Recent UK experiences in investigation, design, assessment and management of hard rock slopes

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ABSTRACT
The paper describes some recent UK experiences in the investigation, design, assessment, and management of hard rock slopes. This includes extensive work on existing road rock slopes for Transport Scotland, The Highland Council and UK Highways Agency. Related work has addressed operational and final quarry slopes and rock slopes affecting rail, public and private developments. The work covers a wide range of hard rock types and situations.

The experiences are being used to improve the design of new rock slopes. Sustainability and whole life cost considerations require the appropriate balance to be struck between construction and long term maintenance and remediation risks, which need to be suitably identified and managed. Increasingly, schemes are being successfully designed for low ongoing risks and low maintenance.

RÉSUMÉ
Le document décrit certaines expériences récentes au Royaume-Uni a propos l'enquête, la conception, l'évaluation et la gestion des pentes de roches dures. Cela comprend beaucoup des travaux aux pentes rocheuses existants pour le Transport Scotland, Le Highland Council and Le Highways Agency du Royaume-Uni. Des autres études s'ont adressés aux pentes rocheuses ferroviaires, et pour des aménagements publics ou privés. On examine beaucoup des types de roches dures et des situations.
Les expériences sont utilisés pour améliorer les désins des pentes rocheuses de nouvelles. La durabilité et l'ensemble des considérations de coût de vie exigent le juste équilibre à ménager entre la construction et l'entretien à long terme et les risques d'assainissement, qui doivent être correctement identifiés et gérés. De plus en plus, les régimes sont conçus pour être réussi à faibles risques en cours et peu d'entretien.

1 INTRODUCTION

UK rock slopes reflect the very extensive and widely varying geology displayed within a relatively small land mass. Many interesting hard rock slopes are encountered in the Scottish Highlands, with geologies dating back to Pre-Cambrian times. Further south and into England, the rocks get younger, but include many interesting formations, including many slopes in Carboniferous limestones and a wide variety of sandstones, quartzites and volcanics.

Many rock slopes are associated with the transport networks. For instance the rail network monitors and maintains over 3000 rock slopes in the North West Region alone. The Scottish highway network has appraised over 1500 hard rock slopes. There are also thousands of hard rock slopes in quarries, where a particular methodology has developed. Thousands more such slopes are in public or private ownership, where the regimes for inspection or management can vary widely, or be absent. The methods described here can considerably assist; an example is given from Local Authority which established such a management system.

Some excavated rock slopes present major ongoing issues requiring expensive remedial works and/or ongoing management and maintenance. Various systems have been devised to appraise such slopes, often in response to one or several serious incidents.

The writers have been involved in a wide range of such projects and in this paper aim to reflect and draw some general findings from these.

In essence:-

- Many rock slopes experience significant and potentially avoidable problems during and following excavation;
- Too many are not suitably rectified at the time, or during the works;
- Many defects and undue risks have gone unidentified or inadequately identified;
- Appropriate investigations and remedial measures could save lives and major infrastructure costs;
- Risks should be explicitly identified at concept and design stage, and suitably managed through design, construction and ongoing operations;
- More attention (in design and remedial works) should be given to aiming for improved risk management, low maintenance and sustainability;
- Good engineering should be suitably integrated with good landscaping to produce desirable long term land forms.

2 SOME RECENT WORK IN SCOTLAND

Studies in Scotland in the 1990s, following two fatalities, led to a development of the Road Rock Slope Hazard Index (RHI) system (Nettleton & McMillan 2000). More than 1500 rock slopes have been assessed in Scotland and many hundreds elsewhere using similar systems, sometimes adjusted to other end-uses.

A review in 1995 (Marshall 1995) found about 16% (one sixth) warranting detailed study or, in some cases, urgent action. A further nearly 20% warranted regular systematic review. Many of these have been remediated on a prioritised basis and work is continuing.

During the authors' work in developing and implementing the RHI on the Scottish Trunk road network and other Local Authority roads it became clear that many hazards on existing rock slopes resulted from defects which could have been most sustainably and cost effectively remediated during the construction process. Many of these hazards were either:

- Not identified during the ground investigation stages and not taken account of during design; or
- Not identified soon enough during the excavation of the rock slopes, and remediated at the time.

To prevent such occurrences it is important that geotechnical risks are highlighted early on in project feasibility studies and are then updated as information is gathered during investigation. This process is highlighted in Highways Agency guidance HD 22/08 (Highways Agency 2008).

