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Targeted Buffer Blasting to Control Movement Along Bedding Plane Shears

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TARGETED BUFFER BLASTING TO CONTROL MOVEMENT ALONG BEDDING PLANE SHEARS

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ABSTRACT: At the Ukhaa Khudag (UHG) coal mine, working part of the Tavan Tolgoi formation located in the southern Gobi desert of Mongolia, there have been minor to moderate slope failures in locations of relatively shallow overall slope angles. The majority of these events have been due to sliding along bedding plane shear zones that are generally associated with the coal seams. The bedding plane shears have low cohesion and friction angles.

For economic reasons not all seams are mined progressively down dip from the base of weathering, leaving some coal and overburden *in situ* up dip of the excavation. A solution is required to enable slopes to be mined at a steeper angle than the strata dip dictates. Targeted buffer blasting has been trialled with encouraging results.

Targeted buffer blasting is designed to disrupt identified plane(s) of weakness, disturbing them in order to increase cohesion and friction angle. The explosive charge weight per hole is generally significantly less than that used for a production hole of the same depth. Once exposed, the batter or slope will appear less damaged than it would in a normal buffer (or softwall) blast. A secondary advantage of buffer blasting is improved drainage, which lowers the phreatic surface.

Seven individual targeted buffer blasts have been analysed of which four have been classified as successful, two were probably successful and one was unsuccessful. The unsuccessful case was probably influenced by a nearby major blast.

INTRODUCTION

The Ukhaa Khudag (UHG) coal mine is situated approximately 250 km north of the border with China. The mine is a large, truck and excavator, open pit (terrace mining) operation producing medium volatile hard coking coal and high energy low sulphur thermal coal. In 2014 a total of 26.3 Mbcm of overburden was removed, allowing 4.6 Mt of ROM coal to be extracted. The operation is capable of significantly higher production rates, 15 Mtpa installed ROM capacity of the coal handling and preparation plant (CHPP) available, matched by available mining production fleet.

The mine is operated by Energy Resources LLC (ER), an indirect wholly owned subsidiary of the Hong Kong Stock Exchange listed Mongolian Mining Corporation (MMC). Thiess Mongolia LLC (Thiess) is engaged as the mining contractor. As at June 2015, the excavated pit measures approximately 2.2 km from the lowwall crest in the east to the highwall crest in the west, and approximately 2.0 km between the northern and southern endwall crests.

The pit is currently around 170 m deep and is planned to have a final depth of 350 m. The strata dips between 3° and 17° into the highwall (towards the west) while the flanks (endwalls) dip into the pit by between 5° and 40°. In order not to sterilise the lowest coal seam, which has yet to be mined, all overburden removed is currently dumped ex-pit.

There have been a number of sliding failures along bedding plane shears associated mostly with the coal seams. This has led to relatively flat overall slope angles (OSA) along the endwalls with a resultant reduction in productivity. A potential solution to this problem was identified as disturbing the bedding plane shears by blasting thereby increasing the friction angle and cohesion. This technique has been called targeted buffer blasting.

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GEOLOGICAL STRUCTURE AND STABILITY ISSUES

East – West structure

The pit is advancing in a westerly direction and the strata generally dips into the highwall by between 3° and 17° as illustrated in Figure 1, noting that three times vertical exaggeration has been applied to the cross section.

