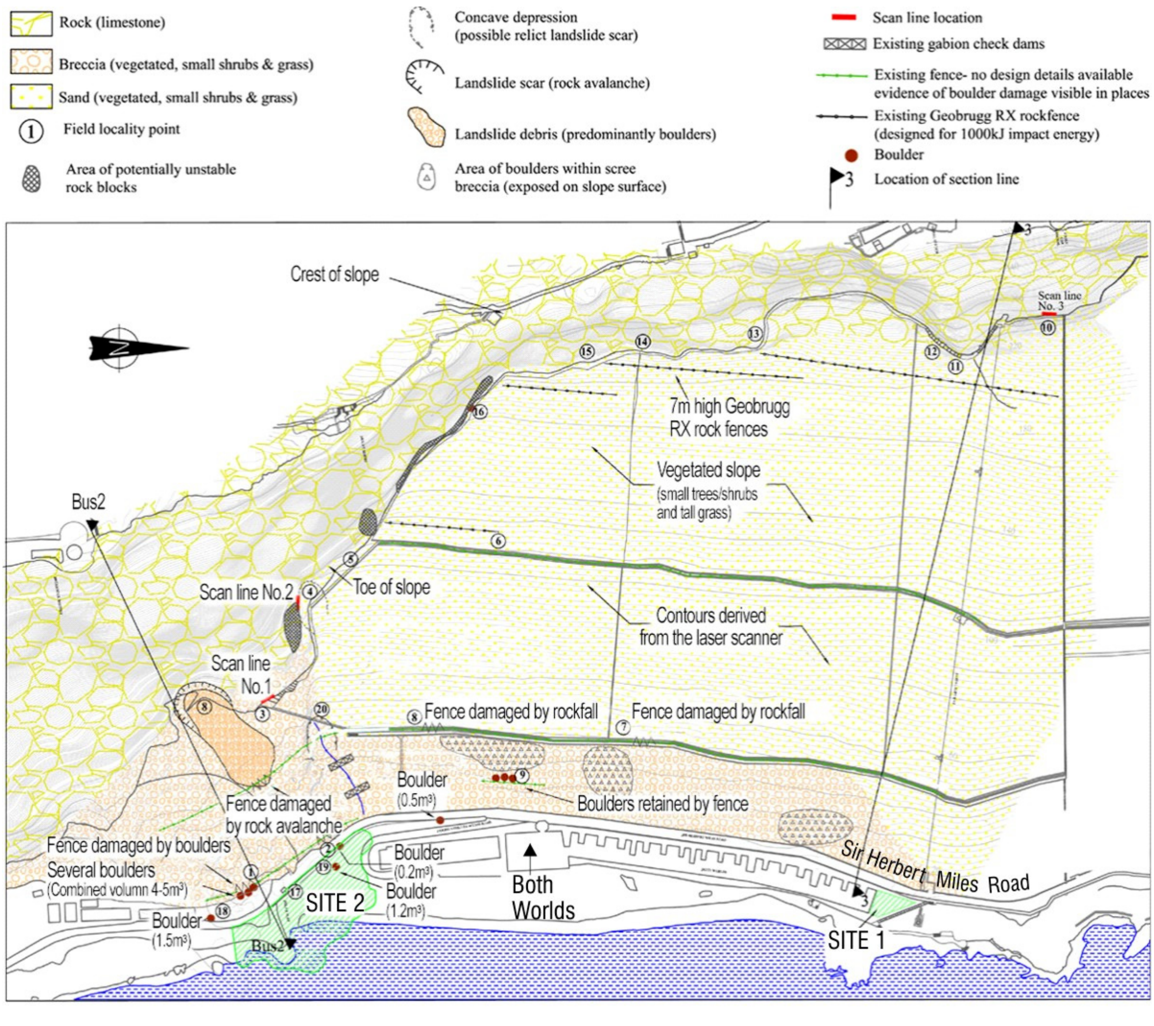

**Figure 2.** Engineering Geology Map of the Site

The cemented scree breccia is predominantly composed of angular boulder and cobble-sized clasts of slightly weathered limestone in a medium-sand and gravel matrix. The percentages of the different clasts within the breccia are highly variable, reflecting the emplacement processes of relict block falls and debris avalanches originating from the limestone cliff. This material has been slightly cemented as a result of calcium carbonate being washed into the matrix from the limestone cliff and from the clastic material within the cemented scree breccia itself.

