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Cost-effective attenuation and stabilization of unstable rock slopes

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ABSTRACT: More and more pressure is being placed on public authorities to ensure safe rock slope conditions for their roads, rails and canals. This, as Africa's marginal spaces become occupied and roads become increasingly overcrowded, where even a small cobble racing downslope can wreak havoc. Appropriate rock slope safety measures are necessary everywhere and require immediate implementation: but with a decreasing public purse and pressure to spend elsewhere, funds for slope safety interventions diminish daily. This paper examines general and specific rock slope stability issues, but moves away from classical rock slope intervention - as brought about by financial constraints - to more modern approaches with new and different cost-effective investigation, analysis, characterization, and rock mass stabilization. These present a move away from all-embracing rock slope protection guaranteeing stabilization to hybrid, or combination, rock stability solutions tending toward energy dissipation with guided attenuation and maintenance management systems. The paper reviews general rock mass and rock fabric instability problems, rock mass characterization, stability analyses, classical methods of rock mass stabilization, and from there moves on to the main theme and embodiment of the paper, namely cost-effective rock mass failure attenuation; control and stabilization.

1 INTRODUCTION

Central to this paper is a call for geotechnical rock slope practitioners to pursue more innovative cost-effective solutions commiserate with available funding. Especially poorer countries. Standard practice in South Africa is investigation via dependable time-tested methods of rock mass slope stability assessment and stabilization and, whilst fully acceptable, can at times result in overly conservative solutions. This paper presents a more simplified approach to rock slope problems where emphasis is centred on cost-effectiveness, via the use of simplified rock classification and characterization, with resultant summated weighted matrix classes geared towards rock slope failure control rather than full permanent stabilization.

2 STANDARD ROCK SLOPE ASSESSMENT PRACTICE

2.1 *Geotechnical Investigation*

Current practice (SANRAL TRH 2019), when investigating unstable rock slopes, and where finances are of relatively minor concern, is to undertake initial on-site reconnaissance investigation followed by more detailed studies. Detailed investigations generally consist of geological mapping; joint discontinuity survey; rotary cored drilling; geophysical investigation; laboratory testing for fabric strength and durability; weighted numerical classification such as the Geomechanics Classification (Bieniawski 1984) or similar rock mass classifications (Q; GSI) and site specific engineering geological rock mass characterization using systems such as the Engineering Geological (EG) Rock Mass Characterization system (Price et al. 1991). All information collated and considered for detailed slope stability analyses.

2.2 *Geotechnical Rock Slope Stability Analyses*

Standard rock slope stability investigation is to initially undertake potential for kinematic rock mass instability using stereonets: to investigate if possible planar, wedge or toppling is kinematically admissible. Thereafter field and laboratory results determine rock mass shear strength parameters, or application of Hoek-Brown failure criterion (Hoek et al. 2002, Davis 2010) conducted to determine rock mass shear strength characteristics. Next global (overall) and localised slope stability analyses are undertaken using Numerical Analyses via finite element software; planar/ rotational slope stability analyses via limit equilibrium analysis; and rock fabric disintegration analysis with prediction for ravelling. These analyses, singly or in combination, provide the basis to determine the spectrum of possible rock slope stabilization design solutions and relevant mitigation measures.

2.3 *Geotechnical stabilization*

Geotechnical stabilization can vary from minor intervention to complex costly solution as determined by available funding. It can consist of lateral support systems such as: mesh or steel fibre reinforced shotcrete in combination with grouted steel dowels; tensioned rock bolts with mechanical anchorage; tensioned ground anchors with reinforced concrete beams or anchored piles; reinforced concrete retaining walls; bridged rock shelters; anchored half tunnel canopies; Mechanically Stabilized Earth (MSE) walls such as concrete blocks with soil reinforcement; gabions with (or without) geosynthetic or wire mesh tail support; untensioned (passive) or tensioned (active) steel mesh drapes anchored via grouted dowels of variable length, spacing & pattern; and gravity mass geobarriers constructed to block downhill discharge.

3 SIMPLIFIED COST-EFFECTIVE APPROACH

3.1 *Geotechnical Investigation*

Elements of rock mass assessment and classification, as previously described, are standard for most situations, via on-site reconnaissance followed by more in-depth engineering geological mapping; joint discontinuity surveys; and initial assessment of rock slope instability type and magnitude. These are relatively inexpensive techniques which can be easily and rapidly implemented. Completed field studies provide for rock mass classification and/ or site-specific rock mass ground reference conditions.