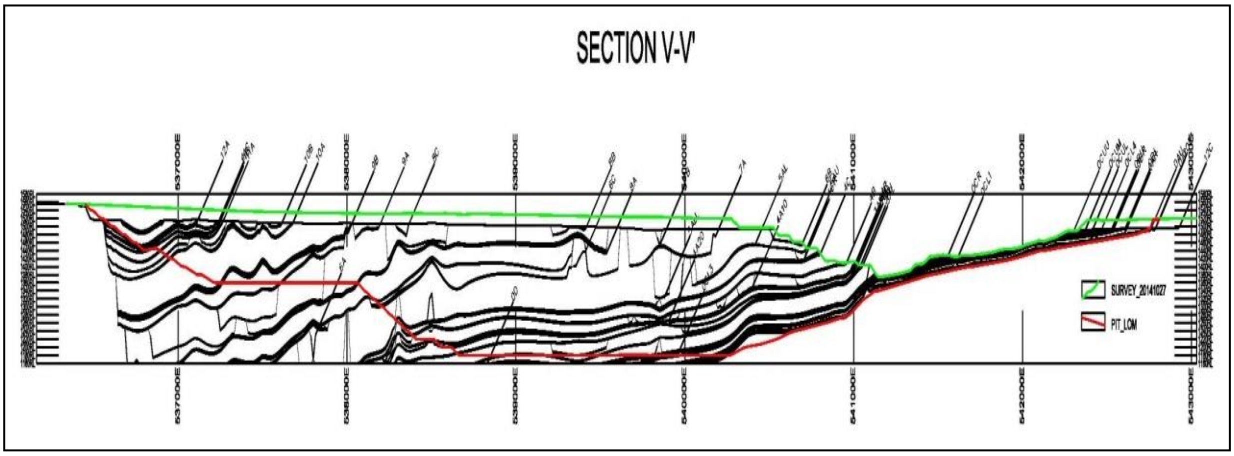

Figure 1: Typical E-W cross section

North – South structure

In the eastern and central portions of the planned pit, the strata forms a roughly flat bottomed basin structure in the N-S direction and the seams generally dip out of the pit walls on both the northern and southern endwalls (Figure **2**). However, further to the west the coal bearing strata is cut off on the northern and southern flanks by faults. The seam dip is generally from south to north and is also much steeper, up to around 35°. The far western area is not considered in this investigation.

There has been a significant degree of folding and thrust faulting resulting in the bedding plane shears that occur. The structural history has been described in the Resource Estimation for Ukhaa Khudag Coal Mine, prepared internally by the ER Exploration and Geology department (MMC, 2012). The geological structure at UHG can be briefly summarised as follows:

Major compressional forces resulted in the entire UHG deposit being transported some distance along the basement contact before the movement stopped due to it encountering a buffer. The compressional forces would then have ramped up into the coal measures creating numerous thrust ramps and associated structures. This would include low angled thrusting within the weaker coal seams, observed as bedding plane shears in the coal.

Other disturbed zones (shears and faults) are present at UHG and can be up to tens of metres wide. These have a wide variety of dips and dip directions and tend to cut through bedding planes. They are most commonly associated with thrust faulting but some are probably due to strike-dip faulting. These features are not considered in this study.

Structural summary

The structure at UHG is complex with multiple disturbance phases. The dominant environment is compression, which results in faulting, folding and shearing. The northern and southern extents of the UHG deposit are generally bounded by major faults while there are numerous other faulted zones. The structure of these other faulted zones is such that although coal seams are present within them, they are hard to model or predict.

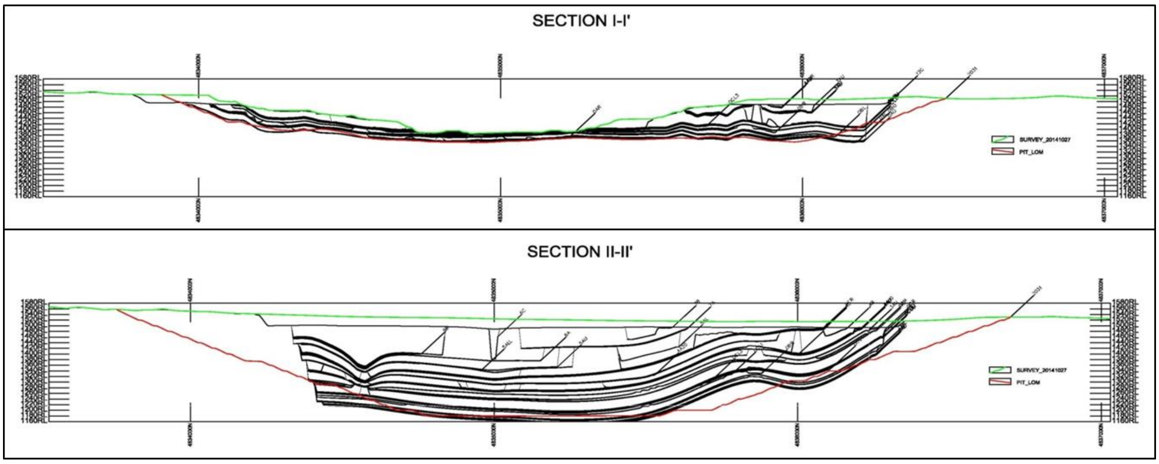

Figure 2: Typical N-S cross sections for the eastern and central areas of the planned pit

