BLASTING IN PROXIMITY TO A WORLD HERITAGE SITE – A SUCCESS STORY

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Abstract

Quarry blasting adjacent to sensitive properties such as key items of infrastructure or ancient monuments is always likely to be contentious and can arouse serious concern and even objection before operations have begun. Most of these perceptions are the result of a lack of understanding of what is being proposed and the methodology that will be used to ensure that no damage can be done.

To alleviate the potential problem described above, it is a routine requirement that all sites where blasting operations are carried out, have a vibration limit set, generally at the nearest sensitive property, by the local Mineral Planning Officer (MPO] with which the operator must comply. As part of this planning obligation, the site management has to demonstrate compliance by carrying out routine vibration and air overpressure monitoring and then making their results available to the MPO after each blast.

However, when blasting operations are proposed near environmentally sensitive areas, the standard monitoring and reporting practices are often not considered to be sufficient by such third party's as English Heritage due to their increased perception of damage that may occur to structures that they own. This inevitably results in a much lower vibration limit being imposed than is usual, sometimes even for residential property. In addition, the operators of the specific quarry have to demonstrate to a higher level of accuracy that the level of vibration likely to be induced in such sensitive structures will not cause damage. This can then result in major changes to standard operating practices and protocols if blasting is to proceed.

The case study presented here relates to Whitwell quarry in Derbyshire where successful blasting operations are currently being carried out in the vicinity of a registered ancient monument (a number of caves) containing some of the earliest known man-made cave painting in Europe. The aim of this paper is to describe the successful implementation of a blast monitoring and vibration prediction protocol. This will be shown to be based on best practice methods such as the use of electronic detonators and linear superposition for vibration control.

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Introduction

This case study builds on the work carried out in the northern area of Whitwell Quarry, where a blasting protocol was developed and successfully employed, enabling the release of high quality dolomitic limestone reserves in close proximity (60m) to an active railway tunnel. The success of the tunnel project to reduce the impact of blast induced vibrations on the tunnel lining, gave the operator confidence in developing a southern extension to the quarry to release further reserves. However, situated approximately 350m south of the proposed extension is a limestone gorge known as Creswell Crags. The Crags consist of a series of caves and fissures (shown on Figure 1) and, over the past few decades, there have been many archaeological finds including ancient hand tools (43,000 BC) and animal remains (Ice Age). The most important pre-historic objects in the Crags are Britain's oldest cave paintings that date back to the ice age. Due to these significant finds, Creswell Crags is one of the most heavily protected sites in Britain. The Crags are designated with Site of Special Scientific Interest (SSSI) and Schedule Ancient Monument (SAM) status. The Crags is also being considered for world heritage status.

Thus there was concern about the potential impact of vibrations, resulting from quarry blasting on the integrity of the caves, crags and Palaeolithic deposits. In order to ensure that Creswell Crags are protected, the Planning Agreement required a number of conditions to be met, which included the development of a scheme for blasting (comprising a notification protocol, blasting