2.1 Highways - A890 Stromeferry Bypass

The A890 Stromeferry Bypass in North West Scotland provides a key case study. The A890 links South Strome to Attadale along the southern shore of Loch Carron and is approximately 8km in length (Figure 1). Currently the A890 carries up to approximately 2000 vehicles per day. Whilst the traffic volumes are modest the strategic importance of the Stromeferry Bypass lies in the fact that it is the only north / south link on the west coast north of Kyle of Lochalsh. If the Stromeferry Bypass is blocked the alternative route is 137 miles in length via Inverness or Beauly on the east coast of Scotland.

The single track road was constructed between January 1968 and October 1970, to replace the ferry at the western end of Loch Carron.

The road was constructed on the landward side of the Kyle of Lochalsh to Inverness railway line and involved cutting into the glacially over-steepened hillsides of the fjord-like Loch Carron valley. In places the road construction involved blasting to form rock cuttings (up to 65m in height) in the lower slopes. Elsewhere, the lower slopes above the road are relict sea cliffs and superficial slopes. They rock cuttings are separated from the road by typically less than 2m and in many cases less than 0.5m.

The geology consists of Pre-Cambrian metamorphic Moinian granulitic and pelitic schists and Lewisian gneisses. The rock strata have been affected by the Moine thrust (90km to 100km displacement to north west) which outcrops close to Stromeferry Pier and then runs parallel to the shore of Loch Carron. The thrust and associated large scale folding have lead to the inversion of strata with the younger Moine schists occupying the lower parts of the slopes, with the older Lewisian gneiss inlier forming the upper parts of the slopes. The rock mass contains localised, complex and highly variable patterns of jointing associated with the large scale and parasitic folds. Tight to isoclinal folds have sheared parallel to their hinge planes creating shear zones. These factors in addition to the excavation process have given rise to ongoing rock slope instability problems.

The cost of the Stromeferry Bypass was some £465k (1970). Which represented a saving of over £200k on the original tender price, largely by relaxation of the blasting and slope formation specifications.

During construction there were a number of large landslides from the glacially over steepened hillsides, the most significant of which blocked the Kyle of Lochalsh to Inverness railway line for 5 months between February and June 1969. As a result of this event an 80m long concrete avalanche shelter was constructed to protect both the railway and the new road. This particular incident was the basis of a major claim.

Since the completion of the road there have been frequent minor rock fall events and several larger events of tens to hundreds of tonnes. As a result The Highland Council have required that the rock slopes be inspected annually. In 1996 a risk assessment of the rock slopes was undertaken by TRL Scotland. Following this a risk based maintenance management strategy was developed for the slopes.

Stromeferry Bypass is a prime UK example of a very difficult scheme designed down to a low construction cost to make it viable, but which has had to live with very high remedial works and ongoing maintenance costs since.

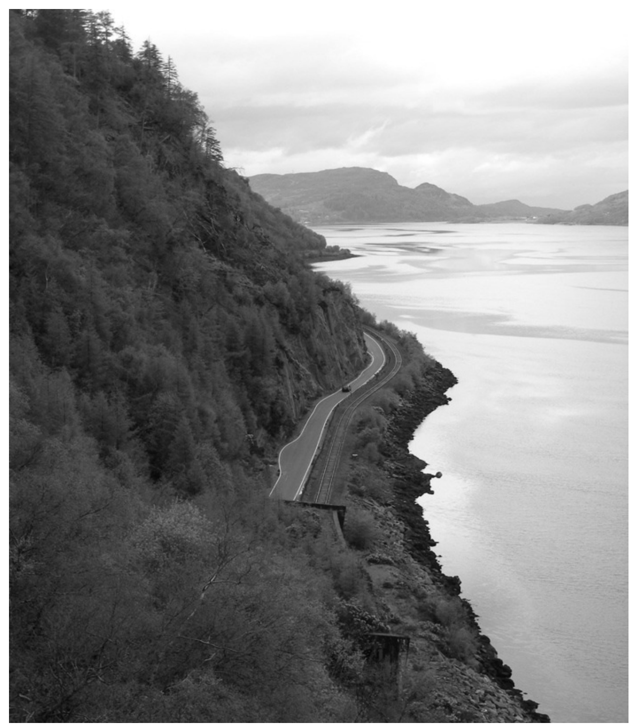

Figure 1. A890 Stromeferry Bypass.

