ROCKFALL PROTECTION TO DUDLEY WARD TUNNEL, NORTHERN APPROACH, GIBRALTAR

S.W. Lightbody

Golder Associates (UK) Ltd, Sirius Building, The Clocktower, South Gyle Crescent, Edinburgh, EH12 9LB, UK.

ABSTRACT

The iconic Rock of Gibraltar is dominated by Jurassic Limestone Cliffs that extend up to 400m above sea level. Physiologically, the Rock provides many rock fall hazards for the 30,000 community as well as posing many challenges for those responsible for providing rock fall protection. In February 2002, a large rock fall resulted in the fatality of a driver passing through the entrance to Dudley Ward Tunnel on the east-side of the Rock. The road was closed indefinitely due to the high rock fall risk resulting in the loss of a circular route around the Rock. In December 2009, Golder was appointed to develop and manage a scheme to safely re-open the highway. The final scheme which is the subject of this paper, was completed by November 2010 and consisted of a rock fall canopy (shelter) on the initial 100m from the tunnel with the remainder of the highway protected by a rock fall catch ditch constructed from re-cycled rubble waste and a 'green' rock fall corridor which was delimitated by a reinforced concrete boundary wall along the highway separating the highway from the rock fall hazard area. 400m of high capacity catch fence were also constructed to provide protection during the construction phase and additional protection to the highway in the long term.

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email: slightbody@golder.com

INTRODUCTION

Gibraltar stands near the junction of the continents of Europe and Africa, and close to the boundary of the Mediterranean Sea with the Atlantic Ocean. Gibraltar has a total land area of approximately 5.8km². It forms a narrow peninsula 5.2km in total length and 1.6km in maximum width, protruding southwards into the Mediterranean Sea from southern Spain, (Figure 1).

Topographically, the peninsula can be described in terms of three parts (Figures 1 and 2). From north to south these comprise:

- The Isthmus. A narrow neck of low-lying land, at approximately 3m above sea level, which joins Gibraltar with mainland Spain.
- The Main Ridge. From the North Face running southwards for nearly 2.5km, the Rock of Gibraltar forms a sharply ridged crest rising to a maximum height of 425m above sea level. In an east-west profile the ridge is asymmetric. The eastern side slopes very steeply down to the sea. The lower parts of this slope are moderated by scree breccia and windblown sands, but the limestone cliffs above are nearly vertical. In places the scree breccia has been quarried leaving steep scree cliffs. In contrast, the western slope is less