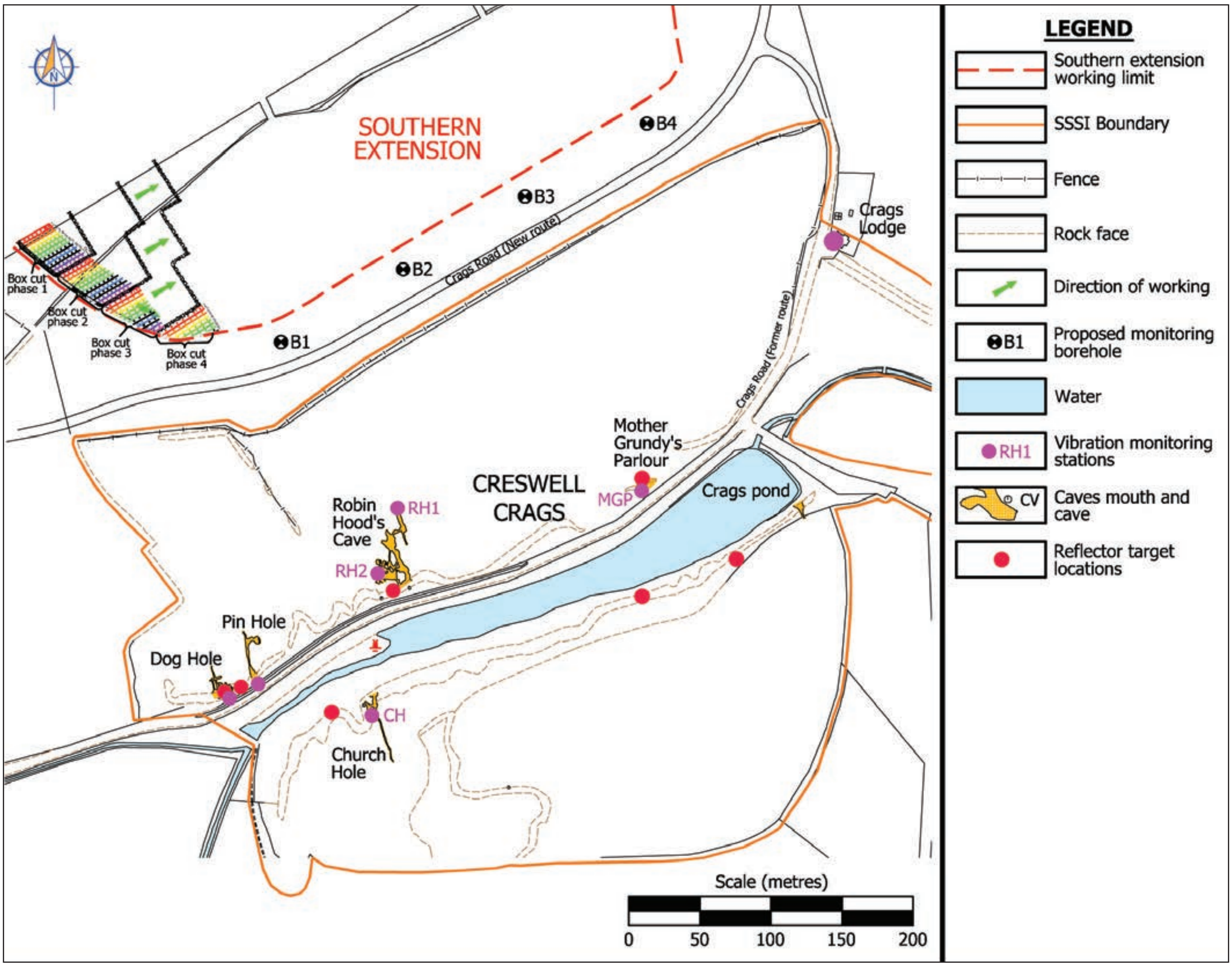

Figure 1. *Whitwell Quarry southern extension and Creswell Crags area.*

protocol and a blast monitoring protocol) and the appointment of an Independent Specialist by Derbyshire County Council.

The appointment was required before any development in the extension area could take place. The Independent Specialist was appointed in May 2008 and immediately familiarised himself with the protocols being proposed. After a number of consultations and the modification of some of the procedures within the protocols, the Independent Specialist reported to Derbyshire County Council on the 25th July 2008 that, in his view the protocols were satisfactory and that the operations could commence.

Agreed procedures

A number of procedures and protocols were agreed which relate to the notification of specific parties and the monitoring of all blasts and their possible impact on the Crags. Within the scheme for blasting, the notification protocol describes who was to be notified of a blast and when, as well as the information to be provided to different parties before and after the blast. The blasting protocol provides procedures for blast hole preparation, charge weight calculation and explosive loading technique, to gain the maximum consistent control during the blast, to minimise ground vibration. The blast monitoring protocol provides procedures relating to vibration monitoring requirements (locations and number of location), the use of single hole blasts to determine suitable inter-hole time delays and blast and vibration regression curve analysis and vibration prediction. In addition to vibration monitoring the protocol details the requirement for crack displacement monitoring, before and after each blast, within the Creswell Crags gorge.

Notifcation protocols

The purpose of this protocol was to give clear guidance to all parties involved, i.e. Independent Specialist, Creswell Crags Visitor Centre, the surveying team and Blast Log Ltd, as to what was expected of them. The Independent Specialist developed a checklist, incorporating all the elements of the scheme onto one side of A4 paper (shown in Figure 2). This acts as an "aide memoir" for the site staff, and also results in a hard copy record of the actions taken. Each step has to be signed off by the Site Manager or his representative and a copy sent to the Independent Specialist after each blast has taken place.

