Rockfall geohazard assessment and protection measures on the highway network, North Wales.

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Abstract: Primarily because of the significance to safety and maintenance, the hazard of rockfall affecting the road network is of considerable interest to highway engineers working in mountainous terrain. Initial assessments of rockfall hazard are crucial for design and construction of rockfall protection measures but follow-up assessments are also important for checking the adequacy and monitoring the effectiveness of such measures. In North Wales, five problematic sites were selected for rockfall hazard assessment using stereoscopic oblique aerial photography (SOAP). All of the sites have a history of rockfall activity which presents a recurring problem for maintenance and safety of the highway. They include two coastal headlands at A55 Penmaenbach and A55 Pen-y-Clip and three mountain passes at A5 Nant Ffrancon, A487 Tal-y-llyn Pass and A470 Bwlch Oerddrws.

The findings of the investigations were used to delineate areas of potential rockfall impact and to provide a basis for improvement strategies and appropriate engineering responses to enhance safety. Methods of reducing rockfalls or minimising their effects either prevent rocks from moving out of place or protect the highway by keeping rocks that do move out of place from reaching the carriageway. Various methods can be combined for increased safety at a single site but the extent of their use must take account of the environmentally sensitive nature of the sites and not obtrude on local landscapes. The principal measures involved rocktrap walls, rockfall checkfences, barrier fences, heavy-duty mesh netting, rockfall catch areas, sprayed fibre concrete (fibrecrete) and modifications to drainage systems including channel training works. Supplementary treatments to safeguard the highway included gabion walls, rock anchors and bolts, vertical dowels, cable restraints, masonry buttressing and dentition. The appropriate combination of countermeasures was selected for increased safety at each point of vulnerability.

Résumé: Les dangers de chutes de pierres affectant le réseau autoroutier intéressent beaucoup les ingénieurs des autoroutes travaillant en terrain montagneux, principalement en raison de leur importance pour l’entretien et la sécurité des autoroutes. Des évaluations initiales des dangers de chutes de pierres sont essentielles pour la construction et conception de mesures de protection contre les chutes de pierres mais des évaluations de suivi sont également importantes afin de vérifier l’adéquation et de contrôler l’efficacité de telles mesures. Dans le Nord du Pays de Galles, cinq sites problématiques ont été sélectionnés pour subir une évaluation des dangers de chutes de pierres effectuée à l’aide de la stéréo photographie aérienne oblique (SOAP). Tous les sites ont des antécédents de chutes de pierres et les chutes de pierres représentent un problème récurrent pour l’entretien et la sécurité de l’autoroute. Ces sites comprennent deux promontoires côtiers sur les A55 Penmaenbach et A55 Pen-y-Clip et trois cols de montagne sur les A5 Nant Ffrancon, A487 Tal-y-llyn Pass et A470 Bwlch Oerddrws.

Les résultats des enquêtes ont été utilisés pour délimiter les zones d’impact potentiel de chutes de pierres et servir de base à des stratégies d’amélioration et des solutions techniques appropriées afin d’améliorer la sécurité. Les méthodes de réduction des chutes de pierres ou de minimisation de leurs effets empêchent les pierres de bouger ou protègent l’autoroute en empêchant les pierres qui bougent de tomber sur la chaussée. Diverses méthodes peuvent être combinées sur un même site afin d’augmenter la sécurité mais la mesure dans laquelle elles sont utilisées doit prendre en compte la nature environnementale sensible des sites et ne doit pas empiéter sur le paysage local. Les principales mesures ont inclus des murs de protection, des barrières de sécurité contre les chutes de pierres, des clôtures, des filets à maille renforcés, des zones de retenue des pierres, du bétonnage par épandage, et des modifications aux systèmes de drainage y compris des travaux de canalisation pour les passages hydrauliques. Les traitements supplémentaires pour protéger l’autoroute ont compris des murs de gabion, des tirants et boulons, des goujons verticaux, des dispositifs de sécurité avec câble et des méthodes d’étayage et de soutènement. La combinaison appropriée des contre-mesures a été sélectionnée pour une sécurité améliorée à chaque point de vulnérabilité.

Keywords: case studies, highways, protection measures, risk assessment, rockfall, slope stability

INTRODUCTION

Snowdonia National Park, North Wales lies within easy reach of several cities and large conurbations in England and around 5 million people visit the area of the park each year. Since much of the highway network in Snowdonia passes through mountainous terrain, rocky slopes adjacent to the highway are commonplace and both natural and man-made slopes exist that create an inherent rockfall potential. Where rockfall conditions are present, engineering geological investigations are required not only to assess the geohazard to road users but also for the design and construction of appropriate rockfall protection measures. Follow-up investigations are also required to monitor the effectiveness of these measures and identify new opportunities to increase the overall levels of protection.