Figure 1. *General view of Gibraltar, from the south.*

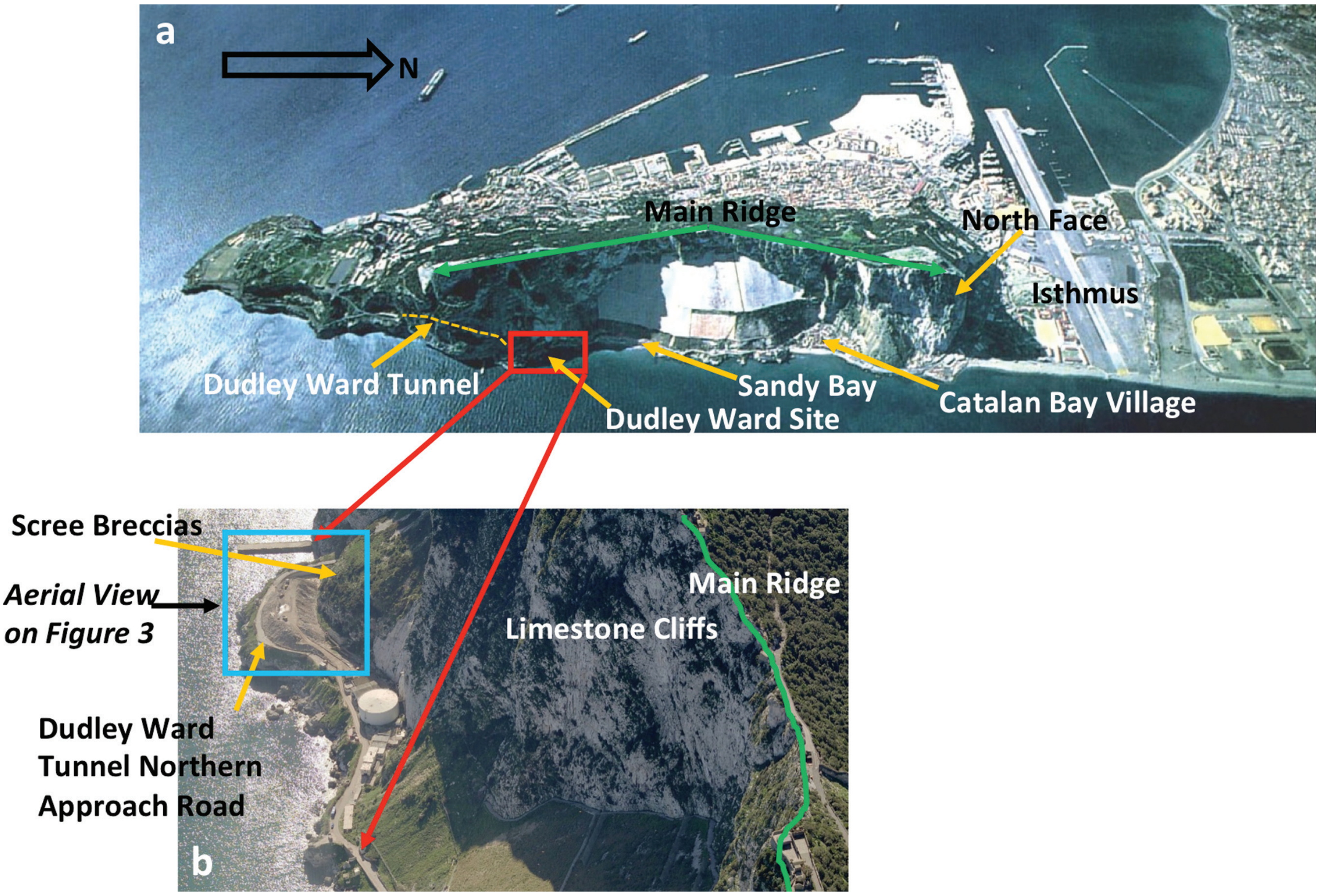

Figure 2. *(a) General view of Gibraltar, from the east, (b) The limit of the Dudley Ward Site, from the north.*

steep. Midway down the western slope there is a north-south trending cliff-line. The lower parts of this slope are covered in sands and locally in scree breccia, and

- The Southern Plateaux. South of the Main Ridge, the Rock slopes steeply down to the Windmill Hill Flats, which is a flat plateau inclined gently southwards from 130m down to 90m above sea level. This plateau is bordered further south by a second abrupt slope that leads down to the Europa Flats plateau, inclined further southwards from some 40m down to 30m above sea level. Steep cliffs fringe this plateau where it meets the Mediterranean Sea.

Physiologically, the Rock provides many rock fall hazards for the 30,000 community as well as posing many challenges for those responsible for providing rock fall protection. This was emphasised when in February 2002, a large rock fall resulted in the fatality of a driver passing through the entrance to Dudley Ward Tunnel on the eastside of the Rock.

The Dudley Ward Tunnel Northern Approach Area (the site) is located on the east side of the Main Ridge (Figure 2). The western side of the site is delineated by steep cliffs covered with sporadic vegetation and many loose boulders. These cliffs extend to some 420 metres above sea level (Figures 2 and 3). Immediately adjacent to the existing tunnel portal, the cliffs are moderated by cemented scree breccia slopes at approximately 25 to 40 degrees (Figures 3 and 4). However, these scree breccias have been quarried in the past leaving near vertical, and sometimes, overhanging sections at their base. The eastern side of this site is delineated by an approximately 20m, near vertical, drop to the sea. The northern limit of the site is demarcated by the ComCen Tunnel that runs east to west through the Rock and is under Ministry of Defence control.

The Old Dudley Ward Tunnel Approach Road took a sharp bend around an old tank farm (Figures 2 and 3) and at this point was over 5m above the original floor level of the tank farm. The road then entered the 720m long unlined Dudley Ward Rock Tunnel through a short concrete rock fall shelter (Figure 4).

GEOLOGY

The rocks forming Gibraltar contain evidence of several major events which took place during the geological evolution of the Mediterranean area. Regional evidence demonstrates that when the Gibraltar Limestone, which now constitutes the main mass of the Rock, first formed some 200 million years ago, the Mediterranean was warmer and much wider than at present; deposition of the sediments that subsequently became the bedrock of Gibraltar took place at the bottom of a fairly shallow sea (Rose and Rosenbaum, 1990). Thrusting, faulting and partial overturning of the nappe containing the Gibraltar Limestone some 15-20 million years ago was a consequence of continent-continent collision, as the African tectonic plate moved northwards against the European plate. This collision partially closed the ancient Tethyan Sea that lay between the plates, and deformed the accumulated sediments.

