An Improved Technique for Predicting Vibration Levels from Tunnel Blasting.

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Abstract

Despite increasing competition from mechanical methods of tunnelling, the drill and blast method is often still the most viable method of excavating tunnels in strong and abrasive rock. To advance a tunnel using drill and blast, explosives are loaded into boreholes in the rock and detonated according to a prearranged sequence. On detonation of the explosive, the rock is fractured and displaced from its original position, leaving behind the desired void. Among the secondary effects of a tunnel blast are ground vibrations caused by elastic disturbances that propagate away from the blasted tunnel face. The possibility that such ground vibrations may cause permanent damage to property and substantial nuisance has generated significant opposition to the use of drill and blast, particularly in urban areas. It is therefore essential that the blasting engineer is able to predict Peak Particle Velocity (PPV) vibration levels at locations in the vicinity of the blast site. Such predictive capability enables the engineer to design blasts so as to ensure that ground vibrations can be kept within acceptable levels. The objective of this project was to analyse data obtained from the ground vibration monitoring program undertaken during the drill and blast excavation of a hard rock tunnel in Central England. Seismograph recordings of tunnel blasts contain a vast amount of information that cannot possibly be expressed using a single PPV value. The main focus of the study was to investigate whether predictive capability could be improved by using scaled distance models derived for selected PPV components relating to specific detonator timings in a given tunnel round. This study has established a method of analysis that can unlock this information for predictive purposes. By permitting the extraction of sub-event Peak Particle Velocity (PPV) values and allowing Scaled Distance (SD) models to be derived for individual period numbers or groups of period numbers, the method has the potential to vastly improve PPV prediction from tunnel blasting. The method established could also help diagnose blasting problems and help target blast design modifications, resulting in improved efficiency and excavation rates.
Introduction

Despite increasing competition from mechanical methods of tunnelling, the drill and blast method is often still the most viable method of excavating tunnels of short length in strong and abrasive rock, it has been used for both mining and civil tunnels and it is deemed by many to be an economical, reliable and safe option.

To advance a tunnel using drill and blast, explosives are loaded into boreholes in the rock and detonated according to a prearranged sequence. On detonation of the explosive the rock is fractured and displaced from its original position, leaving behind the desired void. Among the secondary effects of a tunnel blast are ground vibrations caused by elastic disturbances that propagate away from the tunnel face. The possibility that such ground vibrations may cause permanent damage to property and substantial nuisance has generated significant opposition to the use of drill and blast, particularly in urban areas. It is therefore essential that the blasting engineer is able to predict vibration levels at locations in the vicinity of the blast site, as having this predictive capability enables the engineer to design blasts in such a way that ground vibrations can be kept within acceptable levels.

The objective of this project was to analyse data obtained from the ground vibration monitoring program, undertaken during the drill and blast excavation of the Cliffe Hill tunnel in Leicestershire. The main focus of the analysis was to investigate whether predictive capability could be improved by using scaled distance models derived for selected components of a tunnel round.

The Cliffe Hill Tunnel

The Cliffe Hill Tunnel (CHT) in Leicestershire was constructed to connect the Old Cliffe Hill quarry (OCH) to the New Cliffe Hill quarry (NCH).

The owner of both quarries, Midland Quarry Products, had several objectives, but their primary concern was to minimise the environmental impact of the long-term development of the quarrying activities. They also needed to choose how best to exploit the 60 million tonnes of high quality porphyritic microdiorite (granite) road stone reserves that remained sterilised beneath the defunct processing plant at the OCH site. Midland Quarry Products decided that the best way to fulfil their objectives was to excavate a new conveyor tunnel to transport the granite from OCH to the new processing plant located within NCH.

The initial design proposal involved a tunnel driven partially through the granite, but largely through the marl, with the central section constructed using the cut and cover technique. However the cut and cover proposal was eventually discarded due to the envisaged environmental impact and the difficulties associated with tunnelling through
The decision was made to opt for a tunnel excavated by drill and blast within the more competent granite. Thyssen Technical Services Ltd were chosen to lead the project and worked with Midland Quarry Products throughout the latter part of 2001 to finalise the plans. The planning consent was received during the middle of 2002 and the contract started in August 2002.