2.2 Stromeferry Bypass Slope AA16

One particular slope at Stromeferry, Slope AA16, has been monitored for 15 years due to dominant and dilated joints potentially leading to an estimated 900 tonne plane/wedge failure directly affecting the highway. Figure 2 shows the rock mass prior to remedial works.

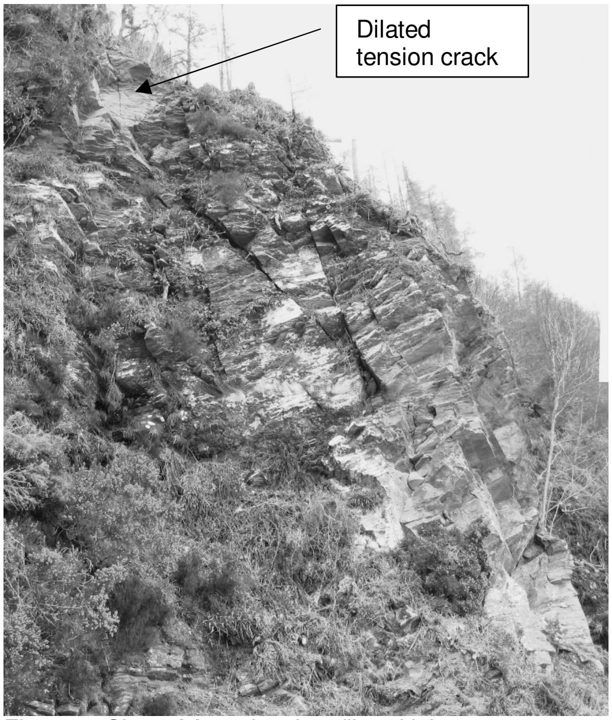

Figure 2. Slope AA16 showing dilated joints

In 2007 observations concluded that a weak weathered band at the base of the rock mass was deteriorating and tension cracks had become dilated at the top of the rock mass. During one of the phases of general remedial works at the site, the contractor was approached to install some rock dowels to help support the rock mass as an interim measure. During drilling for the dowels it was found that the rock mass was even more dilated and fractured than previously thought so an alternative solution was required.

Investigations involved rope access inspections and a laser scanning survey of the rock mass. The information gathered was used to model more accurately the size and likely failure planes. The laser survey was found to accurately highlight the different planes and their angles. Intersections of the different planes could then be extrapolated, thus enabling 3D modelling of the rock mass as a whole. Figure 3 shows an extract of the raw laser survey data, generated from 'point cloud data'.

Removal of the rock mass and re-profiling of the remaining slope was identified as the most appropriate option given the closeness of the highway, the adjacent railway line and the size of the failure involved. This would also effectively reduce future maintenance required for this particular area of the site.

Removal of the rock mass was carried out by long reach excavator; Figure 4 shows the work in progress. The anticipated dominant failure plane was confirmed during the works, as was the loose and fractured nature of the rock mass.

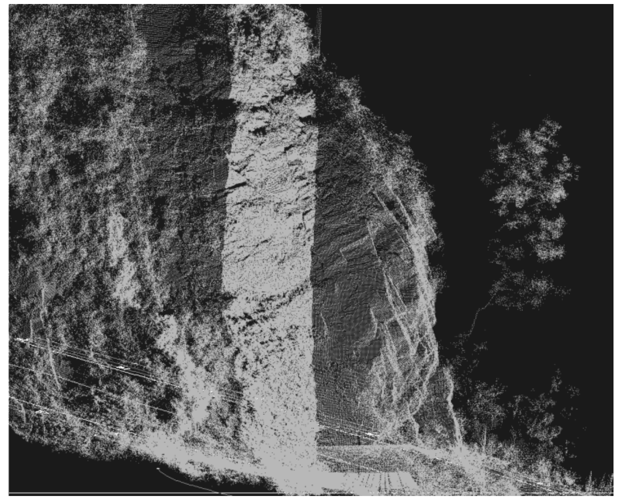

Figure 3. Laser survey raw data showing view in Figure 2.

Due to the steep (35° to 40°) slopes above the rock slopes the upper section of the plane / wedge failure at the back of the discontinuity intersection had to be retained (to prevent undermining the upper slope).