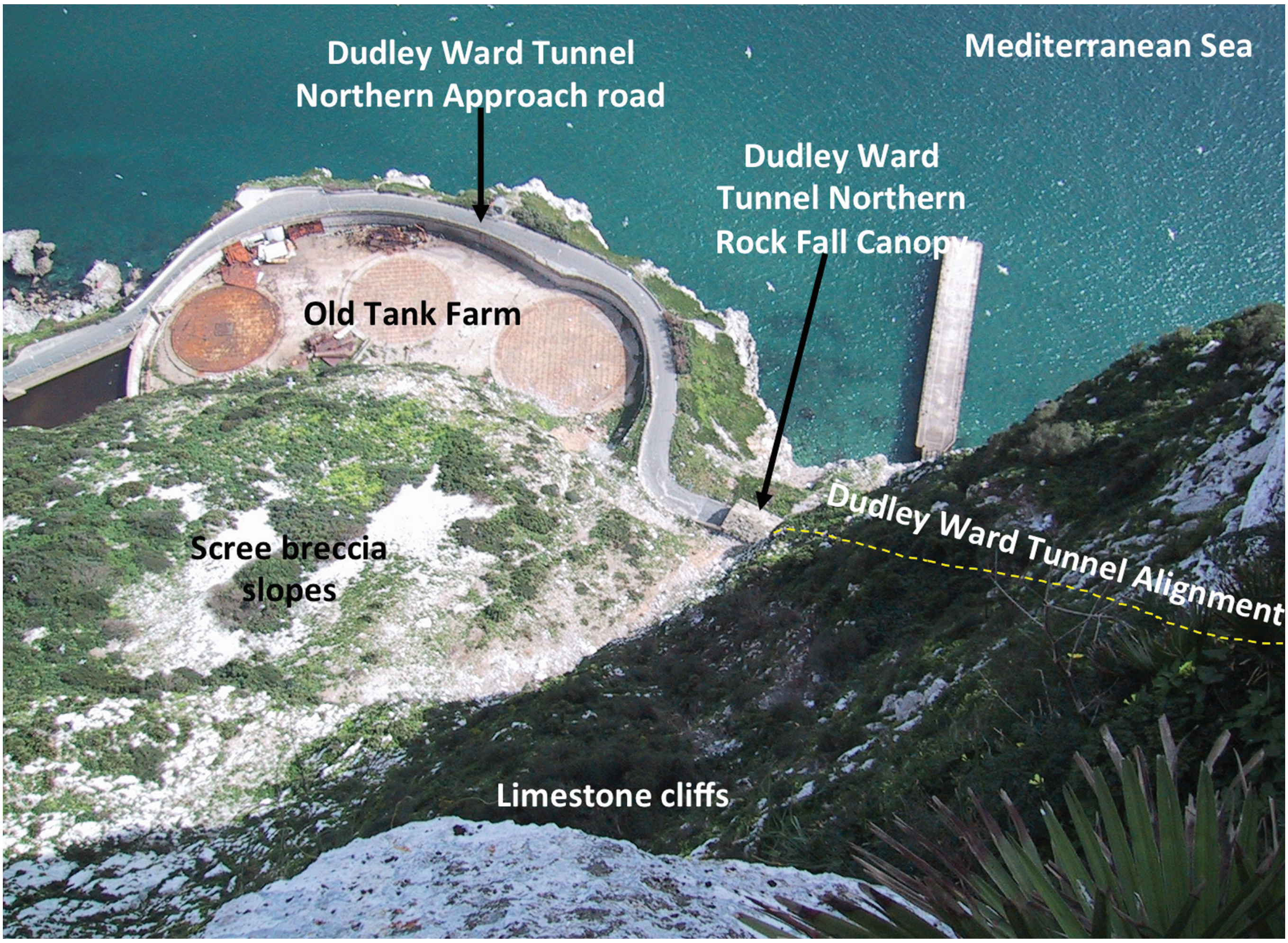

Figure 3. *Aerial view of the original Dudley Ward Northern Approach road and tunnel portal. View looking east.*

Figure 4. *Original Dudley Ward Northern Approach tunnel portal.*

Breaching of the mountain Arc of Gibraltar by the Atlantic Ocean to form the Straits of Gibraltar took place some 5 million years ago, arguably by an immense waterfall. Erosion of the Rock to its current shape is largely a consequence of processes acting during the last 2 million years, as continuing movements progressively raised the Rock above sea level. Sea level changes, most obviously demonstrated by raised wave-cut platforms and beach sediments, were a consequence both of continuing tectonic movements and also global sea level changes, particularly in response to changing global ice volumes during the Quaternary Ice Age. Climatic changes during this period are clearly indicated by the sediments: extensive scree breccias formed by frost action during cold climates, and reddened sands and soils formed during warm climates.

The Dudley Ward area is dominated by the presence of scree breccias with a steeply angled front face beneath the massive Gibraltar Limestone cliffs above, see Figures 3 and 4. The highest point on the Rock is situated directly above Dudley Ward.

Limestone blocks varying in size from sand sized particles to boulders several meters across form the scree breccia slope. The large size of the blocks, the fact that they are all of the same type of limestone as in the cliffs above, and the sharp angular edges of the blocks are all features consistent with their origin as scree accumulated from blocks displaced from the rock mass above.

The scree breccia appears to be partially cemented as a result of groundwater permeating the scree and depositing calcium carbonate. This allows it to stand at angles greater than the angle of repose for scree breccia, which would be around 30 degrees. In some locations, there are vertical quarried faces over 50m high which have only experienced minor raveling of blocks over the last 100 years or more.

The limestone forming the cliff face above is part of the Buffadero Member. This consists of relatively homogeneous sequence of mainly light medium-grey fine-grained limestone often partially dolomitized with near vertical bedding planes and steeply dipping orthogonal joint sets.

ROCKFALL HAZARDS IN GIBRALTAR

The geomorphology of the Rock is such that it is very susceptible to rock fall hazards. Rock falls can cause damage, injury, delay or death to occupiers and owners of sites prone to rock falls. There can also be significant economic losses. Large rock falls could lead to closure of key roads and the emergency nature of stabilisation works could lead to them being carried out at premium rates. Further, road closures could result in significant economic losses to the users of the road as well as the businesses along it.

Even small rock falls, involving a single accident, could result in significant costs incurred through hospitalisation, repairs and, in some cases, for legal costs and compensation.

Generally, rock falls within Gibraltar have had minor consequence and only localised damage to structures has resulted. However, major rock falls have occurred in the past. There are three notable examples. In 1942 a landslide closed the road leading to Catalan Bay Village, on the east side of Gibraltar (Figures 1 and 2) for several years. The closure of this road resulted in the construction of a tunnel to by-pass the landslide (Williams Way Tunnel) and this was no doubt at considerable expense. In 1996 a landslide closed the road leading from Rosia Bay to Camp Bay (Figure 1). This road was reopened in 2001 after carrying out a £1.9 million stabilisation contract.

The rock fall from above Dudley Ward Tunnel in February 2002 was the first rock fall that has resulted in the death of a civilian. However, there are recorded deaths from rock falls during construction of the military tunnels. Coincidentally, one of these deaths occurred during the construction of Dudley Ward Tunnel.