### *Gibraltar Limestone*

Gibraltar is dominated by a steep cliff formed of limestone, which is known locally as "The Rock of Gibraltar". The maximum elevation of the rock is 424 m AOD at the crest of the slope above (west of) Site No. 2. In the field the rock is strong, slightly weathered, whitish grey to pinkish grey in parts, fine-grained crystalline limestone. The limestone forms the upper steeper parts of the slopes above the proposed developments, with slope angles ranging from 75° to more than 90º (overhanging). Generally the rock slope faces appear very irregular, with vegetation clearly visible in areas. Field mapping identified two main structural geological features within the limestone: bedding dipping 45-60º towards 220º to 270º, and undulating stress relief joints dipping 55-90º towards 080º to 130º.

From the mapping it was also apparent that the dominant failure mechanism of the rock slope was that of planar sliding. Observations made in the field indicate that the stress relief joints formed the main surface along which rock blocks can slide, with bedding acting as a release surface. A kinematic analysis of the rock slope was carried out, using data collected only from along the toe area of the steep rock slope. Findings from the kinematic analysis were in agreement with the site observations, indicating that planar sliding is the dominant failure mechanism. However, given the variation in orientation of the two dominant discontinuities and the occasional presence of other discontinuities and the lack of data from higher up the slope, the possibility exists that wedge and toppling failures could occur locally on the rock face.

## ***Establishing the Size of the Rock Blocks***

It was not possible to obtain statistically representative records of historical rockfalls from which to derive a size/frequency relationship. Thus, a method for establishing this relationship was devised based on a combination of desk studies, interviews with local people and field studies, which comprised:

- A boulder survey, which recorded the size and shape of all the rock blocks found on the surface of the slopes around and between Site Nos. 1 and 2;
- Scan line surveys, which recorded structural geological data from scan line surveys carried out on the insitu limestone cliff.

The justification for these two approaches is that once a rock block starts to move down slope, the shape and size of the rock block can change as a result of the movement mechanism. These processes may cause the initial rock block to break into smaller pieces, changing the shape, size and therefore travel distance and impact force of the block. Hence, the initial rock block at source may be much larger than the boulders that actually reach the toe of the slope. The boulder survey was intended to assess the size and shape of rock blocks that had previously fallen from the steep limestone cliff, while the scan line surveys were carried out to assess the 3D geometry of the rock mass, and hence the likely volumes of rock that could source from the rock slopes themselves.

### *Boulder Survey*

A boulder survey was carried out of all the rock blocks that were seen to have fallen from the steep limestone rock slopes around the sites. A total of 27 rock blocks was recorded on the slopes around the sites and of these, 56% were less than 0.5 $m^3$ in volume. The largest rock block observed on the slopes around the proposed development had a calculated volume of 3.2 $m^3$.

### *Scan Line Surveys*

Scan line surveys are a widely recognised technique for collecting structural geological data (Hoek & Bray 1981 for example). The lines used were chosen as being representative and safe to work in after a reconnaissance survey that included part of the Main Ridge. The scan line surveys were carried out in different orientations so that the 3-D properties of the rock mass could be assessed. From these scan line surveys the fracture frequency and mean spacing of the insitu rock mass were calculated. The results of the scan line survey are considered to be a reliable indicator of the most common size of rock blocks and the limiting maximum block size. The maximum discontinuity spacing recorded from the scan line data is 2.2 m, which would equate to a rock block of approximately 10.6 $m^3$. It was apparent from the field mapping that the rock block size distribution was mainly determined by the spacing between the bedding planes and stress relief joints

## ***Establishing the Size/Frequency Distribution of the Rock Blocks***

### *Interviews*

Several of the residents had either witnessed or heard of rockfalls that had impacted the Both Worlds buildings. It was noted that the sizes of these rock blocks were of the order of 0.5 $m^3$ to 1 $m^3$, with no mention of any larger rocks.