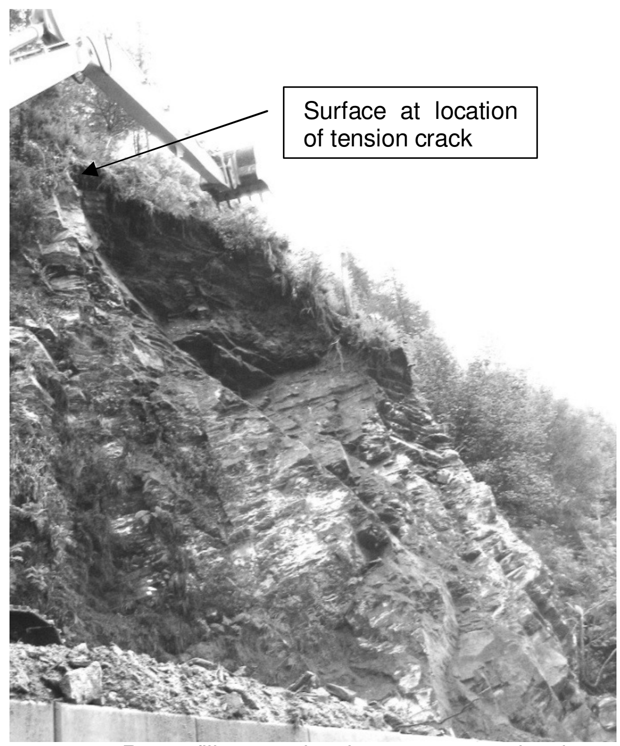

Figure 4. Re-profiling works in progress, showing dominant failure plane.

A supporting anchored stainless steel fibre reinforced sprayed concrete block was designed and installed to support the remainder of the wedge. This was installed using rope access techniques. The site-won rock was formed into a rock trap to the rear of the remaining rock buttress and the slope rock netting to control ravelling failures.

2.3 A830 Loch Nan Uamh to Arisaig Upgrade

The A830 trunk road in the Scottish Highlands connects Fort William to Mallaig over mountainous terrain. The road has been upgraded from a single track road to a single carriageway road over many years and in several phases. The final section of the A830 upgrade began in 2001, promoted by the Scottish Executive.

The final section of the upgrade was from Loch Nan Uamh to Arisaig, approximately 7.5km. The proposed route included 25 rock cuttings, many of which are substantial, some in excess of 35m high. It was paramount that the final design for the whole upgrade scheme was landscaped and environmentally acceptable (Figure 5) being in an area of outstanding natural beauty and through a Special Area of Conservation (SAC).

Figure 5. Curved benches to reduce visual impact.

The ground investigation (G.I) was undertaken in two stages. The first stage was the geomorphological, geotechnical and geological mapping of the line of the proposed route. The mapping identified major persistent discontinuity planes that weathering processes have exploited to form the current topography. These dominant planes have a significant effect on the stability of the cuttings that have previously been excavated during road construction.

The geological mapping identified the geology present beneath the proposed alignment to be composed of metamorphic rock (psammite, pelite and pelitic schists) and igneous intrusions (dolerite, basalt, theoleiite).

The second stage of the ground investigation comprised of a combination of boreholes and trial pits. The boreholes into rock were typical cored, with a limited number of holes drilled using Down the Hole Hammer (DTH) methods. Borehole televiewers optical and acoustic) were used in the DTH holes to provide discontinuity data.

The information gathered from the G.I phase ultimately focussed the proposed alignment. The discontinuity data that was gathered was used by Coffey to produce ‘Specimen’ designs for low maintenance rock cuttings, e.g. minimise potential for significant plane, wedge or toppling failures to be present. Integrated rock traps were designed for each of the slopes based on their height, face angle and expected construction method. The objective of the design of the rock cuttings was to create low maintenance slopes that would not require remedial works during construction or in the future.

Figure 6. Slope with large potential wedge/plane failure identified during excavation.

Following on from the design phase, the construction of the upgrade was let as a Design and Build (D&B) contract in 2006. The contractor was to design the scheme using the information and outline design provided. The contract specified that cuttings were to be landscaped/environmentally acceptable and be low maintenance (require no remedial works, e.g. rock bolts, rockfall netting).

Figure 7. Slope following excavation with large potential wedge/plane failures removed.

Coffey’s role was as the employer’s technical representative. Under this role Coffey supported the D&B designer including identifying potential failures and flagging them during construction.