This paper describes the procedures adopted in North Wales in relation to rockfall assessment, control and mitigation at five problematic stretches of highway; A55 Penmaenbach, A55 Pen-y-Clip, A5 Nant Ffrancon, A487 Tal-y-llyn Pass and A470 Bwlch Oerddrws (Figure 1).

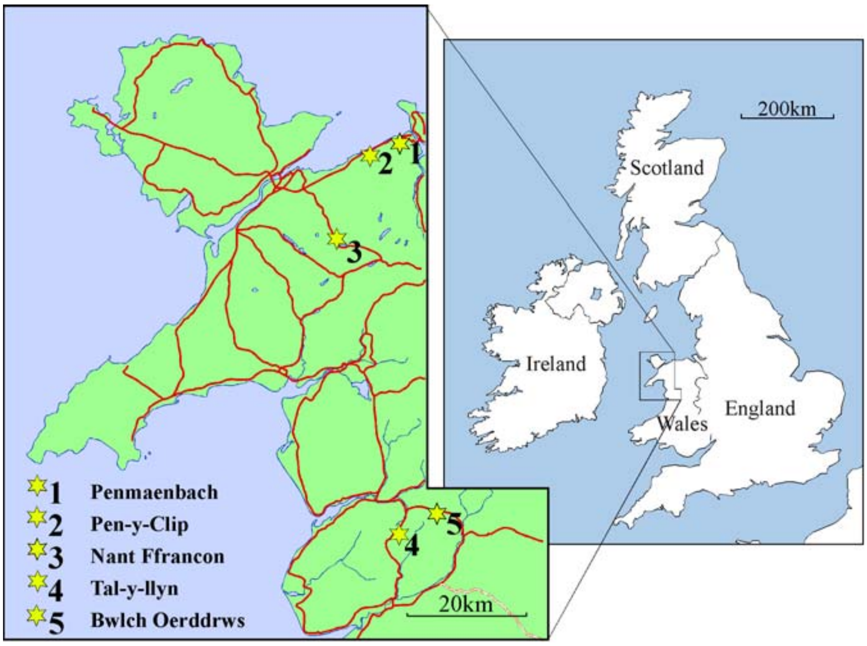

Figure 1. Orientation map and location of case history sites

DESCRIPTION OF CASE HISTORY SITES

The following five sites involve two coastal headlands and three mountain passes where steep terrain and adverse geological factors combine to create potentially unsafe ground above the highway.

A55 Penmaenbach

The spectacular mountainous promontory at Penmaenbach constitutes a natural obstacle on the A55 North Wales Coast Road (Figure 2). Although a road tunnel through the headland accommodates the westbound traffic, the eastbound traffic follows a route only partially in tunnel, the rest being on the open headland.

Figure 2. The headland at Penmaenbach looking eastwards

Geologically, the headland at Penmaenbach comprises a core of acid igneous rocks associated with a late-stage rhyolitic intrusion into the rhyolite lava flows and pyroclastics of the Conwy Rhyolite Formation, a sub-unit of the Llewelyn Volcanic Group of Ordovician (Caradoc) age. The intrusion is generally considered to be a remnant of a lava conduit associated with an Ordovician eruptive centre.

At Penmaenbach the rocks vary from flow banded rhyolites to very fine-grained rhyodacites that are sparsely porphyritic and microporphyritic, with partly crystalline and devitrified glassy groundmass textures. The intrusive rhyolite is grey-green in colour, very fine-grained and only slightly weathered on exposed surfaces. It varies from strong to very strong and compressive strength is about 200 MPa.

The high rocky crags around the headland feature overhanging fretted edges that are naturally spalling and shed rock debris of all sizes. Moreover, the open aspect of the headland in a coastal setting results in high exposure during stormy weather. Additional factors which cause disturbance to both vegetated slopes and rock faces include stress relief, freeze-thaw action, wedging tree roots, grazing sheep and nesting birds. These features combine to increase susceptibility to rockfall activity that presents several hazards to road users.

A55 Pen-y-Clip

The equally spectacular headland at Pen-y-Clip constitutes further natural obstacle along the coastal plain and transportation corridors tend to converge towards the seaward point of the promontory (Figure 3). Again a tunnel accommodates westbound traffic, while eastbound traffic follows a route partially in tunnel, the rest being on open headland.