In addition to these small rockfalls, a much larger event was recorded in February 2002 at the portal of the Dudley Ward tunnel some 300 m to the south of Site No.2. Golder Associates (2004) reported that c.40 $m^3$ of debris was present on the road, but that each individual boulder was <1 m in diameter. It was noted that the morphology of the slopes within the vicinity of the Dudley Ward tunnel portal is quite different from that of Sites 1 and 2. The tunnel portal is located immediately below vertical to overhanging rock cliffs. This difference in slope morphology has a major implication on the impact of any rock falls since a rock block falling from the slopes above the Dudley Ward Tunnel Portal would be expected to fall freely, with limited impacts/bounces, onto Sir Herbert Miles Road. In contrast, for a rock block to impact Site 2 the rockfall analysis has shown that a rock block must bounce several times before impacting Sir Herbert Miles road, with a high likelihood of fragmentation before it reaches the toe.

In the absence of any statistically viable data concerning historic rock falls, it was decided to use the Geobrugg OPTUS® frequency-based approach to determine the required energy absorbing capacity of the mitigation system in order to safeguard the proposed development. This system is based on a daily, 1 in 10 year and 1 in 100 year rockfall return frequency. It should be noted that these return periods are not the actual frequency of rockfall events but are related to the energy absorption capacity of the mitigation design. For example, any mitigation design should be able to absorb the energy from a daily event without damage, requiring only periodic maintenance. In comparison the mitigation design would have to be partially or even completely replaced if impacted by a 1 in 100 year design event. A daily event has been assumed as the largest boulder taken from 90 % of the recorded number of rock falls, a 1 in 10 year event as the largest boulder taken from the top 9% of the recorded rock falls and a 1 in 100 year event as the largest recorded boulder within the vicinity of the site.

Since statistical data was not available, a judgement-based assessment was made from the range of observational and anecdotal evidence collected. In this way three magnitudes of rockfall described broadly as ‘most frequent’, ‘unusual or extreme’ and ‘worst credible’ were adopted as the daily, 1:10 year and 1:100 year events in the Geobrugg OPTUS® frequency-based approach (Table 1).

**Table 1.** Details of the analysed rock blocks. The mass of the blocks was calculated using a unit weight of 25 kN/$m^3$ for the Gibraltar limestone.

| Description of Event | Frequency Equivalent | Rock Block Volume ($m^3$) | Mass (kg) |
|---|---|---|---|
| Most Frequent | Daily Event | 0.5 | 1276 |
| Unusual or extreme | 1 in 10 Year Event | 3.2 | 8163 |
| Worst credible | 1 in 100 Year Event | 12 | 30612 |

The largest boulder identified in the area around the site was 12 $m^3$. This rock block was located within the scree breccia and was probably deposited in the Pleistocene when climatic conditions were quite different from present day conditions (Rose and Rosenbaum 1991). Even though no evidence or reports have been found of any rock block of this size having reached the toe of the slope in the area of the two sites, the scan line surveys indicated that this order of rockfall could be generated from the source area. After discussion with an independent reviewer, it was decided that a 12$m^3$ boulder could not be discounted as a ‘worst credible’ event.

# ROCKFALL MODELLING METHODOLOGY

The Rocscience Rocfall® programme was used to carry out the rockfall modelling. This is a lumped mass-modelling programme in which a single rock block is considered to be a simple point with a mass and velocity. The point is then released down the slope along the mapped profile. As the block makes contact with the slope surface, the velocity normal and tangential to the slope is reduced by the coefficients Rn (normal coefficient of restitution) and Rt (tangential coefficient of restitution), which are dependent upon the material type. The programme also takes into account the roughness of the slope surface and the angular velocity of the rock blocks. For the analysis to be carried out the following parameters were required:

- The size of the modelled rock block;
- The initial conditions of the rock block (failure mechanism);
- Coefficients of restitution for the different materials forming the slopes along the path of the modelled rock fall;
- The angular velocity of the rock block;
- The roughness of the slope along the path of the modelled rock fall.

## *Establishing the Initial Conditions of the Rock Block*

Observations made during the field mapping indicate that the dominant failure mechanism of the rock blocks is that of planar sliding, probably initiated by water pressure and/or root activity in joints. Before a rock block can start to move free-fall it must slide along the failure surface. Thus, at the initiation of free-fall it has an initial velocity. If the size of the rock block, angle of the sliding plane and friction angle of the sliding plane are known then it is possible to calculate the initial velocity of the rock block using the following equation (Giani 1992):

$$V = 2[\sqrt{(g \cdot \sin\alpha - \tan\phi \cdot \cos\alpha) \cdot L}] \qquad \text{Equation 1}$$

where V is the velocity in meters per second, g is the gravity in meters per second, $\alpha$ is the angle of the sliding plane in degrees, $\phi$ is the friction angle of the sliding plane in degrees and L is the length in meters along which the rock block slides before free falling.