An example of this is presented in Figures 6 and 7. A large potential plane/wedge failure was identified during the excavation of a cutting (Figure 6). The potential wedge/plane failure was subsequently removed (Figure 7). This reduced the requirement for the contractor to re-visit the cutting after completion of excavation and the need for remedial works that would require maintenance over the life of the rock slope.

The road upgrade officially opened in April 2009 at a cost of £22.8 million. This was the final remaining section of single track trunk road in Scotland to be upgraded.

3 ENGLAND - VARIOUS HIGHWAYS

3.1 M5 Wynhol Viaduct

The rock slope is located above the M5 motorway, south of Bristol in the south west of England. The M5 forms part of the Highways Agency Area 2 Network. The motorway is used by 40,000 vehicles per day and is a main arterial route in that area of the country.

The cutting has an overall slope angle of 70° and has been excavated out of Carboniferous Limestone (Figure 8). The cutting appears to have originally been formed by blasting two benches into the hillside, unfortunately as excavation progressed the benches were reduced to typically less than 1m. This has produced a series of small broken benches that act like ‘ski jumps’ and project rock fall out from the rock face.

Figure 8. M5 Wynhol Viaduct rock slopes, line of two benches just visible.

The rock slopes within the whole of the Highways Agency Area 2 Network were surveyed using the TRL Road Rock Slope Hazard Index (RHI) system in February 2000 by WS Atkins and processed by EDGE Consultants (now Coffey). The RHI system identified three rock slopes requiring detailed inspections between Junctions 19 and 20 of the M5 (Tonks et al 2008).

The total length of the rock slopes identified was in excess of 2.5km. A walk-by reconnaissance of each slope was initially undertaken, with the purpose to identify areas of high potential hazard or areas of concern/uncertainty. These areas were then inspected by Engineering Geologists/Geotechnical Engineers from ground level or rope access, depending on the height and location in relation to the motorway.

The inspections identified where visible the existing remedial works, which consisted of approximately 4000 rock bolts, anchors, galvanised weldmesh, a 1.8m high rockfall catch fence and a 4m to 4.5m wide by 1.5m deep rock trap (Figure 9).

Figure 9. M5 Wynhol Viaduct rock trap.

No information on the design or maintenance of the remedial works was available. The inspections suggested that the remedial works were generally well-constructed and had performed well over 30 years since their construction and installation.

This method of slope assessment allowed for the recording of data that would be required during the design phase of the remedial works.

The remedial works identified as being required to reduce the level of risk by the slope comprised scaling, dentition, buttressing, additional rock bolts (including strain gauged rock bolts), rockfall netting and a new rockfall catch fence.

The existing catch-fence was identified during the inspection as not being high enough to contain blocks that may originate from above the lowest berm. Therefore, the upper two benches were netted, effectively containing falling material close to the face. This allowed the material to shuttle down between the rockfall netting and the rockface, dropping out of the netting at the lowest berm on the slope, from which point the existing catch fence is high enough to contain any falling material.

Following the works a risk management strategy was provided for the slopes. This includes recommendations for routine maintenance and emergency procedures. The routine maintenance highlighted that the slope should be inspected every 5 years and the remedial works checked, e.g. strain gauges measured, condition of rockfall netting inspected, etc. The 5 yearly inspection would also identify any areas where the slope had deteriorated and require further work/minor maintenance. This also allows a picture of changes with time to be built up. This strategy was aimed at also fitting in well with the Highways Agency guidance HD41/03 (Highways Agency 2003, Perry et al 2003)

4 HARD ROCK QUARRIES

4.1 Quarry Regulations 1999

The UK Quarry Regulations 1999 (DETR 1999) came in to force on the 1st of January 2000, with an accompanying Approved Code of Practice (ACOP), significantly expanding previous Mines and Quarries legislation (HSE 1999). Much of the approach is helpful to assessment and management of rock slopes more generally. Conversely, aspects of other rock slope assessment work, especially use of the Road Rock Slope Hazard Index (RHI) system has been found useful in applications to Quarries. Leading to development of a parallel Quarry Hazard Index (QHI) system (Butler et al. 2000).

The legislation clearly defines a Geotechnical Specialist as "*a chartered engineer or chartered geologist who has three or more year's relevant experience in soil mechanics, rock mechanics or excavation engineering and is competent to perform a geotechnical analysis to determine the hazard and risk arising from the excavation or tip being assessed"*.