DUDLEY WARD ROCK FALL FATALITY AND INVESTIGATION

At approximately 4:30pm on Monday 18th February 2002, there was a major rock fall in the vicinity of the Dudley Ward Tunnel Northern Portal. Eyewitnesses indicated that they became aware of the rock fall as a result of a loud thunder-like noise. These eyewitnesses were able to make visual contact with the rock fall as it descended the cliff face high above the west of the tunnel portal.

At the instantaneous moment the rock fall occurred, two cars passed through the tunnel. Several blocks forming the rock fall struck the second vehicle. The driver of the vehicle suffered a direct hit from an approximately 2 tonne block and is understood to have died instantly. The passenger of the vehicle suffered minor injuries and was taken to hospital suffering from shock.

Golder Associates (UK) Ltd was appointed by the Government of Gibraltar to investigate the fatal rock fall event and to determine whether it was safe to re-open the road.

The study undertaken by Golder identified the following:

- the rock fall originated from over 300m above the road as a 100t block which fragmented into smaller blocks as it impacted on the cliff face and scree breccia slopes below (Figure 5);
- the position of the Dudley Ward Northern Portal meant that it was prone to rock falls from a wide zone as the Main Ridge arcs above the portal in this area (Figure 3);
- the existing rock fall shelter was too short and too low capacity to protect against the frequent rock falls in the area;
- undertaking a semi-quantitative risk assessment - as Bunce et al, (1997) indicated, the risk to life to road users on the northern approach to Dudley Ward Tunnel was higher than societal tolerable levels (HSE, 1988 and 1989; Whitman, 1984 and Ale, 1991) and, therefore, rock fall mitigation measures were required to reduce rock fall risk to tolerable levels prior to the road being re-opened. This was taken to be 1 x 10-6 annual probability of a fatality due to a rockfall onto the highway.

On the basis of the findings of this study, Dudley Ward Tunnel was closed to the public until such time that funding was available to implement suitable rock fall protection measures.

Figure 5. *Location of the failed seeder block involved in the 2002 rockfall incident.*

PLANNING OF ROCK FALL PROTECTION MEASURES FOR DUDLEY WARD

In December 2008, the Government confirmed that, in order to meet its commitments for power generation and the integrated traffic management plan, it required a new highway scheme to be developed for the 500m approach road to the northern portal of the Dudley Ward Tunnel.

This needed to include the following:

- an upgraded highway alignment which would remove the existing narrow, partially one way, winding road arou.nd the old water tank farm;
- the highway would need to be able to support heavy/high sided construction traffic required for the construction of the new diesel power station planned on the south side of Dudley Ward Tunnel;
- the highway needed to be protected from rock falls such that the annual probability of death would be within societal accepted criteria, taken to be 1 x 10-6;
- the new project should, as much as practicable, use processed/re-cycled rubble waste generated within Gibraltar to, firstly, relieve pressure on the existing rubble waste disposal facility and, secondly, to minimise the importation of quarried materials from outside Gibraltar as part of a sustainable approach to the project; and,
- the project needed to be completed by Autumn 2010 in line with the projected commencement of the power station project as well as coinciding with completion of other highways improvements planned as part of the integrated traffic management plan.

Golder Associates (UK) Ltd was appointed as lead consultant for the project.

The requirement to design and deliver this project in less than two years meant that an unconventional approach had to be taken to the design process and procurement of contracting services. It was identified that the project could be broken up into several smaller packages which would allow design and construction activities to be carried out concurrently reducing the overall programme period. In addition, it would allow the direct appointment of specialist contractors in each construction field reducing main contractor and sub-contractor management costs which would have resulted from a hybrid construction team.

The planning of the construction works also considered the significant health and safety issues with working in a high rock fall risk area. Therefore, in planning the project it was recognised that Phase I works needed to include the provision of temporary rock fall protection measures which would reduce the rock fall risk for future phases within the limits broadly accepted in construction.

The design and construction phases were defined as follows:

- Phase I – The installation of 400m of high capacity catch fences above the highway including the construction of a horizontal rock fall canopy and debris net above the tunnel portal itself;
- Phase II – Following substantial completion of the high capacity catch fences, demolition of old structures along the planned highway route, along with advanced earthworks involving the excavation of rubble waste, screening and processing to form the new highway embankment up to the tunnel portal;
- Phase III – Following completion of the Demolition and Advanced Earthworks Contract, the construction of a 100m long rock fall canopy, 50m long transition counterfort retaining wall, boundary retaining walls, 30m covered walkway into existing rock caverns, along with the placement of 60,000 cubic metres of processed rubble waste to cushion the rock fall canopy and provide a secondary rock fall catch ditch outside the rock fall canopy;
- Phase IV – Concurrently with Phase III, geotechnical maintenance and stabilisation works within the 720m long Dudley Ward Rock Tunnel;
- Phase V – Concurrently with Phase III but following sectional completion of Phase IV, the installation of new tunnel infrastructure (by others) including new tunnel lighting and highway improvements; and
- Phase VI – Concurrently with Phase III, widening of a 30m section of highway on the approach to the Dudley Ward Northern Approach Road, from one way to two way traffic for incorporation into the Dudley Ward Highway Improvement Project.

The key design elements are shown on Figures 6 and 7.