Following the checklist ensures that all parties are given adequate notice of a blast to enable them to

Blast Identifier: __Date: Time:

3 days prior to blast (or earlier) — Initials & date

Notify

Independent Specialist (IS) ____________
Creswell Crags Visitor Centre ____________
Survey Dept. ____________
Blast Log Ltd ____________

Blast design

Use existing dataset to determine predicted PPV levels, (for 50%, 95% and 99.9% confidence levels), for proposed MIC and distances ____________

2 days prior to blast (or earlier)

Provide IS with

a. Blast design MIC (value:____________)
b. Distance (nearest shothole to the nearest point on the cave limit line) (value:____________)
c. Distance (closest shothole to closet cave vibrograph) (value:____________)
d. Predicted vibration levels (for c.) (50%:________, 95%:________, 99.9%:________)

____

IS to approve blast design or request mitigating action to be taken.
(*In the case of the IS not being available to approve the Blast, AND the predicted vibration level (95% confidence limit) being less than 2mm/s, the blast may proceed*).

Is the IS available to approve (Y / N)____________
If (Y) then is approval given? (Y / N)____________
If (N) then is mitigation agreed? (Y / N)____________
If (N) then Blast SHOULD NOT PROCEED
If (N) then is pred. PPV < 2mm/s? (value:________) (Y / N)____________
If (N) then Blast SHOULD NOT PROCEED

Prior to Blast

Survey

Blast

Survey all shotholes ____________
Survey rock face in front and to side of the blast ____________
Determine burden for each shothole ____________
Does charging plan need adjustment? (Y / N)____________
Are distances and MIC as specified in the design? (Y / N)____________

Crags

Survey crack monitoring targets ____________

Vibration Monitoring

Set out/activate vibration monitors ____________

After Blast

Survey (Crags)

Survey crack monitoring targets ____________

Vibration monitoring

Collect and verify vibration data ____________

Notification

Provide IS with vibration and crack data within 3 working days ____________
Measured vibration levels (closest shothole and cave monitor) (value:____________)

IS assessment

Do the results necessitate a new single hole test blast? (Y / N)____________

Database update

Is the blast a single hole test blast? (Y / N)____________
If (Y), blast should be used as seed data for new inter-hole delay timing. ____________
If (N), recorded data to be added to database. ____________

Figure 2. *Blasting scheme checklist.*

implement any required actions. The parties involved and typical actions required of them, on the check list include the following:

- Whitwell quarry staff who prepare the blast;
- Staff at Creswell Crags visitor centre who need to know the date and time of the proposed blast in order to avoid booking visits into the caves;
- Staff of GWP Consultants who carry out pre-blast and post blast crack displacement surveys;
- Staff of Blast Log Ltd who need to prepare for the vibration monitoring required, and
- the Independent Specialist who is required to give approval for each blast, and whenever possible attend to ensure the blast is prepared and fired in such a way that it does not constitute a risk to the crags and caves of Creswell Crags.

The notification protocol requires that the Independent Specialist is provided with details of the blast and predicted vibration levels in advance of the blast (shown in Figure 3). The Independent Specialist then decides whether approval for the blast can be given. He is also provided with the results of the monitoring (vibration and crack displacement) after the blast and is able to assess the performance of the blast in relation to the vibration predictions. An example of the results spreadsheet is shown in Figure 4.

INITIAL BLASTS

To commence extraction in the southern extraction area a box cut was developed, formed using a series of single row, multi-hole blasts, shown on Figure 1. After completion of a box-cut, blasting operations were re-oriented by 90 degrees and progress along the working bench from south west to north east continued. In order to minimise blast vibrations, both the sensitive locations (Creswell Crags and Crags Lodge), and the progressive parallel movement of the blasts along the bench would need to be taken into account.

To accomplish this, electronic detonators were employed in conjunction with a blasting technique known as "linear supposition". The successful use of this technique that includes the use of electronic detonators to optimise blast design has been well documented; examples include Birch et al (2006) and Birch et al (2007). The process of linear superposition uses a vibration signal recorded from a single hole blast which is combined with hole delay times to simulate the vibration signal generated by a full-scale production blast. The optimum delay value is found by simulating this process with varying delay times, to calculate the optimum inter-hole delay, to produce the minimum vibration level for each monitoring location.