INFLUENCE OF BEDDING PLANE SHEARS

Bedding plane shears have been identified as being the major driver of significant sliding failures at UHG. The behaviour of the slopes is far more dependent on structure than on rock strength. About 90% of all significant failures have been classified as sliding along bedding shears.

Bedding plane shears at UHG are very often characterised by a weak brown clay fill or alternatively by finely pulverised coal. They can range in thickness from as little as 10 to 20 mm up to as much as 500 mm.

Figure 3 shows examples of some typical bedding plane shear zones at UHG:

A. steeply dipping shear (±40°) near base of coal seam.
B. shear plane after slippage has occurred, note polishing, this fill consists of powdery coal and disintegrates quickly on exposure to air.
C. ± 30 mm wide, clay filled shear in coal.
D. ± 150 mm wide soft clay filled shear at top of seam, some movement of the upper surface is suspected combined with spalling of coal. Obtaining good quality photographs of the pulverised coal filled shears is difficult as the fill has a sugary appearance and once exposed looks like very fine spalled coal.

While no direct testing has been done, zero cohesion and a friction angle of 13° have been assumed in models containing bedding plane shears at UHG. These values have been confirmed by back analysis and the friction angle is in line with those quoted in Barton (1973):

- Clays: over-consolidated, slips joints and minor shears with peak friction angle 12.0° to 18.5° and residual friction angle 10.5° to 16.0°.
- Coal measure rocks: clay mylonite seams 10 to 25 mm thick with peak friction angle 16.0° and residual friction angle 11.0° to 11.5°.

There have been recorded instances of nearby production blasts initiating failure as well as re-mobilising existing failures. This has been confirmed by crackmeter monitoring by the site geotechnical team. Apart from failures along bedding plane shears, the only other major failures recorded so far at UHG have been along unfavourably oriented fault planes, these are however not common.

POTENTIAL SOLUTIONS

At UHG the mining layouts are checked annually by an external consultant based on a set of approximately forty detailed cross sections provided by the site geotechnical team located around the pit. The principal cross section profiles analysed are the current pit walls and the planned pit wall profile at the end of the year. In addition, any unfavourable structures lying between the two profiles are analysed.