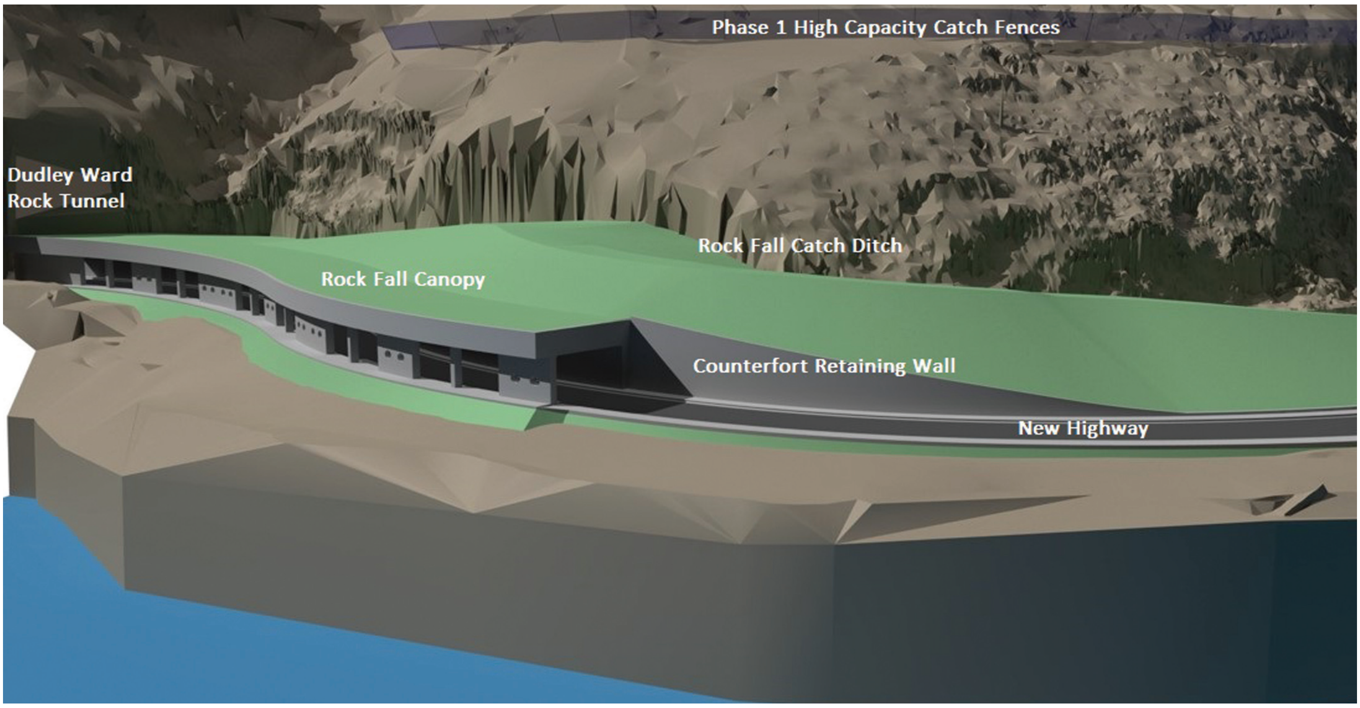

Figure 6. *Key design elements of the project. View looking east toward the limestone cliffs from the Mediterranean Sea.*

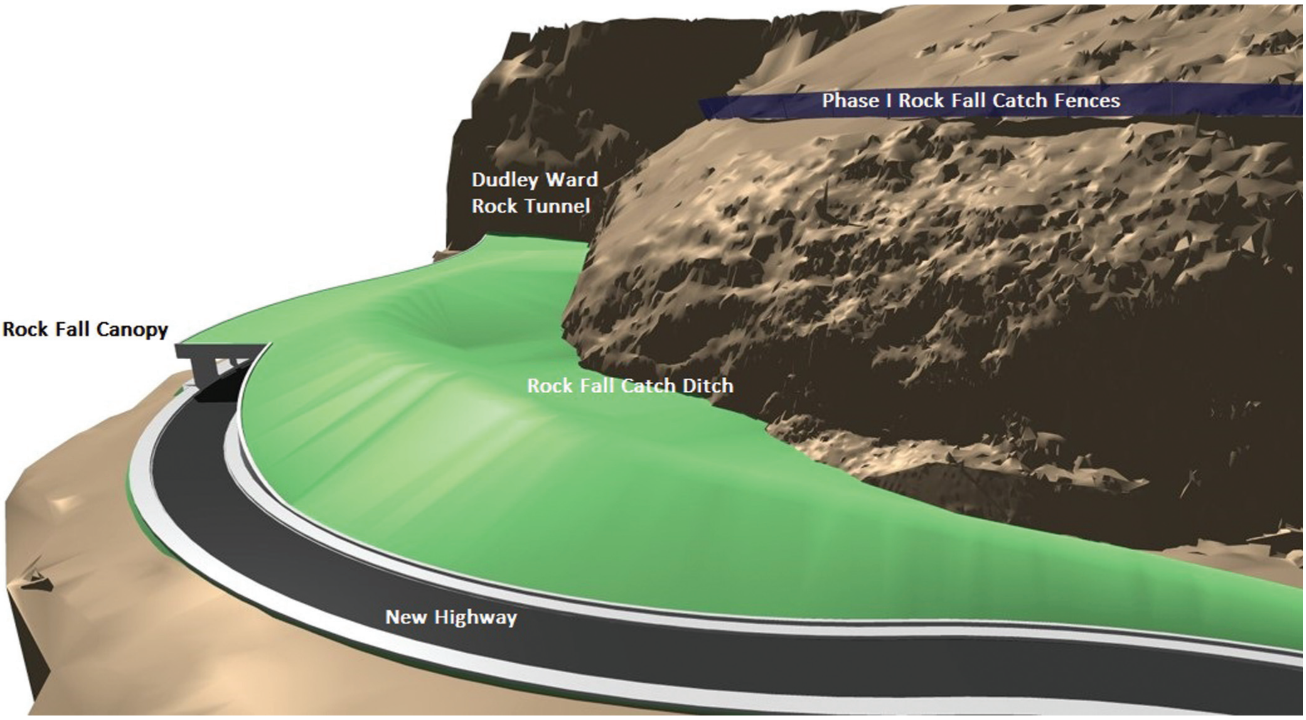

Figure 7. *Key design elements of the project. View looking south.*

ROCKFALL PROTECTION DESIGN CONSIDERATIONS

The critical aspect of this project was the understanding of the rock fall risk, rock fall trajectories, rock fall size, kinetic energies and impact forces. These are discussed in detail in the following sections.