The main advantage in using electronic detonators is that they can accurately control the delay timing of each detonator. This is accomplished by each detonator having an internal clock that can be pre-programmed from 1 to 1000 milliseconds to an accuracy of +/- 0.2 milliseconds. In comparison, typical standard non-electric detonators, which use a pyrotechnic based chemical powder for the delay element, can result in a standard deviation of up to 5% for each detonator. A series of experiments carried out by Birch et al (2011) to determine the actual in-hole detonation time of non-electric detonators, during a five hole blast using 25 millisecond delays, found that none of the holes initiated 25 milliseconds apart. The four time period intervals between holes initiating were instead 9, 17, 30 & 15 milliseconds apart respectively.

Consequently non-electric detonators can initiate at a different delay time than expected. This may result in adjacent blast holes firing out of sequence which can cause unwanted vibration shock wave re-inforcement producing an increase in and/or erratic vibration levels. If the timing error is severe two detonators could initiate at the same time, doubling the MIC and significantly increasing vibration levels. Considering the short distance between the blasting and cave locations and the sensitive nature of the crags and caves and the vibration limit crags lodge, this lack of precision could not be tolerated and as

Vibration Predictions

	Distance	Scaled Dist.	PPV Pred. (mm/s) 50%	95%	99.9%
Mother Grundy's Parlour	455.66	67.93	1.00	1.44	1.89
Robin Hood's Cave 1	314.87	46.94	1.00	1.49	1.93
Robin Hood's Cave 2	335.86	50.07	0.92	1.36	1.77
Pin Hole	351.27	52.36	0.86	1.28	1.66
Dog Hole (mouth)	351.40	52.38	0.86	1.28	1.66
Church Hole (mouth)	411.95	61.41	0.69	1.03	1.34
Craggs Lodge	551.99	82.29	0.40	0.52	0.66
BH1 South (Surface)	186.55	27.81	3.25	4.27	5.45
BH1 South (Top)	186.55	27.81			
BH1 South (Bottom)	186.55	27.81			
BH 2 South (Surface)	250.69	37.37	1.83	2.41	3.07
BH 2 South (Top)	250.69	37.37			
BH 2 South (Bottom)	250.69	37.37			
BH 3 South (Surface)	335.56	50.02	1.04	1.37	1.75
BH 3 South (Top)	335.56	50.02			
BH 3 South (Bottom)	335.56	50.02			
BH 4 South (Surface)	381.77	56.91	0.81	1.07	1.36
BH 4 South (Top)	381.77	56.91			
BH 4 South (Bottom)	381.77	56.91			

Shortest Distance Vibration Predictions (Res)

Location Name	Distance to nearest cave (m)	Scaled Distance	PPV Pred. (mm/s) 50%	95%	99.9%
Robin Hood's Cave	314.87	46.94	1.00	1.49	1.93

***Figure 3.** Example of a vibration prediction sheet.*

Monitored Results (mm/s)

	Distance	Scaled Dist.	Predicted 50%	95%	99.9%	Measured (mm/s)
Mother Grundy's Parlour	455.66	67.93	1.00	1.44	1.89	0.79
Robin Hood's Cave 1	314.87	46.94	1.00	1.49	1.93	1.01
Robin Hood's Cave 2	335.86	50.07	0.92	1.36	1.77	0.95
Pin Hole	351.27	52.36	0.86	1.28	1.66	0.92
Dog Hole (mouth)	351.40	52.38	0.86	1.28	1.66	
Church Hole (mouth)	411.95	61.41	0.69	1.03	1.34	DNT
Craggs Lodge	551.99	82.29	0.40	0.52	0.66	DNT
BH1 South (Surface)	186.55	27.81	3.25	4.27	5.45	2.46
BH1 South (Top)	186.55	27.81				
BH1 South (Bottom)	186.55	27.81				
BH 2 South (Surface)	250.69	37.37	1.83	2.41	3.07	2.21
BH 2 South (Top)	250.69	37.37				
BH 2 South (Bottom)	250.69	37.37				
BH 3 South (Surface)	335.56	50.02	1.04	1.37	1.75	1.63
BH 3 South (Top)	335.56	50.02				
BH 3 South (Bottom)	335.56	50.02				
BH 4 South (Surface)	381.77	56.91	0.81	1.07	1.36	0.74
BH 4 South (Top)	381.77	56.91				
BH 4 South (Bottom)	381.77	56.91				

Notes:

DNT = Did Not Trigger

Shortest Distance Monitored Results (mm/s)

Location Name	Distance to nearest cave (m)	Scaled Dist.	50%	95%	99.9%	Measured
Robin Hood's Cave	314.87	46.94	1.00	1.49	1.93	1.01

***Figure 4.** Example of a vibration results sheet, where the predicted values are shown for comparison.*

such electronic detonators were required for precise control and because the delay times could be set to match the results of the linear superposition analysis.