South African National Roads Agency Limited (SANRAL) is currently undertaking stability assessments of all road cuttings > 5 m for SA's national network. These number thousands of individual slope assessments which require a fast and relatively simple assessment system. A weighted matrix rating assessment, currently in use, is being reworked and upgraded by a committee of SANRAL and private sector geotechnical engineers and engineering geologists (SANRAL 2019). This Committee has been further tasked to produce a new Technical Recommendations for Highways (TRH) document and manual for assessment of rock; soil and embankment slopes.

The new TRH document is still a work in progress with 2019/ 20 set for final completion. It comprises a two-part system of slope field evaluation. Stage 1 comprises of brief and rapid on-site field evaluation, using a weighted rating system, with stability of slope scored out of a maximum numeral rating of 100. Such assessment can be completed in less than half an hour. Should this initial rating surpass a predetermined rating value, it triggers Stage 2; a more in-depth evaluation with the slope in question subjected to a more rigorous DER rating process. DER being an acronym for: D = Degree of defect: How severe is the defect? E = Extent of defect: How widespread is it? R = Relevancy of defect: What are the consequences with respect to functional integrity of the adjacent roadway, or safety of road users, or ongoing functioning of the slope cut face?

This paper has as objective: rapid, low cost, innovative approach to rock slope assessment; stabilization design, and stabilization construction. Here Stage 1 tabulation is quick and cost-effective. Table 1 from Stage 1 over page describes only the rock cut slope element of the greater proposed TRH tabulation which will include cuttings and embankments. It is presented as a first glimpse of the new TRH deliberations and compilations and Step 1 in initiating rapid rock cut slope field assessments.

Table 1 provides a series of rock slope descriptive parameters each sub-divided into 4 classes. In each is a unique weighted rating. Descriptive parameters describing general slope conditions are: maximum height of cut; initial overall assessed stability (an important evaluation since it describes primary evaluation prior to any external or later evaluation influences); and groundwater seepage from the cut face. Rock mass descriptions requiring rating are: slope angle; physical rock attributes; weathering/ durability; jointing; failure mechanisms and magnitude; drop zone dimensions; signs of previous problems; and stormwater drainage control. Elements of the exposed rock face are pigeon-holed within the various subclasses to present a unique numeral value: tempered to accommodate any existing lateral support elements. The final rating provides a particular rock cut slope with a Class value; Class description, and an anticipation of stability measure requirements:

Rating > 76: Class = Good: No stabilization
Rating 51 - 75: Class = Fair: Monitoring required
Rating 25 - 51: Class = Poor: Minor works
Rating < 25: Class = Very poor: Major works.

3.2 *Geotechnical Analysis*

Geotechnical analysis objective for this paper is to suggest quick and easy systems of rock cut slope stability assessment while at the same time maintaining high level data integrity, and therefore a high standard of stability assessment. It is recommended to follow a similar route as previously described in Sxn 3.1, namely kinematic rock mass instability assessment using stereonets; estimates of rock mass engineering properties (without reliance on rotary cored drilling and laboratory testing), followed by extensive numerical and limit equilibrium analysis iterations. Rock mass properties, especially shear strength values, can be determined from Hoek and Brown failure criterion, with residual / completely weathered shear strength values estimated from NAVFAC (1971) values (Byrne et al. 2008), or from many empirical estimates available from literary sources.