The regulations state that any excavation, tip or lagoon must be designed, have a set of rules for working them and be appraised on a regular basis, not exceeding two years. An Appraisal can be conducted by a person deemed competent under the regulations. If a slope, tip or lagoon is deemed a Significant Hazard during the Appraisal, then a Geotechnical Assessment is required.

A Geotechnical Assessment has to be conducted by a Geotechnical Specialist who defines what slopes; tips and lagoons pose a defined Significant Hazard and how they should be managed accordingly.

4.2 Tunstead Quarry

Tunstead Quarry is operated by Buxton Lime and Cement, part of Tarmac. It is located in the Peak District National Park (UK) and produces 6 - 7 million tonnes of limestone per year. The limestone is used for the production of cement and aggregates, as well as for roadstone and the chemicals industry. The quarry covers an area of 14km^2 and includes over 230 rock slopes, 4 active tips and 2 active lagoons.

Coffey Geotechnics have acted for many years as Geotechnical Specialist for the quarry undertaking Geotechnical Appraisals and Assessments as well as being responsible for many rock slopes and other works.

The slopes are appraised based on the Quarry Hazard Index system (QHI). *The QHI is a method of estimating the hazard and the associated relative risk presented by quarry rock slopes based on visual assessment of field conditions. The system is based around rapid, standardised field data collection in which influential geotechnical, geometric, exposure and remedial works factors are recorded on a standard form.* This has been developed over the years to match the requirements of the regulations and working practices, especially enabling continuous improvement as the performance of slope and changes with time are assessed.

Coffey work closely with the quarry management in the development of procedures for continually improving the safety of their personnel who operate around the slopes, tips and lagoons. We meet on a biennial basis to discuss the current working methods, potential geotechnical issues in new areas for extraction and any projects occurring within the quarry that may require a geotechnical input.

The team has produced "Traffic Light" hazard plans based on a three tier system. The system assigns each rock slope within a working area one of three colours (red, amber or green). Red slopes are rock faces that are greater than 15m in height and have significant geotechnical features present (Figure 10). Amber slopes are other slopes greater than 15m in height or less high slopes which have significant geotechnical features present. Green slopes are faces that are less than 15m in height and where there are no significant geotechnical features present.

Figure 10. Red Slope (>15m with significant geotechnical features).

Each of the three slope categories has a specific design and method to which they are worked and managed. All are agreed between the Geotechnical Specialist and the Quarry Management. The "Traffic Light" hazard plans are reviewed during the Appraisal and Geotechnical Assessment of the whole site.

Part of the ongoing development and working together between the consultant and the quarry is the review of the Buxton Lime's yearly development plan produced by the resource geologist. We review the plan and comment on where operations are likely to encounter areas containing geotechnical features, (e.g. faults, solutions features, etc) and how they should be managed / worked. The identification of these areas gives the quarry operator advanced knowledge and the ability to plan ahead, thus decreasing the potential risk to personnel working within the areas of extraction.

5 SOME REFLECTIONS AND WAYS FORWARD

5.1 Methodologies

The examples above are drawn from a very substantial range of rock slope projects. In particular, the Rock Hazard approach has been applied to several thousand hard rock slopes for the rail network. Some further examples are discussed in the papers by Nettleton and Tonks et al cited in the references.

Based on the experience of many historic rock slopes, recent new-build rock slope schemes have adopted a sustainable approach, whereby the Employer's Requirements in design and build contracts (D&B) aim for no rock slope remedial works. Whilst unforeseeable localised conditions can still require some remedial measures, the many recently constructed hard rock slopes have been formed with no need for such.

One of the key elements in this process is the development of a specimen design prior to letting the design and build main contract. This should ensure appropriate land take is secured at the start of the contract. This is of particular importance where rock slopes are cut into already steep terrain, where even minor changes in slope geometry can have major effects on land take and stability.

Those involved in the specimen design should continue their role during construction as part of the Employers Representative's team, ensuring that the Employer's Requirement are met and supporting the design and build designer.

In other contractual frameworks, a similar approach may be achieved by the use of independent, peer review from an early stage, with a suitable role and scope to address options, whole life costs and value. The earlier this is introduced into the feasibility and design process, the greater the opportunities to add value. Some further discussion of these topics is given in Tonks et al, 2008.