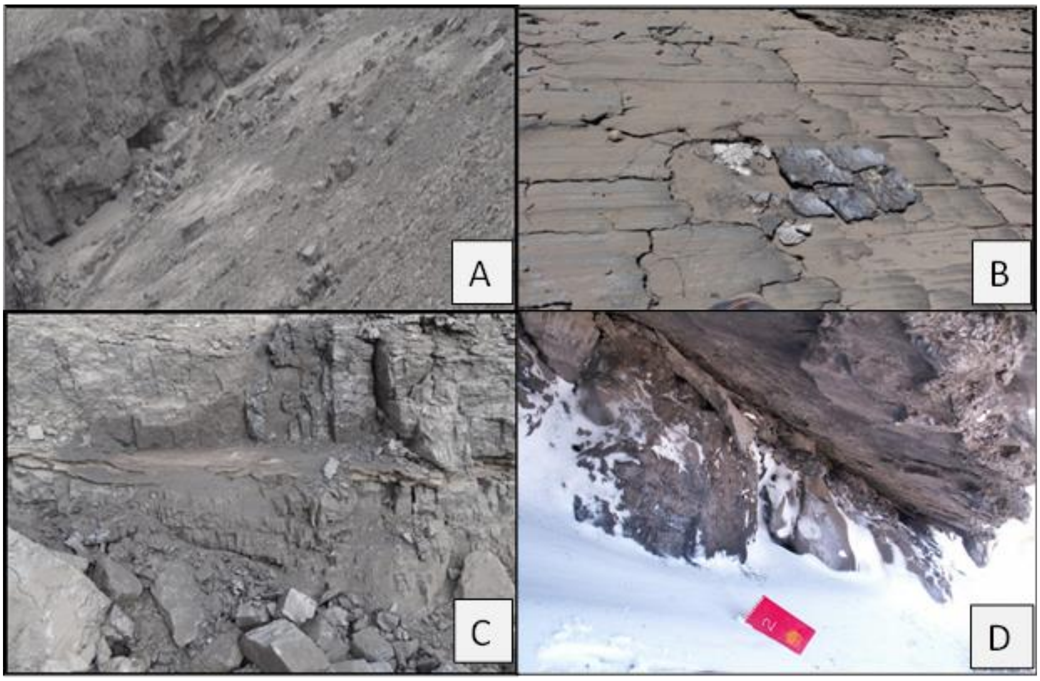

Figure 3: Bedding plane shear examples

It is at this stage that potential low factor of safety (FOS) slopes are identified. These may be the entire slope or, more commonly, a portion of the slope or an individual batter stack. Where the potential instability is due to the presence of bedding plane shears the following three remedial actions are usually considered:

- Mine the coal from the top down following the seam dip where the dip is less than approximately 20.0° or terrace along strike where the dip is steeper. The resultant slope angle is about the same as the seam dip or shallower. In many cases this is not optimal for coal recovery especially in tough financial times where it is necessary to target the most advantageous stripping ratio. In some instances this means that slopes containing unfavourably dipping bedding plane shears are left.
- Potentially unstable slopes or batters may be controlled by forming a waste rock buttress at the toe. However, UHG is currently constrained in that the lowest seam in the succession has yet to be mined, and as a result in-pit waste dumping is not able to be used on a routine basis.
- Targeted buffer blasting is a third option. This entails placing a relatively light charge in the vicinity of the zones containing bedding plane shears to "rough-up" the contacts. This has the effect of increasing the cohesion and friction angle of these zones and is the main focus of this paper. The effect of targeted buffer blasting is shown in Figure 4.

Buffer blasting disturbs the bedding plane shears, resulting in disrupted continuity along the shear zones. This will hold true in cases where the disruption is greater than the thickness of the shear zone. To be effective the blast must only be powerful enough to disturb the rock on either side of the shear and not pulverise the entire blast block.

It must be pointed out that the idea of blasting to disturb planes of weakness is not new:

- The earliest example identified is in a civil engineering context. A "shot-in-place rock buttress" was used in the late 1960's to control a block glide landslide above a highway in Tennessee. Following this, a set of six further "shot-in-place rock buttresses" were formed between 1976 and 1980. These were all still stable in 1986 (Moore, 1986).

- A more recent reference to a similar approach describes blasting of the overburden to turn a geologically disturbed section of overburden into a relatively homogenous block of blasted rock. The blasting removes the influence of jointing and faults and the overburden face is then battered back to about 45.0° with the dragline. This method is referred to as softwall blasting in Australia (Kelso, 2011) and is widely practiced in the Bowen Basin.