The first blast in the Southern Extension area was a single-hole "signature" blast, carried out in September 2008. This was used to produce a "seed" waveform which is required by the linear superposition technique. By employing the single hole vibration signal recorded from each vibration monitoring location shown on Figure 1, it is possible to calculate the best time interval for the delay detonators in subsequent multi-hole box cut blasts for all monitored locations. Since then five single-row, multi-hole blasts were carried out, designed to open up the initial box cut on the upper bench.

It should be noted that the condition of the rock in this south-western corner of the box-cut was poor. Figure 5 shows the rock to be broken, with considerable amount of clay material infilling a number of fissures. This caused a problem with two blasts, where on each occasion one of the drilled holes could not be loaded with explosive. The broken nature of the rock also given rise to uneven quarry faces which had caused some variability in the burden, although not sufficient to prevent any holes from being used.

MONITORING PROCEDURES

Procedures in the blast monitoring protocol for the Southern Extension are designed to measure blast vibration levels in and around Creswell Crags, as well as surveying a number of previously designated locations on the crag faces to determine whether there has been any displacement that could be attributed to blasting.

Crack displacement monitoring

The Planning Agreement stipulates that a number of fissures or cracks in the rocks at Creswell Crags should be monitored to determine if there is any relative displacement, indicating movement of the rock mass. A total of seven cracks were identified (shown on Figure 1 as reflector target locations) and three reflector points around each crack were measured on a monthly basis between March 2004 and the commencement of blasting in the Southern Extension in September 2008. The absolute locations of the points in the gorge are surveyed from a number of control stations using a 1 second total station. Any displacement of these points can be determined, together with any relative displacement between the points around each crack to an accuracy of between 1 to 2 mm.

On the commencement of blasting operations in the Southern Extension area the frequency of monitoring increased to pre blast and post blast surveys (both typically on the same day as the blast) and for every blast.

Vibration monitoring

The Planning Agreement stipulated that vibration monitoring should take place for all blasts in the Southern Extension at three locations in and around the caves of Creswell Crags, however it did not specify the exact locations. A maximum vibration level was not specified because the absolute priority was to avoid damage to the caves and crags rather than meet an arbitrary vibration limit. In the blast monitoring protocol it was suggested that all blasts were designed such that 95% of all blasts fired produced less than 12 mm/s in the nearest cave. This would keep vibration levels well below that at which damage may be caused based on an extension of an existing crack in plasterboard occurs at 14.3 mm/s (White et al, 1993).

The Independent Specialist agreed with this approach, but added that vibration levels should be maintained at as low a level as is practically possible.

The Planning Agreement also stipulated that blast monitoring should be carried out at the nearest residential property known as Crags Lodge (Figure 1) and that 95% of blasts fired should not exceed 6 mm/sec, and should never exceed 8.5 mm/s.

Based on the typical theory that blast vibration levels decreases proportionally as distance increases, it was predicted that as blasting progresses in a north easterly direction, closer to Crags Lodge and further from the caves and crags (Figure 1), the vibration limit applicable at Crags Lodge would become the controlling level (rather than the crags vibration level), which would further restrict the vibration levels in Creswell Crags.

Figure 5. *Box cut face showing broken rock clay with material infilling a number of fissures.*

The purpose of the vibration monitoring was to ensure compliance at Crags Lodge and to continually review the vibration levels in the Crags. The recorded vibration results would be used as the basis for predicting vibration levels of each subsequent blast for each monitored location. New data would be added to the existing dataset immediately after each blast and a scaled distance regression model would be developed and used to ensure the predictions and the MICs for the next blast were based on the most up to date data set and therefore would be as accurate as possible.

To add further accuracy to the vibration predictions it is planned to drill a number of boreholes along the southern extension boundary (Figure 1). Each of the boreholes would be instrumented with vibration monitoring arrays at the same horizon (elevation) as the caves.