Figure 3. The mountain promontory at Pen-y-Clip looking eastwards

Geologically, the headland at Pen-y-Clip comprises a core of igneous rocks associated with the Penmaenmawr intrusion. The intrusion measures approximately 3 km by 1 km in area elongate in an east-west direction. According to Tremlett (1997) the intrusion formed by pulsational emplacement of sheets of magma probably during Upper Ordovician time. It intrudes dark grey silty mudstones of the Nant Ffrancon Subgroup (Ogwen Group) of Lower Ordovician (Arenig – Caradoc) age.

At Pen-y-Clip, the rocks vary from quartz-microdiorite to microgranodiorite that commonly contain equigranular plagioclase, orthopyroxene and clinopyroxene, with variable amounts of orthoclase, quartz and biotite. The microdiorite varies from very strong to extremely strong with a compressive strength value of about 250 MPa.

The microdiorite has been intensely quarried for building stone and construction aggregate and one major quarry currently operates to the south of Pen-y-Clip summit. Rock outcrops predominate on the crag and foreshore at Pen-y-Clip but loose scree derived solely from the outcrops above, extensive deposits of quarry related debris and accumulations of fossil scree mantle the flanks of the headland. The scree comprises angular and subangular gravels, cobbles and boulders. Slope angles typically vary between 30 and 50^{o} and the slope is up to 500 m high.

The principal concerns for rockfall activity involve ravelling rock from roadside rockfaces, loose material associated with the scree slopes and large boulders falling from high on the mountainside.

A5 Nant Ffrancon

The magnificent valley of Nant Ffrancon provides a mountain corridor for the A5 trunk road between Lake Ogwen and Bethesda. Here, the highway decreases in elevation in a northerly direction from approximately 300 m AOD to almost 200 m as it traverses a sidelong stretch of rocky ground across the eastern mountainside of the valley (Figure 4).

The valley of Nant Ffrancon, with its characteristic U-shaped profile, is a classic example of a glaciated valley. On its flanks is a series of high cwms, arêtes and hanging valleys. At the head of the Pass, the scouring effect of the debris-laden ice at the base of the ice sheet is evident from numerous roches moutonnée with glacially striated surfaces. The results of periglacial activity related to cycles of freezing and thawing are particularly well developed across the high ground. They include extensive screes and blockfields.

Figure 4. Nant Ffrancon Pass looking southwards

The road traverses a sequence of steeply dipping strata of mainly Ordovician (Caradoc) age that form the western limb of the Idwal Syncline (Howells, Reedman & Campbell, 1991). From the top of the Pass they are sandstones of the Cwm Eigiau Formation (Ogwen Group), acidic ash-flow tuffs of the Capel Curig Volcanic Formation (Llewelyn Volcanic Group), and rhyolites and acid ash-flow tuffs with basaltic tuffs of the Braich T• Du Formation (Llewelyn Volcanic Group). Mudstones of the Nant Ffrancon Subgroup (Ogwen Group) crop out at the bottom of the Pass.

The rhyolite lavas typically show flow banding. Texturally, they are characterized by a high proportion of phenocrysts of both sodic plagioclase and alkali feldspar set in a devitrified groundmass of subspherulitic intergrowths of quartz and feldspar. The ash-flow tuffs contain lithic and cognate chlorite clasts, vary from weakly to strongly welded and in places appear pervasively brecciated. Engineering characteristics vary widely but rock strengths typically range from strong to extremely strong.

Four principal landforms are evident along the eastern side of Nant Ffrancon. From Lake Ogwen, the road passes through a narrow cutting in a ridge of hard rock and the Afon Ogwen cascades down a series of rock ledges to form the Ogwen Falls. The highway then traverses the steep and precipitous flank of the rocky ridge of Braich T• Du. Northwards, the ridge diverges progressively away from the road and increasingly, the mountainside features scree deposits with overlapping talus cones and fan-shaped feeder gullies. Typically, the gullies merge into a single channel cutting through an intervening rock ridge and the streams have incised deeply into the scree deposits. Near the bottom of the Pass, the highway crosses a protalus rampart that rises from the edge of the road, but levels out to form a relatively flat platform that extends to the main rock ridge behind.

The principal concerns for rockfall activity involve ravelling rock from roadside rockfaces, loose material on scree slopes, debris flows associated with stream channels and large boulders falling from high on the mountainside.