For the calculation of the horizontal and vertical components of velocity it was assumed that the sliding plane was inclined at 70°, the friction angle of the sliding plane was 55° (derived from observations and measurements made during the field mapping) and that the length of the rock block in sliding motion (before free fall) was 2.2 m (derived from the scan lines and represents the largest recorded fracture spacing).

### *Coefficients of Restitution for the Different Materials forming the Slopes*

In the Rocscience Rocfall® program the rock block is thrown down the slope along the mapped profile. As the block makes contact with the slope surface, the velocity normal and tangential to the slope is reduced by the coefficients Rn (normal coefficient of restitution) and Rt (tangential coefficient of restitution), incorporated within the Rocfall® program.

The value of R ranges between 0 and 1. If R = 0, then the rock block would stop on impact (representing a perfectly inelastic material) and if R = 1, then the rock block would have the same outgoing velocity as the incoming velocity (representing a perfectly elastic material). The coefficients of restitution influence the travel distance and impact force of a rock fall, and are therefore dependent upon the material that forms the surface of the slope along which the rock fragments travel.

As discussed previously, there are three main materials that form the slopes above the proposed developments: cemented aeolian sand, cemented scree breccia and limestone. The initial values of R have been assumed from a review of available literature (Pfeiffer and Bowen 1989, Giani 1992 and various values contained in the Rocfall® program). The coefficients of restitution derived from the literature review were then modified based on the modelling (back analysis) of several known rockfall events that had occurred previously within the vicinity of the sites using slope profiles generated from the laser scan survey (Table 2). To allow for variations of the chosen mean coefficients of restitution a standard deviation was incorporated in the analysis.

**Table 2.** Coefficients of restitution adopted for the rock fall analysis

| Material Type | Tangential Coefficient of Restitution (Rt) | Normal coefficient of Restitution (Rn) |
|---|---|---|
| Cemented Aeolian Sand | 0.70 | 0.29 |
| Cemented Scree Breccia | 0.81 | 0.33 |
| Limestone | 0.93 | 0.47 |

### *Angular Velocity*

Angular velocity is an optional parameter that can be considered in the Rocscience Rocfall® program. If angular velocity is included then the rock block can rotate during its trajectory down slope. For analysis purposes models have been run both with and without the angular velocity. Based on this sensitivity analysis rock blocks modelled without angular velocity travelled further and had higher impact energies.

### *Roughness of the Slope*

Slope roughness was used to model local variations in slope geometry. The Rocscience Rocfall® program uses the angle of each slope segment (taken from the surveyed slope profile) to model roughness. Based on the field mapping, the slope surfaces of both the limestone rock slope and the slopes formed of scree breccia were very irregular. This was included in the model by applying a standard deviation value of 5º to the slope angle in the analyses. In the Rocscience Rocfall® program, before a bouncing rock impacts a slope segment, the angle of the segment is calculated from the geometry (e.g. 15° from the horizontal) and the slope roughness is determined from the material specified for the segment (e.g. a standard deviation of 5° if the segment is classified as either limestone or scree breccia). From these parameters a normal distribution is sampled with a mean of 15° and a standard deviation of 5°. This normal distribution is sampled and the programme then uses this value for the impact calculations.

## RESULTS OF THE MODELLING

A total of ten slope sections (five for each site) was analysed using the rockfall modelling programme. Each section was analysed using 1000 simulated rockfalls, with the source area for each detachment being evenly distributed from the toe to the crest of the rock slope portion of the section. Figure 3 shows the modelled rockfall trajectories for the most critical sections from the two sites (Site 1, Section 3; Site 2, Bus Stop Section 2). The outputs from the rockfall analyses are presented in Table 3. These values were calculated for collectors located along the toe of the slope on the western side of Sir Herbert Miles Road.