Vibration monitoring results

The recorded vibration data can be divided into three separate sets; the data recorded in and around the caves in Creswell Crags, at the monitoring location at Crags Lodge, and at the surface locations of the proposed monitoring boreholes.

The monitoring locations in Creswell Crags are the most important as they enable the response of the caves and crags to blast induced vibration to be determined. The highest Peak Particle Velocity (PPV) value so far recorded in the Crags is 1.56 mm/s at monitoring location RH1 shown on Figure 1, to the northern extent of Robin Hood's cave. This occurred when the blast was at its nearest approach to date, at a distance of 295 m.

During blasting operations the author has positioned himself in the gorge, in order to directly experience the effect of the blasts. On only one occasion has he personally felt the vibrations while standing near to the caves, although a faint sound was heard indicating the blast had been fired.

A brief summary of the vibration records from each monitoring location is given below.

Church Hole: Only one blast event (the signature blast) triggered the blasting seismograph which received 0.70 mm/s in the cave mouth. This resulted in a vertical PPV being twice as high as the horizontal measurements, and indicating a significant ground-roll component.

Mother Grundy's Parlour: The vibration levels recorded ranged from 0.83 to 1.27 mm/s which are typical for recordings of blasts at similar distances (~450m). Most of the energy was below 10Hz, with the maximum amplitude often occurring at around 5 Hz.

Pin Hole: The vibration results from this location ranged from 0.57 to 0.95 mm/s. The PPV amplitudes and frequency content were typical for blasts monitored at the surface at these distances (~350 m).

Robin Hood 1: The results recorded ranged from 1.02 to 1.56 mm/s. This monitoring location gave rise to significantly different waveforms from the other monitoring locations. For the multi-hole blasts, the radial component of the blast vibration wave form had a very dominant frequency at 29 Hz, and was always the highest magnitude of the three orientations (radial, vertical and transverse). It appears to show a resonance effect, which may be due a coupling effect or it may be due to the way the cave is responding, as this location is deep within Robin Hood's Cave. The precise reason is uncertain, so it would be wise to investigate this further to determine whether it is a spurious monitoring effect or a true indication of the way the cave is responding.

It should be noted that the single-hole blast did not show this effect, having a broad range of frequencies for all orientations and with the vertical giving the maximum PPV. It will be interesting to note if future single-hole "signature" blasts are similar.

Robin Hood 2: The vibrations received ranged from 0.95 to 1.02 mm/s. The signals recorded here appeared to be normal surface vibration waveforms, with amplitudes and frequency content typical for measurements at these distances (>300m). PPV values were around 1 mm/s and most of the energy was below 20Hz. The blasting seismograph failed to trigger for two blasts which is somewhat surprising, given the magnitudes elsewhere.

With the exception of the first blast, which was a single-hole "signature" blast and therefore different to the others, the recorded PPV values correlated well with the predicted values, an example of this is shown in Figure 3. The single-hole blast resulted in vibration levels several times higher than the predicted values for most locations, which was probably a result of the data set used in the prediction. That data set was made up of single hole vibration data recorded at another area of Whitwell Quarry, as no other single hole blasts have been carried out and monitored at the southern extension. Blast vibration predictions can now be based on vibration results from the southern extension. By adding data to the southern extension regression model after each blast the accuracy of the predictions should keep improving.

All blasts have been monitored at Crags Lodge and so far the maximum vibration recorded was 1.2mm/s.

Conclusion

To date, the monitoring protocols have been functioning well as no individual blast had predicted vibration levels greater than the imposed vibration limits, and no vibration levels have reached the vibration limits. The greatest vibration received at the Creswell Caves and Crags Lodge were 1.56 mm/s and 1.2 mm/s respectively.

The results of the relative displacement monitoring showed that all the results lie within normal measurement errors (1 to 2 mm), thus indicating that no relative displacement has been detected along the cracks being monitored.

Currently, blasting operations are approximately 295m from the nearest cave. In future, operations will approach within 200m of the nearest cave. The aim going forward as blasting approaches the caves being to keep the vibration as low as practicably possible at the Crags to enable production to continue.

If the monitoring scheme and use of electronic detonators for vibration minimisation were not in place and proven to work efficiently, it may not have been possible to gain permission to extract the c.4.1Mt of limestone available in the southern extension area.

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