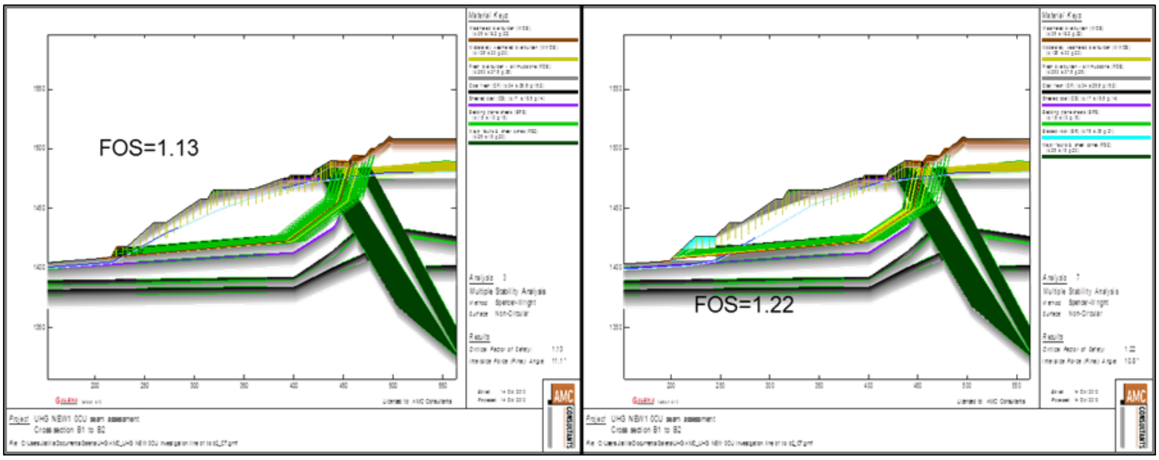

Figure 4: Low FOS slope stability improved by forming a buffer blast at the toe

BUFFER BLASTS FOR DIFFERENT PURPOSES

The type of buffer blast used at UHG depends on the condition that must be controlled, the two types used to date are bench buffer blasts and targeted buffer blasts. Buffer blasting at UHG is understood to be any blast where the blasted material will largely be left in place to form the batter or slope face.

- A targeted buffer blast strip (shot-in-place buttress) is utilised where a target zone, usually a coal seam containing bedding plane shears, has been identified. The intention of the targeted buffer blast is to disrupt the bedding plane shears at seam level and then displace the rest of the overlying strata without completely fragmenting it. This technique is generally applied where the seam dip lies between 5.0° and 20.0°.
- A bench buffer blast (softwall) is used where the entire batter face and the bench behind it is assessed as being so structurally disturbed that it is better to blast it and obliterate all structure, as far as is practical. The batter and bench are blasted with a similar charge weight as a normal production blast and the blasted material is battered back to between 40.0° and 45.0°. This method would generally be used where the majority of structures are dipping at over 20.0° and is not covered in this paper.

MATERIAL PROPERTIES OF BLASTED ROCK IN SITU

No direct tests have been carried out at UHG to determine the shear strength properties of blasted rock left in situ. Rock properties and strengths used for limit equilibrium analyses at UHG have evolved with time and the values currently used are as follows: Unit weight 21.4 kN/m^3, cohesion (c) = 60 kPa and friction angle (ø) = 33.0°. These values are based on the following from the literature:

- Bowen Basin unsaturated cat 4 Spoil (Simmons and McManus, 2004) where c = 50 kPa and ø = 35.0°
- Bowen Basin softwall (Kelso, 2011) ø = 30.0°
- Bowen Basin softwall (communications with site geotechnical engineers) c = 50 to 100 kPa and ø = 35.0°
- Tennessee, in jointed sandstone with shale bands, (Moore, 1986) ø = 38.0° and unit weight = 22 kN/m^3.

PHREATIC SURFACE

The locality of the phreatic surface (water table) is critical in producing a valid limit equilibrium analysis. At UHG the phreatic surface model has been derived by dipping the water level in selected blast holes prior to charging up. The following simplified model for the average water depth below various pit wall features is as follows:

- At surface = 23 m
- Below bench or batter crests = 15 m
- Below bench or batter toes = 6 m
- Below overall slope toe and under pit floor = 1 m

Where a buffer blast is present the assumption has been made that the buffer blast zone is freely draining. The phreatic surface is therefore assumed to conform to the base of the buffer blast.

LIMIT EQUILIBRIUM ANALYSES

Galena (Clover Technology 2015) has been used for limit equilibrium analyses at UHG. Models are built by tracing geological cross sections supplied by the site geotechnical team and in some cases these cross sections are very complex. Occasionally the models have used up all fifty material profiles allowed in Galena. Examples of Galena models are shown in Figure 4.

Buffer blasts are limited to a maximum depth of 40 m in the design stage due to equipment limitations. However, occasional buffer blasts to a depth of around 50 m have been conducted. The aim of the blast drilling is to intersect known, or suspected, zones of bedding plane shears.

The required width of the buffer blast is arrived at iteratively by modelling in Galena and targeting a minimum FOS of 1.2. In some cases it is necessary to add a supplementary waste rock buttress to achieve the target FOS. The length of the buffer blast is derived by considering a set of cross sections along a section of the slope (Galena is a two dimensional code).