**Table 3.** Worst-case impact energies recorded at each site.

| Site No. | Section No. | Impact Energy at Collector (kJ) 0.5 $m^3$ Rock Block | 3.2 $m^3$ Rock Block | 12 $m^3$ Rock Block |
|---|---|---|---|---|
| 1 | Section 3 | 250 | 1,660 | 6,600 |
| 2 | Bus Stop Section 3 | 2,200 | 12,000 | 80,000 |

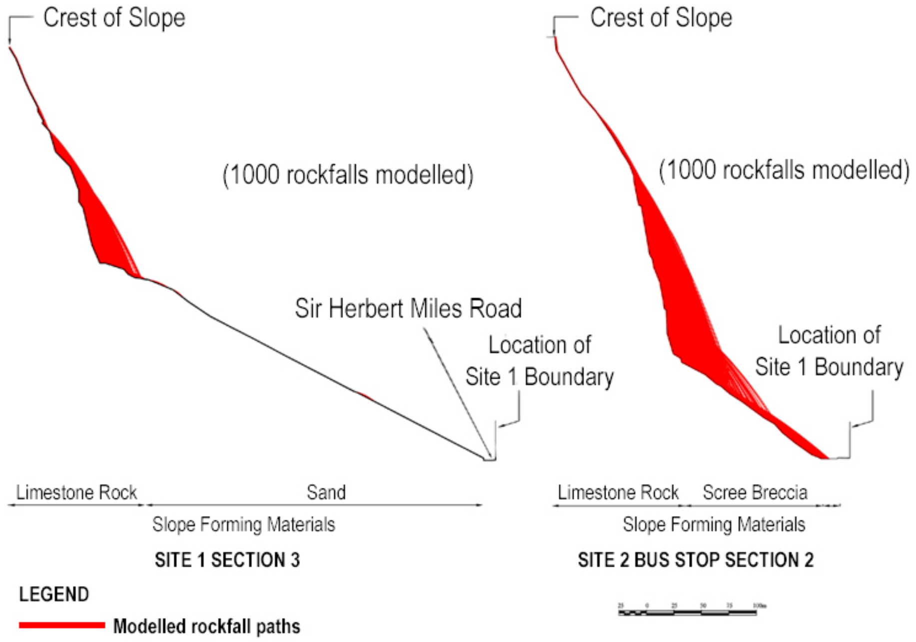


**Figure 3.** Modelled rockfall trajectories for the most critical sections from Sites 1 and 2.

## SENSITIVITY OF THE MODELLING

The sensitivity of the modelled rockfall trajectories and impact energies derived from the rockfall analysis of Section 3 were assessed against the slope roughness. As discussed previously the Rocscience Rocfall® program models slope roughness by applying a standard deviation to the slope angle of each particular slope segment that the modelled rock fall impacts. The length and angle of each slope segment, which makes up the slope profile, are traditionally derived from either contour maps or topographic line surveys. The slope profiles derived from the laser scanner, however, were so detailed that the number of slope segments linking the surveyed points for any particular section had to be greatly reduced so that the data could be imported into the program. In order to make sure that the numbers of points were reduced while making sure that the overall shape of the profile was not lost the data was filtered using the Archaeoptics Demon 1.5.0 software.

It was decided to test the sensitivity of the rockfall modelling against slope roughness by carrying out a rockfall analysis using a section derived from the contour map, shown in Figure 3. Although this contour map was produced from the laser scanning the contour intervals are 2 m so the definition of the contours is far less than the 0.1 m accuracy of the laser scanner. However, these contours are still more accurate than a slope section surveyed by conventional means bearing in mind the topographic constraints of the site. From the rockfall modelling it was found that the maximum impact energy of the modelled rock fall trajectories derived from the slope section generated from the contour map was 205 kJ for a 1 in 100 year design event. This is much lower than the 6,600 kJ impact energy derived from Section 3, using the more detailed slope section. The results from the rockfall modelling are shown in Figure 4. This difference in impact energy is substantial. Thus, if conventional survey techniques were used to map the slopes above Site Nos. 1 and 2 then the impact energies of the modelled rockfalls would have been far less, leading to an inadequate design.