Rock fall block sizes

In order to determine the design block size that could impact either the rock fall canopy or the dynamic catch fences, the following was studied:-

- historical rock fall records in the area, particularly originating from the Buffadero Member;
- physical discontinuity mapping of the cliff face to determine joint sets, spacing and persistence through a restricted roped access inspection and cliff base walkover survey; and
- a review of recently formed scree material on the scree breccia slopes above the Dudley Ward Tunnel.

The conclusion of this assessment was that a block size of 1.5m diameter would be assumed to fall within the serviceability limit of the rock fall protection structures. This was considered to be equivalent to a 1 in 200 year event based on a review of historical rock falls and structural mapping. This block size was larger than the actual block sizes that reached the highway generated by the fragmentation of the seeder block shown on Figure 5. Fragmentation of the seeder block was the result of numerous high energy impacts with the hard clean limestone cliff and vegetated scree breccia slopes on its trajectory towards the highway.

This was further verified by photogrammetric and LIDAR surveys of the limestone cliffs which utilised ROCKSCAN (Ferrero et al, 2004) and Split-FX (Split Engineering, 2016) software to develop remote three-dimensional information about the rock mass, including, stereonets of fracture orientations, distributions of fracture size and roughness estimation.

ROCFALL modelling

Cliff face geometry is seen to vary considerably both vertically and laterally and most rock fall simulations are very sensitive to small changes in the slope geometry. Therefore, in order to maximise knowledge of the slope geometry, a laser survey was undertaken in addition to conventional topographical survey techniques.

Rock fall modelling was carried out using ROCFALL software (Ritchie, 1963; Stevens, 1998 and Hoek, 1987), a statistical analysis program designed to assist engineers with the probabilistic simulation of rock falls and the design of remedial measures. It was important that the results of the rock fall modelling were calibrated to back analysis of known rock fall trajectories in the area (i.e. seeder locations, block size and end points) to verify their credibility and coefficients of restitution for slope materials were adjusted accordingly. This is particularly important on this site as the ROCFALL Version 4 utilised at that time could not accurately assess fragmentation or variations in block shapes.

The output from the modelling identified that the use of high capacity catch fences could not provide full protection along the full route due to the rock fall trajectories and high energies which exceeded catch fence heights and design energy levels respectively. Therefore, it was determined that a rock fall canopy (shelter) would be required in the initial 100m from the tunnel, with the remainder of the highway protected by a rock fall catch ditch constructed from re-cycled rubble waste and a ‘green’ rock fall corridor (Figure 6), delimitated by a reinforced concrete boundary wall along the highway, separating the highway from the rock fall hazard area.

High capacity catch fence design

In order to represent new catch fences constructed on the slope, barriers were constructed within the ROCFALL program. These barriers are a line segment (with one end on the slope surface) that can be placed anywhere along the surface of the slope in order to stop falling rocks, or absorb some of their energy, as they travel down the slope.

Barriers in ROCFALL are assigned a capacity (in energy units). The capacity defined needs to reflect the known capacities of available catch fences. The modelling was carried out using geometries and design kinetic energies for Geobrugg and Maccaferri designed catch fences available within Europe. This enabled the capacities to be applied to the ROCFALL modelling. ROCFALL modelling was used to determine the optimum positions for the 3000kJ high capacity catch fences to be placed above the Site to initially provide temporary rock fall protection and to provide primary rock fall protection along part of the road in the permanent case.

The limitations of high capacity catch fences was recognised in that they work by dissipating the energy imposed by a rock fall exclusively by plastic deformation meaning that the remaining capacity and, perhaps, height due to sagging, is significantly reduced for a second event prior to maintenance being undertaken.

On this basis, it was decided to support the dynamic catch fences by designing a secondary environmental barrier for the external slope of the embankment approaching the rock fall canopy consisting of ‘Tamarisk Africana’, an indigenous saline environment plant which forms dense thickets up to several metres in height with girths in excess of 150mm. Natural barriers have been effective in other areas along the eastside of Gibraltar in stopping or significantly reducing the energy of rock falls reaching the highway below. It is hoped that this species becomes sufficiently dense and well established that it will provide long term protection by the time the dynamic catch fences reach the end of their design life and/or are no longer maintained.

Rock fall canopy (shelter)

Selection process

The need for a 100m long rock fall canopy extending from the tunnel portal was determined as follows:

- A rock fall canopy is more likely to absorb a multiple rock fall event or a larger singular rock fall event (1 in 10 year event); the frequency of rock falls at the tunnel portal, due to the unique topography of the Main Ridge above the Site, was so high that dynamic catch fences would need constant maintenance;
- The trajectories of the rock falls would exceed the maximum height of dynamic catch fences; and
- Even if a catch fence could be constructed above the tunnel portal, near horizontally, it would not retain smaller particles through the ring nets and, therefore, any trapped rocks or falling finer particles would be a distraction to passing road users.