Table 1. Rock slope weighted matrix assessment

PARAMETER	DEFINITION & WEIGHTING	DEFINITION & WEIGHTING	DEFINITION & WEIGHTING	DEFINITION & WEIGHTING
		GENERAL SLOPE CHARAC +		
Max H of Cut	<5m	5 - 7m	7 - 10m	>10m
Weighted Score	10	7	4	2
Initial overall assessed stability	Stable	Minor problems	Major problems	Unstable
Weighted Score	10	7	4	2
Water (slope or foundation)	Dry	Moist	Very moist to wet	Wet with seepage
Weighted Score	10	7	4	2
		+ ROCK CUT SLOPE		
Slope V:H (°)	<1:2 (<26.6)	1:2 - 1:1.5 (26.6-33.7)	1:1.5-0.5:1(33.7-63.4)	>0.5 (>63.4)
Weighted Score	10	7	4	2
Rock type	Massive	Blocky	Striated	Soft to very soft
Weighted Score	8	6	3	1
Weathering/ Durability	Slight / unweathered	Medium Weathered	Highly / Disintegrating	Completely / Disinting
Weighted Score	8	6	3	1
Jointing	Favourable	Mostly favourable	Unfavourable	Highly unfavourable
Weighted Score	10	7	4	2
Failure mechanism & magnitude	Nil / Dribble	Toppling / small wedge (1m3 -5m3)	Wedge/ planar/ topple (6-25m3)	Major wedge / planar / topple (>25m3)
Weighted Score	10	7	4	2
Toe drop zone	>3m	1-3m	0-1m	0m
Weighted Score	10	7	4	2
Signs of previous probs	None	Isolated & minor	Frequent and serious	Freq. & very serious
Weighted Score	6	4	2	1
Stormwater drainage features	Lined summit drain	Unlined. Drain steeply sloping	Unlined. Drain slightly sloping	No interceptor drain
Weighted Score	8	6	3	1
		LATERAL SUPPORT RATING ADJUSTMENT (NB: Total Rating < 100)		
Lateral Support	Full Support (+50)	Retaining Wall (+20)	Minor toe (+10)	Nil (0)
		TOTAL RATING & CLASS		
Rating Total	>76	51 - 75	25 - 51	<25
Class Description	Good	Fair	Poor	Very Poor
		ANTICIPATED GEOTECHNICAL INTERVENTION		
Anticipated Stability measures	None	Monitor	Minor Works	Major Works

1 (Unpublished TRH SANRAL data under consideration)

An important requirement at this stage of analyses is to determine whether rock failure is a rock fabric stability problem, or a rock mass stability problem. If the former rock material characteristics will determine stability, and for the latter rock mass issues of discontinuity and slope interrelationships will govern stability. For rock fabric instability further considerations are necessary with determination of whether slope problems are intact shear strength related, or geological fabric disintegration related: the latter relating to disintegrating mudrock undermining and collapsing more resilient overlying rock such as sandstone. Also requiring consideration is location and stability of large hard corestones within a weak weathered rock mass and their effect on stability: and finally, stability of free standing large individual corestone boulders capable of loosening, rolling and crashing onto structures.

Back analyses plus repetitive stability iterations should provide accurate analysis from which slope stability intervention can be decided in hard rock zones with rock mass related stability issues. This without having to rely on costly laboratory testing which could in any case provide a skewed or inaccurate result. Emphasis here is on repetitive analyses with consideration of all eventualities. A sensitivity analysis with extended iteration which, with appropriate experience, could provide an even better basis for stability analyses rather than what poor; ineffective, or inaccurate laboratory test results might create.

These stability analyses will all require in depth consideration before determining best possible geotechnical slope stabilization solution. Remembering that poorer countries can often not afford state of the art geotechnical intervention thereby making innovation mandatory in providing cost-effective solutions.

3.3 *Geotechnical stabilization*

Methods of stabilization are separated into rock fabric related requirements and those requiring rock mass solutions, with emphasis on simplistic rock fall analysis and innovative solution at minimal cost. In sections following geotechnical problem types are presented followed, firstly, by geotechnical solution where funding is inexhaustible, then by more modest solution geared toward attenuation and control. Robust cost-effective solution always being paramount.

3.3.1 *Boulder corestones in high steep rock slopes*

Steep cut faces in weathered rock with surface cobbles and boulders, and fabric located corestones, are inescapable when no better route location is available, or when a route, such as a road or railway, has to be widened to accommodate greater traffic flow. There is then no alternative but to stabilize in loco.

A no holds barred approach is to stabilize with permanence using items like reinforced retaining wall with summit raised to trap boulders rolling down the higher slope; or tensioned ground anchors (or grouted steel nails) with reinforced shotcrete cladding; deep drain holes to lower the phreatic surface; weep holes; summit drain and catchfences to trap rolling boulders above the cut summit - or draped steel mesh anchored by grouted steel dowels. Or an active drape system with tensioning via selective dowel positioning and tightening in hollows and crags. Or the drape passively designed to trap or slow downslope migration. These are though relatively costly solutions which cannot always be justified for district roads; marginal irrigation canals, or minor rail lines.

A more innovative approach is to allow, but attenuate, boulder movement to a control point for removal leaving toe assets free of impact (see Fig. 1).