Limit equilibrium analyses at UHG have indicated that:

- Targeted buffer blasting to control movement along bedding plane shears is a practical option within the seam dip range of 5.0° to 20.0°.
- No sliding along bedding plane shears is expected where the seam dip is less than 5.0° and no purpose would be served by targeted buffer blasting in this range.
- Practical limitations indicate that targeted buffer blasting will be difficult where the dip exceeds 20.0°. At steeper dips the option of extracting coal along dip from the top down should be considered. Alternatively, the entire affected slope may be bench buffer blasted in a series of 50 m high batters.

BUFFER BLAST LAYOUT AND DESIGN

Issues to be considered when designing a targeted buffer blast include:

- Drilling equipment capabilities (maximum practical drill hole depth) which determines whether the targeted bedding plane shear zones can be intersected
- The berm or bench where the holes must be drilled must be suitable for safe drilling, i.e. wide and flat enough.
- Whether angled buffer blast holes will give better access to suspected zones of slippage (not yet done at UHG but likely to be as successful as vertical holes).
- Scheduling: occasionally it is too late to buffer blast an area because the overburden has already been blasted. For a targeted buffer blast the charge weight is typically around 40% of the normal charge weight used for production blasts of the same depth in the same area. Some typical blast design parameters for UHG are as follows:

- Burden = 7.5 m to 8.0 m (typical)
- Spacing = 9.0 m to 9.5 m (typical)
- Drill hole diameter = 229 mm (typically)
- Average charge weight per blast hole:
  - Deep holes (≥ 40 m) = 1,010 kg
  - Intermediate holes (20 to 40 m) = 332 kg
  - Shallow holes (<20 m) = 316 kg]
- Average powder factor = 0.36 kg/bcm (with range 0.14 to 0.52)
- Maximum instantaneous charge (MIC) initiated within 8 ms duration = 2,532 kg.

RESULTS

A total of seven UHG buffer blasts have been assessed for effectiveness in this study, four were successful, and two were classed as probably successful while one was unsuccessful. The results are shown in Table 1.

Table 1: Summary of successful and unsuccessful cases

Blast Block	Pit Sector	Date	Remarks
586a	NEW1	3/09/2013	Probably unnecessary in retrospect, as flat seam dip was identified in a subsequent (closer) cross section. Indicated dip at time of design 6.0°.
605	NEW1	25/09/2013	Successful (without subsequent placement of waste buttress).
397	ELW	3/12/2012	Successful (ramp operating on top of buffer block - no cracks observed).
433	NEW1	4/02/2013	Successful.
480	NEW1	23/03/2013	Successful.
512	SEW1A	6/05/2013	Unsuccessful (major endwall failure, triggered by box cut blast, overran buffer strip). Waste buttress not placed on top. Buffer may have prevented the failure from extending further down slope.
675	SEW1A	26/11/2013	Probably successful - slope behind buffer stable but narrow strip between buffer and toe is unstable (where they overlap) - floor heave at toe.
343	SEW1	12/10/2012	Probably successful (slope stable but exposed buffer portion of slope does not appear very disrupted)

Site personnel report that there were no cases where:

- A buffer blast was recommended but not implemented and then the slope failed
- Recommended buffer blast was not done but the slope remained. Mining personnel, when asked, were of the opinion that buffer blasting helps the slope stability because of the result of the successful buffered slopes, especially those along the Northern Endwall.

The case classified as unsuccessful (Blast Block 512) requires additional discussion. It is possible that this buffer blast did assist stability to some extent but there is no doubt that the major south endwall failure which occurred upslope from this buffer blast strip overran the buffered area. Crackmeter monitoring indicated that slope movement was triggered by a nearby, high energy, confined production blast. In addition to the high energy blast nearby, a 6 m high by 10 m wide waste buttress planned for placement on top of the buffer strip was not constructed.

One indication that the buffer blast was at least partially effective was the absence of signs of floor heave on the downslope side of the buffer blast strip indicating that bedding plane shear movement was probably arrested by the buffer blast.

The geometries and FOS values for the buffer blasted slope areas are summarised in Table 2.