A487 Tal-y-llyn Pass

To the south of Cadair Idris, the scenic valley of the Afon Fawnog provides the mountain corridor of Bwlch Llyn Bach, occupied by the A487 trunk road (Figure 5). Here, the highway decreases in elevation in a southwesterly direction towards Tal-y-llyn Lake from about 300 m AOD to almost 100 m as it traverses a sidelong stretch of rocky ground across the southeastern mountainside of the valley.

Geologically, the Pass traverses a sequence of acid tuffs of the Craig Cau Formation (Aran Volcanic Group) of Ordovician (Caradoc) age. The strata dip at moderate angles southwards and form a fault-bounded block lying between the Bala and the Tal-y-llyn Faults.

The acid tuffs vary from block-rich tuffs in the lower part of the sequence to clast free tuff in the upper part. Impersistent bands of rhyolites, basalts, pumice-rich tuffs and mudstone debris flow deposits are also present (Pratt, Woodhall & Howells, 1995).

The high rocky crags and precipitous natural cliffs of Craig-y-Llam feature overhanging fretted edges that are naturally spalling and shed rock debris of all sizes. On the lower slopes, outcrops with intervening scree-covered areas predominate. In two quarries at the head of the Pass, tuffs and mudstones are crossed by numerous fault crush zones and slickensided minor faults.

A series of streams flowing down the hillside are incised into the scree deposits. During rainstorm events, the stream culverts beneath the road frequently become blocked with rocky debris that spills over onto the road and affects the highway. The principal concerns for rockfall activity involve ravelling rock from roadside rockfaces, loose material on scree slopes, debris flows associated with stream channels and large boulders falling from high on the mountainside.

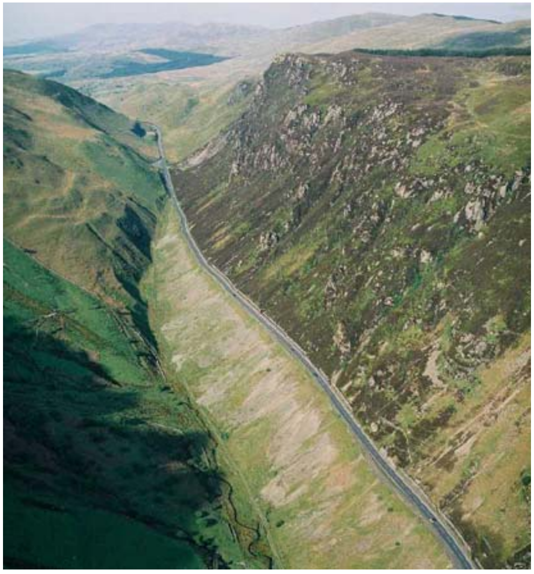

Figure 5. Tal-y-llyn Pass looking northeastwards

A470 Bwlch Oerddrws

To the east of Dolgellau, the col at Bwlch Oerddrws and the valley of the Afon Cerist provide a mountain corridor for the A470 trunk road. This is the highest mountain pass in Wales (Figure 6). The highway decreases in elevation in an easterly direction from about 360 m AOD to almost 160 m as it traverses a sidelong stretch of ground across the northern mountainside of the valley.

Figure 6. Bwlch Oerddrws looking northwestwards

The road traverses a sequence of moderately dipping strata of Ordovician (Caradoc) age. From the top of the Pass they comprise massive acid ash-flow tuffs of the Craig Cau Formation (Aran Volcanic Group) that are overlain conformably by mudstones and siltstones of the Ceiswyn Formation (Ogwen Group).

At Bwlch Oerddrws heterogeneous glacial materials and deposits of scree, colluvium and peat mantle the bedrock. A series of streams flowing down the hillside are incised deeply into these superficial deposits. During rainstorm events, the stream culverts beneath the road frequently become blocked and rocky debris spills over onto the road and affects the highway. Many of these blockages appear associated with minor landslides further up the hillside within the stream tracts. The principal concerns for rockfall activity involve debris flows associated with the stream channels.

ROCKFALL HAZARD ASSESSMENT

The Rockfall Hazard Rating System (Pierson, Davis & Van Vickle, 1990; Pierson 1992) provides a comparative method for ranking rockfall sites by hazard. It was used to assess the rockfall hazard in the five study areas. The parts of the Rockfall Hazard Rating System (RHRS) on preliminary and detailed ratings of slopes were applied. However, based on the estimated potential for rock on the roadway and the historical rockfall activity all five areas received a preliminary rating of *Class A*.