Tunnelling works commenced mid January 2003, and was completed in September 2003. The majority of the tunnel length was excavated in one direction only, from OCH towards NCH. However to ensure the project was finished on time a second blasting crew were brought in to advance the tunnel in the opposite direction. The monitoring data supplied for analysis in this project comprises only of blasting events from the first 500m on the OCH to NCH advancing face. The finished tunnel was driven 726 m in length some 50 m below the surface within the Markfieldite granite, which had a Unconfined Compressive Strength of up to 200 MPa.

**Typical Round Design**

In bench blasting the boreholes are drilled parallel to the free face against which the breakage can then take place. In tunnelling, however, the only free face is that of the tunnel face. Drilling parallel to a free face is consequently not possible. To achieve satisfactory blasting results an opening or void known as the initial cut must be created into which the surrounding rock can be blasted. The establishment of an accurate cut is a prerequisite for satisfactory tunnelling work, and there are a number of different types of cut that are commonly in use. The type of cut employed at the CHT is known as the parallel cut, where all the holes are drilled perpendicular to the tunnel face parallel to the direction of the tunnel.

With the round design used at the CHT there were four large diameter void holes drilled in the lower middle of the tunnel face, these were surrounded by five tightly packed loaded holes in a configuration known as a ‘burn cut’. With this design the initial breakage is against the void holes, with the rock being thrown out of the face leaving behind a central cavity. Once formed, the central cavity is gradually opened up by the successive detonation of the adjacent loaded holes of the ‘bulk’. The ‘lift’ holes are then used to take out the floor section. Finally the closely spaced ‘trim’ holes loaded with a lighter charge of explosive are used to obtain the final contour with the minimum damage to the roof and wall rock.

The tunnel round employed at the CHT comprised four main components known as the Cut, Bulk, Lift and Trim as illustrated in figure 1. The numbers in the diagram
correspond to the period numbers of the NONEL® LP detonators used in the round. Each hole has been colour coded to identify the different components of the tunnel round i.e. cut, bulk, lift and trim. The cut, bulk and lift holes were loaded with nitro-glycerine based explosive cartridges. The trim (or contour) holes were loaded with either 80 or 100 gram m⁻¹ detonating cord.

Figure 1. Contractor’s blast design (initiation pattern and hole loading).
Examination of explosives receipts from the CHT has revealed that the zero period number detonator was not used in any of the tunnel rounds, however the five hole burn cut configuration as shown in figure 1, was used throughout the operation. The burn cut incorporated delay period numbers one to five, with period number one in the centre.

**Method of Data Analysis**

The analysis of vibration monitoring data obtained from the Cliffe Hill tunnel (CHT) was performed on two levels of detail. The first level of analysis is referred to as ‘standard regression analysis’, and was performed on the event resultant peak particle velocity (PPV) values. The second level of analysis is referred to ‘detailed regression analysis’, and was performed on the PPV values associated with each detonator delay time.

The use of “Scaled Distance” is necessary in order to be able to predict the attenuation of PPV when both the maximum instantaneous charge weight (MIC), and the distance (D) vary. The two most popular approaches are square root and cube root scaling, the relative merit of both methods has been discussed by Dowding\(^1\). A site-specific method of scaling also exists and has been described by New\(^2\). The method of scaling chosen for the analysis of the CHT data was the standard square root scaling.

\[
SD = \frac{D}{\sqrt{MIC}}
\]

Where:

- **SD** = scaled distance (m.kg\(^{-0.5}\))
- **D** = slope distance between blast and monitoring location (m)
- **MIC** = maximum instantaneous charge weight (kg)

Once the SD values are calculated it is then possible to produce a bi-logarithmic plot with PPV as a function of SD. Once plotted, a line of best fit can be fitted to the data using least squares regression analysis, giving rise to an empirical formula (SD model) of the following form:

\[
PPV = a \times SD^b
\]

Where:

- **PPV** = Peak particle velocity (mm s\(^{-1}\))
- **a, b** = dimensionless site specific factors