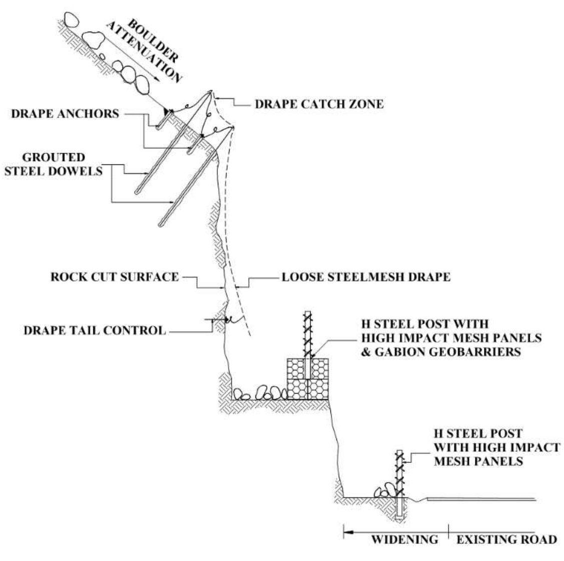

Figure 1. Corestone & loose boulder attenuation on steep cut

Emphasis here is on control rather than complete stabilization. Boulders rolling downslope, or falling from the face, are controlled via a partially pinned steel mesh drape of high tensile strength to prevent ripping, and then allowed to fall onto a berm protected along its outside edge by a gabion geobarrier with fixed steel H-beam posts and high strength interstitial steel mesh. H-beams grouted into the road edge with additional interstitial mesh provide a final barrier against boulder access to the roadway. The literature will define these as hybrid steel mesh barriers, or in some cases as attenuation steel drapes, aligned to a particular commercial product or system. But these are in essence simply an ordered system of energy dissipation; fall control; problem removal; and final back-up for traffic flow protection.

3.3.2 *Loose boulders on an inclined slope*

Geo-practioners are at times faced with the task of having to prevent, or accommodate, large rounded boulders from rolling down and incline. Accelerating as they gather momentum before bouncing from the lip of a downslope cut face, and crashing onto civil assets at the cut slope toe. Both low angle gentle natural, and excavated rock cut slopes, unwittingly energise boulder movement by allowing a runway of gathered momentum. This is a major problem given the same boulder falling from vertical height into ditched drop zone would probably thud down and lie immobile.

Modern methods used to immobilise boulder movements mostly comprise erection of catchfences, singly or in series. Alternatively, anchored high tensile active or passive steel mesh drapery can be used. Catchfence / steel mesh drape products are much improved in recent time. They are rust-resistant, consist of high tensile strength steel wire, are installed, joined, and are anchored using special clamps, steel anchor dowels, summit and base anchor cables, and cable rope cross-bracing. The quality is excellent and designs meet requirements. But they can be costly. Especially if imported; which some countries cannot afford. Other rolling boulder accommodation include effective, but costly, rock shelters or half-tunnel excavations into a cut face. But what of these other less expensive methods:

Geobarriers constructed midslope and along toe of slope, on natural slopes, can prevent further downslope boulder rolls. These take several forms: stacking nearby cobbles and boulders to form a natural barrier wall; or the latter shotcreted to provide stability; or gabions constructed as a pyramid; or wide concrete block walls with internal soil reinforcement (wall widths varied according to need); or a deep and wide drop zone ditch constructed as boulder trap.

Dowel or net anchorage of individual boulders teetering on the lip of cut face excavations, by bracing using high strength drape squares dowelled at each corner, or braced using anchored cables, or by drilling through individual boulders and anchoring with tensioned rockbolts into underlying rock. Even steel prop underpins supporting individual potentially unstable boulders, or large loose rock benches, can prove effective.

Toe drain lined drains, space-willing, can be considerably enlarged by widening and deepening, and lined to act as both drop zone debris trap and as stormwater drain. Added here could be geobarriers on steep mountain slopes directing boulder flow to portal culverts: allowing boulders to rumble harmlessly further downslope beyond civil assets.

3.3.3 *Weak rock fabric & disintegrating rock*

Weak rock fabric, or weak strength of intact rock, is much akin to a very stiff, or very dense, soil profile where sloughing or circular rotational instability is a norm rather than an exception. Weak rock fabric occurs in highly or completely weathered rock, or rock poorly indurated in origin. Cretaceous rock deposits scattered around South Africa's seaboard being an example of the latter. Mudrock disintegrating on exposure, and via erosion undermining harder more resilient rock layers such as sandstone and siltstone, is a widespread Karoo rock problem over much of southern Africa. Massive blocks or undermined shelves of rock collapsing onto lower platforms not only creates a massive maintenance problem, but is also highly dangerous for local people or machines.