For detailed rating purposes, the rock slopes of the study areas were subdivided into zones presenting different levels of rockfall geohazard, each having different RHRS ratings. Within each zone RHRS values and scores were determined for the following criteria.

- Slope height (m); represents the vertical height of the slope. Rocks on high slopes have more potential energy than those on lower slopes and therefore present a greater hazard and receive a higher rating
- Ditch effectiveness; represents the ability of rockfall catch areas to restrict falling rock from reaching the road
- Slope length (m); represents the length of the rockfall hazard zone measured along the stretch of road
- Average vehicle risk; measures the percentage of time that a vehicle will be present in the rockfall hazard zone
- Sight distance (m); measures the length of road a driver has to make a complex or instantaneous decision
- Percent of decision sight distance; this is critical when obstacles on the road are difficult to perceive or when unexpected or unusual manoeuvres are required.
- Road width (m); represents the available manoeuvring room to avoid a rockfall.
- Geologic character; for slopes where discontinuities dominate or where differential erosion conditions apply.
- Block size or volume of rockfall per event; this measurement also helps in determining remedial measures.
- Climate and presence of water on slope; water contributes to the weathering and movement of rock materials.
- Rockfall history; represents the known rockfall activity at the site.

To illustrate the procedure, the results for segments A-F (Figure 7) at Tal-y-llyn Pass are compiled in Table 1.

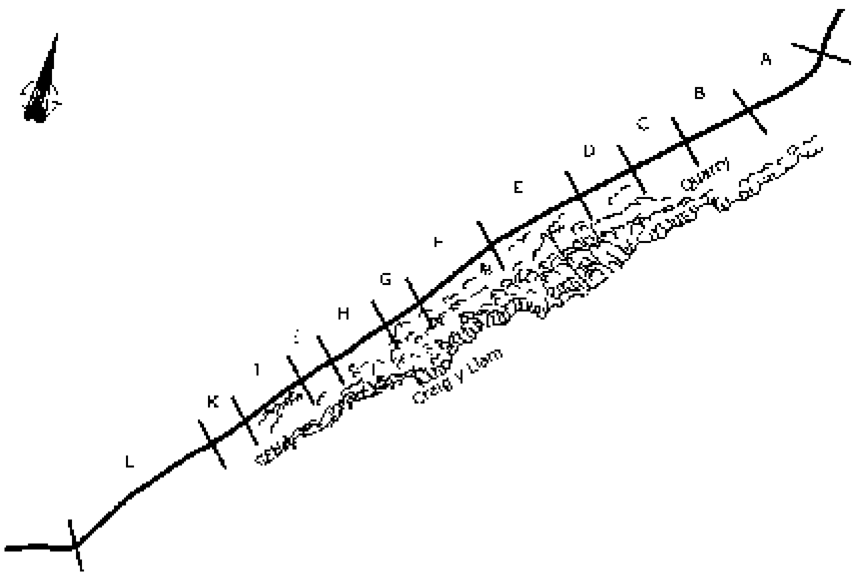

Figure 7. Rockfall Hazard Rating System (RHRS) Zones A to L inclusive along the A487 Tal-y-llyn Pass

Table 1. Rockfall Hazard Rating System (RHRS) results for the upper part of the A487 Tal-y-llyn Pass

Zone	A		B		C		D		E		F	
	Value	Score	Value	Score	Value	Score	Value	Score	Value	Score	Value	Score
Slope height (m)	2	3	130	100	205	100	160	100	190	100	180	100
Ditch effectiveness		3		3		9		55		70		45
Slope length (m)	250		232		212		140		325		285	
Average vehicle risk	33	4	30	3	28	3	18	2	43	8	37	7
Sight distance (m)	26		232		18		55		46		254	
Percent sight distance	15	97	136	1	11	98	32	92	27	92	149	1
Road width (m)	6.5	71	6.4	74	7.8	38	6.9	51	6.1	84	5.9	93
Geology structure		2		9		81		75		75		81
Rock friction		2		15		50		50		50		50
Block size (m)	0.3	3	0.8	20	1.2	78	0.5	8	0.5	8	1.0	35
Climate		18		18		18		18		18		18
Rockfall history		3		3		9		20		25		20
Total		206		246		484		471		530		450

Zones A and B include the north approach to the Pass and relatively little rockfall activity on this stretch gives a comparatively low rating. The slopes in Zone C are considerably higher than within the other sections, but this does not affect the scores because an upper limit of 100 applies to each of the category scores in RHRS. The percent sight distances are low in Zone C due to poor vertical alignment and in Zones D and E due to poor horizontal alignment. Zones C, D, E and F contain areas of fractured rock and receive high scores for geological structure. High scores for ditch effectiveness and road width together with unfavourable rockfall history gives Zone E the highest total score.