Static equivalent force determination

General

Although rock fall catch fence systems are designed and specified in terms of kinetic energies, most concrete structures are not designed on this basis. Therefore, there is a requirement to convert the impact kinetic energy to a concrete structure to an impact load.

In order to convert a kinetic energy to a load, one of three variables must be known; the deceleration of the mass, the time over which the mass comes to rest, or the distance over which the mass comes to rest.

This is derived from equation (1) below:

$$F.d = ½\ mv^2 \qquad (1)$$

where:

F = impact load;
d = deflection required for at rest conditions;
m = mass of impacting body; and
v = velocity of impact.

As concrete structures are inflexible structures, it can be inferred from the above equation that the impact loads would be very high as the deflection would be very small.

In order to reduce the magnitude of the impact force that will be transmitted to the concrete structure, it is beneficial to apply a cushioning material against the concrete structure so that the actual force transmitted to the concrete structure is mitigated. Furthermore, it can be determined that the energy absorbed by the supporting concrete structure can be minimised by increasing the volume of the struck mass and by ensuring as far as is possible that the impact is plastic (Kirsten, 1982).

The quantification of this equivalent impact force was considered using three approaches, the First Principles Approach, the Swiss Approach and the Japanese Approach, described below.

First Principles Approach

The mechanism of a rock fall impacting a cushioning material can be described as follows.

As the rock impacts on the surface of a cushioning material, the maximum load which can be sustained is the bearing capacity of the cushioning material. This load is applied to slowing the boulder. As the boulder moves into the cushioning material, energy is used up at a rate equal to the applied force times the distance travelled by the boulder. At the same time, the surcharge confinement increases, resulting in an increase in the resisting force so that the boulder is further slowed. This process progresses until the boulder comes to rest. It was recognised that there will be some losses in energy at the maximum penetration due to losses of energy in heat, sound, bearing failure, compaction and shearing of the fill and attrition of the soil particles. Therefore, the net energy may only be 80% of the initial impact energy. The maximum bearing capacity at this point is the maximum force applied to the boulder and equal in magnitude to the force applied to the structure.

This method was adopted by using the general expression for ultimate bearing capacity of a soil, as developed by Terzaghi (Tomlinson, 2001) (equation (2) below):

$$q_f = 0.4\gamma BN\gamma + cN_c + \gamma dNq \qquad (2)$$

where:

q_f = ultimate bearing capacity (kN/m^2);
γ = unit weight of soil (kN/m^3);
B = width of foundation or, in this case, diameter of block (m);
$N\gamma$ = wedge weight factor;
c = cohesion of soil;
N_c = cohesion factor;
d = depth of embedment (m); and
Nq = overburden factor.

Using different block sizes, falling from different heights, it is then possible to calculate the point or depth where the block comes to rest when equation (1) is satisfied. This can be rewritten as equation (3):

$$q_f\pi r^2.d = ½\ mv^2 \qquad (3)$$

The theoretical approach proposed here was compared to the actual rock fall impact performance of twenty two impact craters resulting from the 18th February 2002 rock fall event to determine whether the theoretical termination depths of embedment are reasonably consistent with field evidence.

These results showed a closer correlation at the top end of the range, with block sizes above 600mm, which were determined to be more critical when considering likely maximum design loads.

The First Principles Approach can, therefore, be used to calculate the depth of embedment, from which the maximum bearing capacity at the point where the rock fall comes to rest can be calculated. This resulting pressure is taken to be the pressure that is applied to the structure through the remaining cushioning material. From this pressure distribution and known impact area on the concrete structure, the total impact force can be calculated.

There were several limitations with this approach as, firstly, it is not directly applicable to rock fall assessment due to the likely irregularity of the fallen block and, secondly, the shearing of the cushioning material will change the material properties. Therefore, the approaches outlined below are considered to be more reliable.

Swiss Approach

In Switzerland, there are more than 350 protective rock fall galleries, including avalanche galleries above roads and railways (ASTRA, 2008; Schellenberg and Vogel, 2005; Schellenberg et al. 2008.) Most of these structures have been built since 1960. Most existing galleries in Switzerland consist of reinforced concrete with 80% of them covered by a cushion layer.

After several significant failures of rock fall galleries in 2003, an expert group was formed by the Federal Road Office (ASTRA) to review Swiss guidelines. In 2008, the guidelines were revised but with the technical content the same as the previous guidelines produced by ASTRA in 1999.

A static equivalent force A_d to consider the impact force F_k is used with this equation (4):

$$A_d = C.F_k \qquad (4)$$

The coefficient C considers either ductile (C = 0.4) failure of the structure where members are reinforced for flexure, and shear or brittle (C = 1.2) failure where members are not reinforced for shear or punching shear.

The characteristic value of equivalent static force is given by equation (5):

$$F_k = 2.8 \cdot e^{-0.5} \cdot r^{0.7} \cdot M_{E,k}^{0.4} \cdot Tan\phi_k \cdot [0.5 \cdot m_k \cdot v_k^2]^{0.6} \quad (5)$$

where:

F_k = [kN] Characteristic impact force
m_k =…[t] Characteristic mass of the boulder
r =…[m]… Radius of the idealised sphere
v_k =…[m/s] Characteristic velocity
e = [m]… Total depth of cushioning layer
$M_{E,k}$ = [kN/m^2] Characteristic value of the modulus of the cushioning material
ϕ_k =…[°]… Characteristic value of the angle of internal friction of the cushioning material

The characteristic value of the modulus of the cushioning material is taken to be 20,000kN/m^2 which is representative of medium dense sand.