5.2 Investigations and Design of New Rock Slopes

Investigations and preliminary studies should in the first instance consider the widest range of governing factors for rock slope design. This includes geomorphological evidence of geological structures which control rock slope design and stability. These can be too commonly missed, as can evidence from other nearby exposures. Hence, it is vital that initial mapping and ground investigation is targeted at integrating the awareness of these with plans for intrusive investigations.

The intrusive ground investigations and testing (in-situ and laboratory) should be targeted at those features that will govern and control the stability and geometry of new rock slopes.

As construction commences the 'true' ground conditions will be revealed. There should be a culture of continuous improvement of the geological model with 'well-winnowed' experience. The newly revealed ground conditions should be carefully assessed against the design conceptual model, so that changes revealed are addressed at the earliest possible opportunity. The client/ scheme promoter needs to understand and allow for this process.

In many areas of the UK there are now numerous comparable slopes and extensive experience to draw on. Elsewhere a 'pioneering' route through new terrain may encounter many surprises. It is then especially important that the project is set up to learn rapidly as the 'true' ground conditions are revealed.

The complexity of the technical issues and judgements required cannot be over-emphasised. There can be great benefit from design reviews at appropriate stages, as further information is obtained and interpreted. Matters they should address include:-

- Adequacy and extent of geological models
- Adequacy and extent of investigations
- Provision for uncertainties and change
- Need and value of pre-works

Risks should be formally identified with prior discussions between the parties as to ownership and management of the risks.

5.3 Remedial measures

Remedial measures can be systematically assessed and costed, with works ranging through:

- Controlling or reducing the hazard at source (e.g. by scaling, bolting),
- Breaking the pathway (e.g. rock trap, catch fences, vegetation barrier),
- Modifying the receptors (e.g. controlling infrastructure and development).

For sustainability remedial works should follow the hierarchy of (Nettleton et al 2000; McMillan et al 2000):-

- Avoidance – move the infrastructure away from the slope or vice versa
- Removal – e.g. scaling, controlled removal or reprofiling
- Control and Containment – e.g. rock fall netting or rock traps
- Strengthening – e.g. reinforcement, support or protection

Avoidance is not always practicable and, hence, the other three techniques are more typically applicable here.

Where failures do not have the potential to undermine material or exacerbate other potential failures, then removal or control and containment are the appropriate sustainable options.

Where failures are likely to undermine material or exacerbate other potential failures, then strengthening or protection are more appropriate, but the durability and ongoing management and maintenance of such works (especially anchors) need careful consideration.

5.4 Sustainability and Ongoing Management

The concept of a design life (sometimes stated as e.g. 60 or 120 year) is rather meaningless for rock slopes, as is the belief that they do not require maintenance. It is more appropriate to consider likely change and degradation, in discussion with those who will carry the responsibilities and costs for ongoing management and maintenance.

All significant rock slopes warrant an inspection regime (e.g. HSE 1999, Network Rail 2008, Highways Agency 2003) which should identify ***maintenance works*** which are targeted at keeping the slope into a serviceable condition, consistent with the risks. Undertaking such inspection and maintenance works should prevent unforeseen ***emergency events*** (failures) and extensive unplanned ***remedial works*** (works required to bring slope back to a serviceable condition) being required.

All the above need to be allowed for and built in when assessing sustainability and whole life cost. This is particularly true for active support (e.g. anchors) and for control and containment measures (e.g. netting and rock traps – cleaning out; catch fences – cleaning out and repair).

It is important to keep appropriate records of all inspections, maintenance and remedial works to enable the ongoing performance and degradation of the slope to be assessed, thereby enabling prediction of future maintenance and remedial work priorities and costs.

The work described in the case histories presented, along with hundreds of other slopes the authors have worked on, has entailed work on all the stages in the life cycle of rock slopes. This has enabled the principal constraints and challenges to be identified, and areas where changes in management and inspection regimes can be made to capture vital information.

The authors have recently been using this experience to input into revisions to the UK Highways Agency procedures (HD 41/03) for the risk assessment, design and management of rock slopes, which are expected to be published shortly.

6 CONCLUSIONS

- Rock slopes need to be properly 'owned' and pro-actively managed sustainably to suit long term risks and costs.
- The design process should include and develop long term management plans, and should work to optimise these to end of construction.
- Following construction or remedial works, rock slopes should be 'handed over' with suitable records and inspection and management manual.
- Addressing long term requirements and costs in this way will focus attentions of all parties on seeking low maintenance and overall economies through best practice in design and construction.

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