Addressing problems of rotational, or translational slide / sloughing, or rock disintegration can be achieved by any number of geotechnical solutions as determined by the magnitude and propensity for failure. These could include reinforced concrete retaining walls; contiguous pile walls with, or without, ground anchorage; grouted soil nail solutions with reinforced shotcrete and appropriate subsoil drainage; MSE walls; gabion and concrete block retaining walls with geosynthetic, wire, or steel strip soil reinforcement; and cantilevered piles with concomitant lagging. These would all inevitably require solution assessment, irrespective of costs, but following are other less costly solutions to consider:

Grouted soil nails with gabion cladding has been used successfully in many parts of South Africa and elsewhere. This requires steel dowels of design length; spacing and pattern to be connected to gabion revetment using enlarged anchor plates located within the gabion, or attached to gabion fronts. Gabions are preferred to reinforced shotcrete cladding (or others) because of opportunities to provide labour to surrounding communities. In this solution closely spaced nails, generally less than 2m apart, are what provide the actual cut slope stabilization.

MSE gravity structure whereby an MSE structure is built hard-up against unstable cut faces to offer the passive stabilization resistance required.

Separation of the civil asset from the cut slope can be achieved by relocating a road outwards and away from the cut slope, space allowing, with construction of a free standing geobarrier in between. Space between problem cut face and geobarrier will fill through progressive slope failure and must therefore be wide enough to allow machine access to remove failed debris: and in so doing restart the process. This solution has proved highly effective for rural roads located below large slow-failing landslide slump debris, or below wide and high translational slide / landslide zones. Drainage is invariably required through the geobarrier to prevent damming of the inside.

Shotcreted gabions with new soil nailing is an effective stability measure when free standing gabions have started to rotate, or topple, or when poorly chosen gabion rock disintegrates and travels through the wire openings. Steel fibre reinforcement is recommended, plus extensive weephole drainage, plus steel spiders at dowel heads to prevent soil nail punch-out.

Disintegrated mudrock shotcreting, or some other form of rock cover such as hand placed mortar washed over exposed rock, will prevent further rock fabric disintegration and undermining. Overlying more resilient rock layers may require presplit blasting to mirror the undermined mudrock face, or addressed via considerable thickening of shotcrete to underpin overlying more competent rock strata. Steel mesh above and below shotcrete dowelled into more competent rock may be required to reinforce the system. Conchoidal fracturing in certain sandstones also has relevance here.

3.3.4 *Steep unstable hard rock mass*

Unstable hard rock masses in high steep cuttings can be stabilized by lateral support techniques such as pattern bolting with grouted steel dowels connected to mesh reinforced shotcrete. Dowel lengths; spacings; and pattern varied according to requirements, as well as steel reinforcement weight, and shotcrete thickness and strength. Deep drain holes, and geofabric band drain installation behind the shotcrete tied into weep holes is a ubiquitous requirement. So too summit and toe drains. High tensile strength steel mesh can be used as drape instead of shotcrete. All these as determined by geological/ geotechnical conditions for a particular site. Other more elaborate support techniques include half tunnel construction, with crown support, to allow unstable wedge/ planar / toppling rock to fall clear.

Consider though the following more cost-effective methods in support of the above:

Steel fibre reinforcement proves excellent in fractured and craggy rock faces as it mirrors the slope face thereby cutting costs of excessively thickened shotcrete should mesh reinforcement been specified.

Flattening slope angle via simple effective presplit blasting to create increased cut slope stability.

Undertake remote-controlled drilling using rope anchored rock drills emplaced via abseiling hugely speeds up dowel installation and radically lowers costs when compared to ponderous scaffold erection.

Concentrated rock-face scaling via barring down of loose rock by abseilers can at times be all that is needed to ensure a relatively stable rock cut slope.