Geological condition

To determine the geological conditions for RHRS purposes, initial assessments involved a combination of desk studies of published and unpublished geological maps and records, walkover surveys along the lower accessible slopes and helicopter surveys to observe the steep, upper slopes. However, detailed terrain analysis of rockfall zones was carried out using stereoscopic oblique aerial photography (SOAP) methods.

SOAP is a specialized photographic technique resulting in a series of overlapping, high-resolution, colour images that permit the RHRS zones to be viewed in three dimensions using a mirror stereoscope. Acquisition of the oblique aerial photographs from a helicopter allowed detailed and accurate selection of the most appropriate height, distance and angle to highlight the relevant geological and geotechnical aspects of the terrain to best advantage. Importantly, the SOAP technique ensures that vertical and horizontal scales are kept much the same so that natural features can be viewed without scale exaggeration.

The SOAP images were used to delineate the boundaries and extent of different kinds of rock masses. They were also used to identify recent rockfall paths or tracks and predict the engineering characteristics and behaviour of various rock masses in rockfall zones. SOAP observations of topographic, drainage and discontinuity patterns together with other evidence of rockfall activity provided an ideal basis for assessment of the geological categories in RHRS.

Documented rockfall history

Systematic recording of all rockfall events at the five sites only commenced in the 1990s and so the modern records have limitations. In addition, only rocks larger than about 100 mm in diameter are recorded by geotechnical personnel and usually only following a significant rockfall. However, local highway maintenance personnel were able to provide considerable amounts of background information on the history of rockfall activity at each site.

The published records on rockfall incidents tend to highlight the large events that occur extremely randomly in nature, depending on rainfall amounts, groundwater, slope erosion and other factors. For example, Humphreys (1937) observed persistent and recurring rockfalls at Penmaenbach Headland during the 1930s and he described the largest ever rockfall on the headland that happened in 1932 when some 3000 tonnes of rock fell onto the road.

Similarly, Williams & Doherty (2002) outlined the history of rockfall at Nant Ffrancon starting with the earliest event recorded in 1645. Several huge blocks of rock together with loose soil and gravel blocked the highway in the central part of the Pass in 1954. Multiple debris flows severed the road in 1983 when some 800 tonnes of material fell at several locations through the Pass and stranded four cars in intervening areas. In 1998, another major fall in the central part of the Pass involved some 50 tonnes of material including a single block of rock weighing around 25 tonnes that demolished a 6 m section of masonry parapet (Figure 8).

In addition, Flower & Roberts (1987) recorded noteworthy rockfall events in 1926 and 1927 that blocked Tal-y-llyn Pass and closed the road for 4 months (Figure 9). Interestingly, both of these rockfall events occurred in RHRS Zone E which also yielded the highest total RHRS score for the Pass.

More recently, Doherty & Scott (2005) described the debris flows in January 2005 at Bwlch Oerddrws that closed the A470 trunk road for several weeks (Figure 6).

Figure 8. A5 Nant Ffrancon rockfall event of 3 November 1998; looking south

Interpretation

RHRS scores are intended as a means of comparing different rock slopes alongside the highway and as a tool for prioritizing treatment works. The RHRS system itself does not attach any particular significance to the total score for each slope and leaves it to the individual users to draw their own conclusions based on an understanding of the local conditions that apply. Other considerations may include economic impacts, importance of the highway and availability of alternative routes. However, Hoek (1999) notes that in the State of Oregon, USA slopes with a rating of less than 300 are assigned a very low priority while slopes with a rating of more than 500 are identified for urgent remedial action. Using this precedent for A487 Tal-y-llyn Pass, minor works programmes and further investigations were recommended for Zones C, D, E and F with greatest emphasis placed on improvements within Zone E. A similar approach was adopted at the other case history sites.

Figure 9. A487 Tal-y-llyn Pass rockfall event of 18 July 1926; looking southwest

ROCKFALL CONTROL

Fookes & Sweeney (1996) and Peckover & Kerr (1977) have given methods for preventing rockfalls or minimising their effects. The various methods either prevent rocks from moving out of place or protect the road by keeping rocks that do move out of place from reaching the road or provide warning when rocks arrive in the vicinity of the road. Various methods can frequently be combined for increased safety at a single site.