The application of the guideline is limited to a penetration depth in the cushion layer of smaller than half of the cushion thickness, where, t, is calculated from equation (6):

$$t = [m_k \cdot v_k^2/F_k] \quad (6)$$

Japanese Approach

Japan has studied rockfall protection since the 1970s. Several documents have been produced but the most significant document was produced by the Japan Road Association in 1983. A new edition of the handbook was published in 2000 (Japan Road Association, 1983). From the Japanese handbook, the equivalent static force is given by equation (7):

$$P = 2.108(m \cdot g)^{0.667} \cdot \lambda^{0.4} \cdot H^{0.6} \cdot \alpha \quad (7)$$

where:

P = [kN] Static equivalent force
λ = [kN/m^2] Lame constant
g = [m/s^2] Acceleration due to gravity
H = [m] Falling height
m = [t] The boulder mass
α = [-] Amplification factor for cushion thickness

where:

$$\alpha = (T/D)^{-0.5} \quad \text{equation (8)}$$

and

T = [m] Thickness of cushion layer
D = [m] Diameter of Falling Body

The Lamé's constant is proposed as λ = 1000 kN/m^2. However, Kishi (2005) has demonstrated that Lamé's constant is a function of the thickness of the cushioning material and may be closer to 2000 kN/m^2 for a cushion thickness of 1.5m and almost 8000kN/m^2 where the cushion thickness is less than 1.2 m.

In addition, Kishi (2005) has shown that a triple layer cushion consisting of a granular layer (top), reinforced concrete core slab and expanded polystyrene blocks (bottom), over the initial 20m of the canopy, and in lieu of the conventional 2m granular cushion layer on top of the canopy structure would greatly improve the dissipation of impact forces for the design scenarios considered herein.

Discussion

The results from the different analysis approaches considered for the different design scenarios, yielded similar impact force values for critical loading conditions.

From the ROCFALL modelling, it is apparent that the final 20m approach of the rock fall canopy to the rock tunnel may have potential impact forces up to three times that for the remainder of the rock fall canopy due to the topography close to the tunnel portal. In order to reduce the impact force on the final 20m of the canopy, the three layer cushion was adopted in lieu of a homogeneous granular blanket.

Therefore, adopting this triple layer cushion, the static equivalent force, A_d, as defined by the Swiss Standard and assuming a coefficient of C=0.4 for a ductile failure i.e. assuming sufficient shear resistance is incorporated in the reinforced concrete, this is equal to 2000kN. This equivalent force was factored by 1.6 for ultimate limit state design.

CONSTRUCTION OF ROCKFALL PROTECTION MEASURES

Construction of the rock fall catch fences commenced in June 2009. 400m of 3000kJ catch fence were constructed by CAN Geotechnical Ltd.

The catch fences required the foundations and anchorages shown on Table 1, to carry an ultimate load of 330kN under worst case 3000kJ kinetic energy impact.

Foundations for fence posts	2 No. micropiles, 150mm diameter, fully grouted, with 40mm GEWI® system ground anchors installed into rock
Foundations for lateral fence anchors	150mm diameter, fully grouted, 40mm GEWI® system ground anchors installed into rock
Foundations for upslope anchors	150mm diameter, fully grouted, 40mm GEWI® system ground anchors installed into rock.

Table 1. *Foundation and anchorages to catch fences.*

The superstructure was transported to the slopes using a helicopter. The catch fences were completed in September 2009 (Figure 8). The catch fences successfully retained a large rock fall at the northern end of the Site during the canopy construction. The catch fence was repaired and continues to provide the primary line of rock fall protection to the highway.

The advanced earthworks contract commenced in July 2009 and was completed in December 2009. This included screening and crushing of existing building waste and the demolition of existing structures along the new road alignment, including the old rock fall canopy structure (Figure 9).

Figure 8. *Completed rockfall catch fences. View looking north to Sandy Bay, Catalan Bay and the North Face.*

Figure 9. *Demolition of the Dudley Ward Northern Approach old rock fall canopy.*

The rock fall canopy construction and associated highway improvements commenced in January 2010 and were completed on 1st November 2010 (Figures 10 and 11). This was a particularly challenging phase of the project as the January 2010 to April 2010 period was the wettest since records began, meaning that the works had to be carried out under significant rock fall risk management procedures and protective measures. These were not only provided by the Phase I rock fall catch fences but also the allowance in the contract for non-productive days where rock fall conducive events were forecast. This helped ensure there were no rock fall related injuries during construction.

Figure 10. *The completed 100m long rockfall canopy. Rock fall catch fences visible above the canopy. View looking northwest.*

Figure 11. *The completed rock fall canopy, counterfort retaining wall, rock fall catch ditch and approach road.*

CONCLUSION

The whole of the works were completed and the highway re-opened on 2nd November 2010 by the Chief Minister of Gibraltar. The project was significant in that it now allowed safe use of Dudley Ward Tunnel, two way traffic around the Rock and, in the process, eased traffic fluidity to and from South District.

In memory of the fatal rock fall, the new approach road to Dudley Ward Tunnel was renamed Brian Navarro Way.

In the time since the project was completed, the dynamic rock fall catch fences, rock fall catch ditch and rock fall canopy have been effective in protecting the highway from rock fall events and there are no reported rock fall events on these protected sections of this critical eastside highway.

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