Table2: Buffer blast slope FOS and geometries

Blast Block	Pit Sector	Seam Dip (ψ_p) (°)	Slope angle above buffer blast (ψ_f) (°)	Angle between slope face and seam dip* (ψ_f-ψ_p)	FOS		Design dimensions		Remarks
					Before BB	After BB	Depth (m)	Width (m)	
586a	NEW1	2 to 6	15		1.25	1.42	40	10	Probably unnecessary
605	NEW1	8	20	12	0.88	1.14/1.22	27	40	Successful
397	ELW	15	NA		0.64	1.23	22	38	Successful**
433	NEW1	5	27	22	1.17	1.5	50	10	Successful
480	NEW1	5	16	11	1.01	1.36	15	30	Successful
512	SEW1A	5 to 11	18		1.14	1.25/1.21	10	30	Unsuccessful
675	SEW1A	9 to 12	13	2.5	0.62	1.03	32	30	Probably successful
343	SEW1	5 to 10	24	16.5	0.81	1.1	22	43	Probably successful

* *Only successful and probably successful cases, seam dip average values used*

*** Ramp constructed over buffer blast remains stable. Slope above ramp 28° but in a different geotechnical domain.*

SLOPE FAILURE INFLUENCED BY BLASTING

The extensive failure on the southern endwall which overran the buffer blast strip (unsuccessful case) is suspected to have been influenced by nearby blasting. A confined, high energy production blast in the box cut sited on the western end of the failed area was shown by crackmeter monitoring to have led to acceleration of sliding which culminated in the slope failure. The blast in question, Blast Block 547, had a MIC of 4,604kg.

Considerable work was subsequently done on site to quantify slope damage due to blast vibrations but will not be covered in detail in this paper. Intact rock was expected to be damaged for a distance of up to 150 m from the blast edge and a single blast of the magnitude of Blast Block 547 was estimated to be enough to cause failure up to about 50 m away, as discussed briefly below.

Naismith (1984) indicates that peak particle velocity (PPV) values for a confined (box cut) blast may be as much as three times that of a blast with at least one open face. The same paper quotes the following damage criteria from other authors:

- Oriard (1972) states that falls of loose rock can occur between 50 mm/s and 100 mm/s, partially loosened sections (both underground and on surface slopes) can occur from 130 mm/sec to 380 mm/sec, while damage to intact rock is expected over 635 mm/sec.
- Kiel and Burgess (1977) conclude that the formation of new cracks occurs from 305 mm/sec to 610 mm/sec.

In the absence of seismograph data for blasts at UHG, the PPV was estimated using the following equation, suggested in Müller *et al* (2007) to determine the PPV for sedimentary rocks:

$$PPV = k * L_B^{0.6} * r^m$$

Where:

L_B = Charge weight per delay or MIC (kg)
r = Distance between blasting point and point of interest (m)
k = constant of 969, modified to 1,410 subsequent to observation of blast damage
m = constant of -1.51

Using the equation above including update where k = 1410, the PPV at a distance of 50 m from the blast block edge is estimated as 600 mm/sec dropping to 115 mm/sec at a distance of 150 m. As this was a confined blast, the PPV values may have been as high as 1,800 mm/sec at a distance of 50 m and 345 mm/sec 150 m away.

UHG now designs endwall blasts and those close to endwalls, so that at critical structures (e.g. bedding plane shears dipping >5°) the forecast PPV is not to exceed 130 mm/sec within 100 m of the Blast Block.

CONCLUSIONS

It should be noted that this is a relatively small sample of cases and as such the following conclusions should be treated with caution:

- In 86% of cases studied, the buffer blasts have been successful or probably successful in stabilising the slope.
- Blast vibration has influenced movement in some cases. This has received significant attention on site and is far better controlled now.
- It appears that, on average, a slope of up to 13.0° above the strata dip (ψ_f-ψ_p) can be maintained with the aid of buffer blasting. There is as yet, insufficient data to warrant any statistical analysis of the results.
- Conditions at UHG are generally quite dry, rainfall is low and there are no strong aquifers so the effect of water may lead to different outcomes elsewhere.

ACKNOWLEDGEMENT

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