Based on the findings of the RHRS and SOAP investigations and the individual appraisal of the rockfall zones, programmes of works were formulated to provide increased protection at each site. These included :-

- limited duration improvements such as scaling and trimming of roadside rockfaces to remove loose rocks
- highway works such as modifications to the horizontal or vertical alignments
- earthworks to create intercepting ditches or berms along rockfaces to catch falling rocks
- drainage works to collect or divert fast-flowing or uncontrolled water flows
- other countermeasures such as removing or pruning vegetation or erecting sheep-proof fencing

However, the following special measures for rockfall protection were also deployed on a site-specific basis.

Rocktrap walls

Concrete retaining walls built on the hillside form a rigid barrier to intercept free falling rocks as large as 2 m in size and prevent them from reaching the road. The walls must be long enough to cover the rockfall hazard zone, sufficiently high to cover the path of bouncing rocks and sufficiently robust to withstand impacts of the largest blocks of rock. A series of rocktrap walls have been built on the headlands at Pen-y-Clip and Penmaenbach (Figures 2 & 10). Here, the walls are generally founded on rock outcrops and pinned by stainless steel dowels grouted into the rock. They are either mass concrete or reinforced concrete and faced with masonry.

Figure 10. Rocktrap walls at Penmaenbach

Rockfall checkfences

Checkfences are installed to shield the highway from falling rocks. The primary function of the checkfences is interception either to bring falling rocks to rest on the slope or, in the case of large blocks, to reduce speed so that they may be retained by other countermeasures further down the mountainside. Usually, the checkfences are sacrificial and designed to fail in a controlled manner and typically, each checkfence consists of: -

- vertical posts founded either at shallow depth on a concrete base in the scree or in some cases on exposed rock
- wire cable stays from each post secured either into the scree slope using duckbill anchors or into rock outcrops using dowels
- five rows of tie wire strung horizontally between the posts
- chain-link mesh fixed to the horizontal straining wires

Other design features include turnbuckle type tensioning devices on each guy and tie wire, and chain-link mesh apron or skirting laid on the uphill ground along the bottom of each checkfence. To combat corrosion, metal components of the checkfences are made of stainless steel or galvanized steel and mesh is coated with PVC (Figure 11).

Figure 11. Rockfall checkfences at Pen-y-Clip

Impressive arrays of checkfences have been erected across the headland at Pen-y-Clip (Nichol, 1999). Here, there are 110 checkfence units on the mountainside. They range from 9 to 55 m in length depending on local conditions but are commonly about 30 m long by 3 m high. The total length of checkfencing exceeds 3.25 km. Layout generally comprises at least two and usually three horizontal lines of checkfencing with the independent bays in a staggered configuration.

Barrier fences

Barrier fences around 1 m high of wire mesh supported on posts are generally employed along roadside verges or at the base of a slope to prevent rocks rolling on to the road (Figure 12). They are suited to rock slopes where only minor or local instability is likely to occur and where the slope is liable to slow degradation. Rock debris accumulates along the bottom of the fence and needs to be removed at regular maintenance intervals.

Figure 12. Barrier fence at Tal-y-llyn Pass

Gabion barriers

Gabion walls can be used to form a barrier to catch rolling or bouncing rocks up to a size of about 1.5 m (Figure 13). Gabion baskets are flexible under impact and cheaper than concrete, but the mesh is susceptible to damage. In addition, gabion barriers may appear unsightly and obtrude on the local landscape in environmentally sensitive sites.

Figure 13. Gabion barrier on mountainside at Pen-y-Clip

Netting

Heavy-duty mesh netting draped over rock surfaces can restrain rockfall and prevent ravelling of loose material from roadside rockfaces (Figure 14). It is also deployed on scree slopes and boulder fields for stabilization purposes.

Netting is most appropriate for rockfaces with moderate to widely spaced discontinuities and medium to large block sizes. Generally, the netting is fixed in place using a combination of rock bolts and wire cables. A typical wire mesh slope protection system consists of a main cable support anchored along the top of the slope from which the mesh is suspended. The mesh drapes down the rockface, seams are wired to form a continuous blanket, rock bolts are installed to fix the netting around irregularities or protrusions in the rockface and the bottom and sides of the mesh blanket are secured by additional anchored straining-cables.