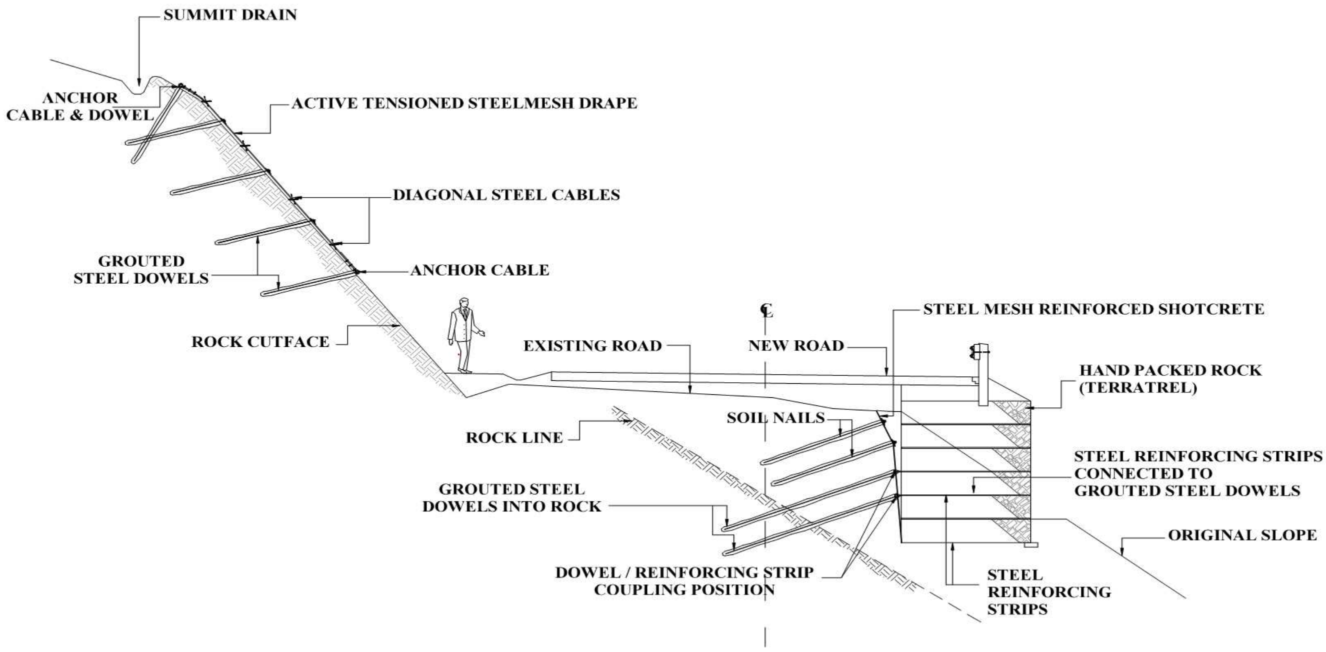

Figure 2. Rock slope stabilization systems in combination

Summit drains on rock tops can be constructed using portable canvas-cement; or shotcreted rock packed walls, or shotcrete summit lip; or use of natural drain lines along joints with concrete diversion as necessary; or hand placed stone pitching. All cost savers.

Substantially widen toe drop zone and move roadway outwards by incorporating downslope toe stabilization using an MSE wall founded on rock. Underlying rock is not unexpected in steep terrains.

Combinations of support systems are encouraged. Figure 2 above provides a unique cost saving system in widening of the N2 Kei River Cutting. Upslope rock cut face is stabilised using steel mesh drape reinforced with diagonal steel cables (these designed prior to current off-the-shelf products); then initial reduction of the roadway into half-widths supported with soil nails and shotcrete: basal nails extended and grouted into adjacent mountain slope rock; followed by construction of MSE Reinforced Earth with steel strips *connected* to steel dowels via special design. It is these forms of cost-saving geotechnical innovation which allow geotechnical rock slope intervention and stabilization in poorer countries.

4 CONCLUSIONS

Rockslope engineering is not an exact science and often the methods used, and systems followed are those currently en vogue, and though effective, are at times beyond the pocket of poorer cash strapped countries. This paper attempts to impress on the geotechnical community to always undertake a lateral approach to rock slope problems by applying innovative and cost-effective *control* which is often just as effective as sophisticated geotechnical lateral support stabilization.

5 RECOMMENDATIONS

Geo-practioners, whilst being knowledgeable of current rock slope engineering investigation and lateral support stabilization, should start pursuing innovative cost-effective rock failure attenuation and control systems. Especially in poorer 3rd world countries where sophisticated geotechnical intervention is beyond their means.

6 ACKNOWLEDGMENTS

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