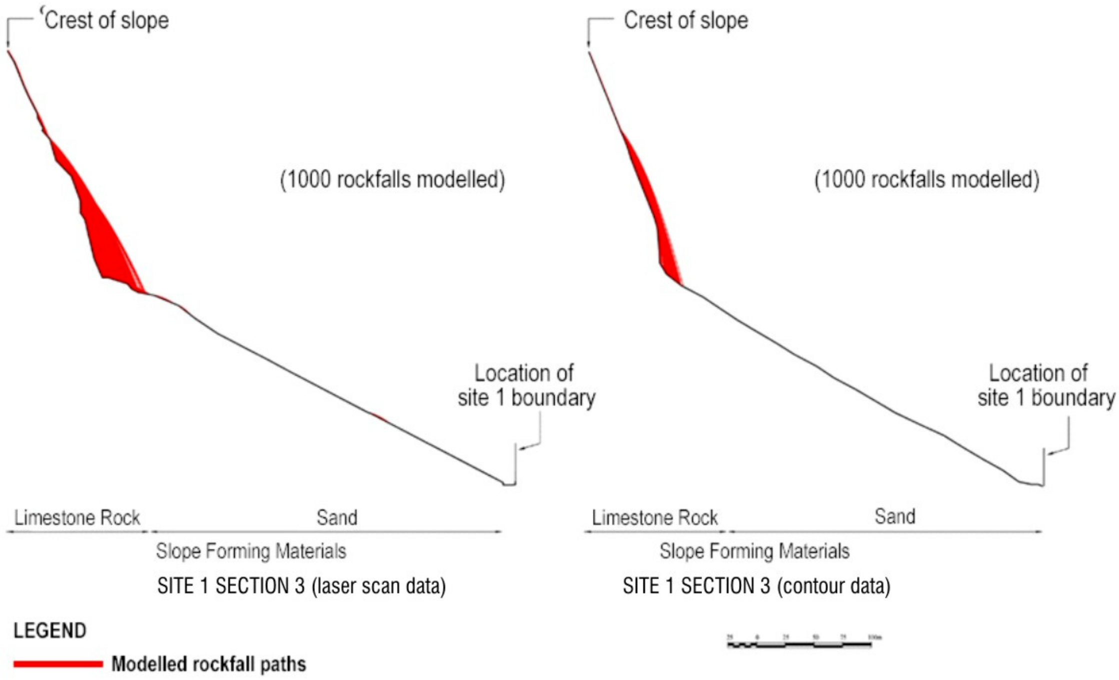


**Figure 4.** Results from the sensitivity modelling carried out for Site 1

## DESIGN OF SAFETY BARRIERS

The impact energy of the largest modelled block was found to be much greater than the maximum capacity of the safety fences currently available. Further rock fall analyses were carried out with sand traps of various widths at the toe of the slope until it was found that the energy of the particle either stopped in the sand or dropped to below the capacity of a suitable safety fence. This process established the technical feasibility of constructing a barrier system that would provide adequate protection to the proposed development. Further work would be required to investigate alternative configurations, one of which is the use of multiple fences. This requires sophisticated mesh analysis, which has been carried out by the Snow and Avalanche Research Institute at Zurich University on behalf of Geobrugg.

## CONCLUSIONS

A novel methodology has been devised to investigate and evaluate the risk posed by rockfalls for a proposed coastal development below a cliff face on the Rock of Gibraltar. In the absence of historical rockfall records use was made of a combination of structural geological mapping, inspection of the scree deposits and loose boulders on the slope and local interviews in order to establish design rock fall sizes. Detailed laser scan mapping was used to obtain topographical information from which cross section profiles were generated for the analysis. Not only was this technique found to provide the necessary information for the modelling in the absence of published topographic mapping, but its greater detail compared with any conventional topographical survey significantly influences the results of the rockfall simulations because it more accurately models the roughness of the ground surface. Laser scan mapping is therefore to be preferred for this type of modelling even if topographic survey data is available. The Rocscience Rocfall® program is relatively simple to use and appeared to provide realistic and credible rockfall models and terminal energy values. Its use can be extended as a design tool for sand traps and selection of safety fences.

**Acknowledgements:** The authors are grateful to Mr Abe Massias of Abco (International) Ltd for permission to publish this study and to the following for their contributions to the project: Steve Handsley (methodology), Martin Griffin (Rocfall analyses) and Pam Stafford (CAD) of Scott Wilson, Nick Rosser and Stuart Dunning of Durham University for the laser surveys and Jennifer Sackett of Connell Wagner for graphic design.

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