Figure 14. Heavy-duty mesh netting drape on rockface at Penmaenbach

Retaining walls

Retaining walls provide strength by applying direct support to a rockface or a scree slope and are extensively employed at roadside positions (Figure 15).

Figure 15. Retaining wall on roadside at Nant Ffrancon Pass

Doweling and rock anchorages

Rock dowels are steel rods grouted into holes drilled in rock. They are not tensioned and so effectiveness in offering resistance when rocks tend to move is largely dependent on the quality of the grouting. In general, dowels are used to prevent individual rocks from falling or sliding along a free surface.

Rock anchorages on the other hand are tensioned to compress the rock mass and increase the friction between blocks. The two principal types of anchorages are rock bolts and rock anchors. Bolts are typically about 1-2 m long and used either to pin individual blocks of relatively small dimensions in place or to fix netting to a rockface. Anchors may range up to several 10s of metres in length and are employed in arrays to stabilize relatively large masses of rock.

Fibrecrete

Sprayed fibre concrete (fibrecrete) provides a strong and durable ground reinforcement skin that follows the structure and relief of a rockface (Figure 16). A thin layer of fibrecrete has a considerable capacity to limit rock displacement.

The fibres improve the material properties, including post-crack ductility, toughness, and most importantly, flexural strength. Fibrecrete systems also bond and seal the rock surface and preserve the integrity of the rock mass by the application of support pressure. Nichol (2002) describes the extensive treatment of roadside rockfaces around Penmaenbach Headland using fibrecrete.

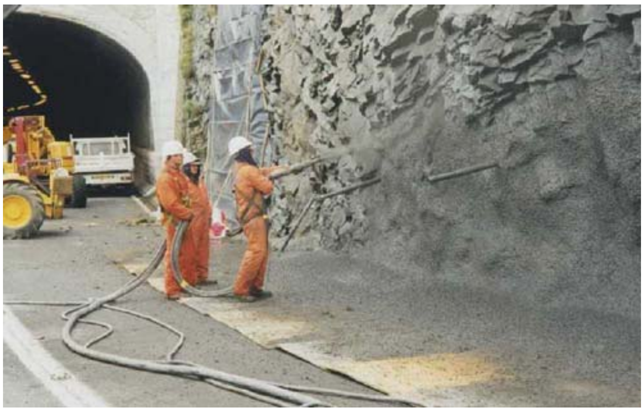

Figure 16. Application of fibrecrete to rockface at Penmaenbach

Buttressing and masonry dentition treatment

Buttresses provide a simple, effective and permanent support under larger rocks in danger of falling (Figure 17).

Often, such rocks are not removed from sloping ground because of difficulties of access or because they may release considerable material above them. Small buttresses can be made of concrete and faced with the local rock not only to prop individual blocks of rock liable to roll but also to avoid obtrusion on the local landscape.

Figure 17. Buttress at Nant Ffrancon

Channel training works

Debris flows are usually confined to steep narrow stream channels above the road and can present significant hazards to the highway during periods of extremely high rainfall. They may be one-time occurrences or may be reoccurring events in a given area. Mitigation works may include ditch deepening, reshaping and lining (Figure 18) and construction of large culverts.

CONCLUSIONS

A combination of the Rockfall Hazard Rating System (RHRS) and stereoscopic oblique aerial photography (SOAP) was used successfully to assess five problematic rockfall sites affecting the highway network in North Wales. They include two coastal headlands at A55 Penmaenbach and A55 Pen-y-Clip and three mountain passes at A5 Nant Ffrancon, A487 Tal-y-llyn Pass and A470 Bwlch Oerddrws where steep terrain and adverse geological factors combine to create potentially unsafe ground above the highway.

Figure 18. Trained watercourse alongside road through Nant Ffrancon

The findings were used to identify various engineering solutions to reduce or remove the potential rockfall hazards and protect the highway. The principal measures involved rocktrap walls, rockfall checkfences, barrier fences, heavy-duty mesh netting, rockfall catch areas, sprayed fibre concrete (fibrecrete) and modifications to drainage systems including channel training works. Supplementary treatments to safeguard the highway included gabion walls, rock anchors and bolts, vertical dowels and masonry buttressing. The appropriate combination of countermeasures was selected for increased safety at each point of vulnerability.

Regular geotechnical inspections as well as monitoring and maintenance programmes seek to ensure that all installations continue to function effectively, provide continuous assessment of the rockfall geohazard and identify new opportunities to improve safety against rockfall. They are also important for quick discovery and understanding of any variations at problematic sites.

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