Taking logarithms of both sides of the equation allows the relationship to be expressed as follows:

\[
\log PPV = \log a + b \log SD
\]
With such bi-logarithmic plots there will often be a high degree of scatter about the best fit line, therefore it is often necessary to calculate and plot additional regression lines that correspond with statistical confidence levels. The most common approach is to plot both the best fit (50% regression) line as well as a line representing the upper 95% confidence level. To calculate the upper 95% confidence level a standard deviation multiplier of 1.645 is used as only the confidence level above the mean is required. The standard error about regression (Standard Error) is used as a means of analysing the contained error in the derived scaled distance models. The standard error of a data set is calculated directly from the standard deviation of the data about the best fit line. The tighter the data points fit to the line the smaller the standard error will become. For a given set of data, containing logPPV and corresponding logSD values, the standard error about regression is calculated in the manner, as described by White, Birch & Pegden

**Method of Prediction**

The prediction of PPV from tunnel blasting is usually based on the regression analysis of single PPV values extracted from seismograph recordings. The initial analysis work undertaken in this project was associated with performing this type of analysis on the CHT data. This used the advanced blasting data base developed at the University of Leeds and described by Birch W.J., Pegden M. & Stothard P

The first SD model to be derived was for the test blast data. As the test blast only involved one charged hole, the MIC was known to be exactly 1 k, for this reason the test blast model is extremely useful in providing a base line against which initial assumptions regarding the calculation of MIC for the tunnel blasts can be tested. Two further SD models were established using the tunnel blast data, one with MIC equal to the maximum charge weight per hole, the other with the MIC equal to the maximum charge weight per delay time. The two plots were then compared with the test blast plot to establish which method of scaled distance calculation would be most valid for the NONEL LP system. The standard regression analysis also helped to assess the effectiveness of the NONEL LP system in staggering the detonation of the blast holes.
Test Blast Model

Using the seven seismograph recordings of the test blast event, it was possible to produce the scaled distance model, as shown in figure 2. The derived relationship found from the least squares best fit line is given below, along with the correlation coefficient and standard error.

- **Derived relationship:**
  \[
  \text{PPV} = 8310.76 (SD)^{-2.0249}
  \]

- **Standard error =** 0.1814
- **Correlation coefficient =** -0.9942

The correlation coefficient gives a very high negative correlation and a minimal standard error, indicating that the points are an excellent fit to the best fit line and have very little scatter, as can be observed in figure 2. The test blast model gives an indication of the attenuation of PPV for the local geology over a reasonably wide range of scaled distance values.

![Test Blast Model](image)

**Figure 2 - Test Blast using proposed burn cut and 1 kg charge weights**

Maximum Charge per Delay Model (max MIC model)

The max MIC model assumes that all the charged holes fired at the nominal initiation times. If this was to occur then the MIC would be equal to the largest charge weight on a single delay time.
The max MIC was calculated in the following manner:

$$\text{max MIC} = \text{Max}[Q \times W]$$

Where:

- max MIC = maximum charge weight per delay
- Q = number of detonators of the same period number (usually Q = 10)
- W = charge weight of single hole

The maximum charge weight per delay had to be calculated for all 43 events as both the quantity of explosives and detonators used varied between blasts. However, the greatest number of bulk holes of the same period number (Q) was found to be almost always equal to 10.

Figure 3 shows a bi-logarithmic plot incorporating both the test blast and tunnel blast data, using the max MIC in the SD calculation, best fit lines have been added to both sets of data. All of the tunnel blast data points lie well beneath the test blast best fit line, which suggests that the max MIC values used to calculate the SD were too high. Therefore the assumption that all the holes fired at exactly the nominal time is almost certainly incorrect. The PPV values are less than would be expected from the max MIC values, based on the test blast SD model, this is almost certainly due to the scatter in initiation times. The derived relationship for the max MIC model is given below. The values calculated for the standard error and correlation coefficient indicate that there is a high negative correlation with a reasonably low amount of scatter.

- Derived relationship:
  $$\text{PPV} = 20368.4(\text{SD})^{-2.89}$$

- Standard error = 0.29261
- Correlation coefficient = -0.9139
Figure 3 - Maximum Charge per Delay and Test Blasts models plotted together

Average Bulk Charge Weight Model (min MIC Model)

The min MIC model is based on the assumption that every hole in the round fired independently, i.e. the initiation times of all the holes were scattered to the extent that there was no wave reinforcement, even between holes on the same delay. The MIC values used to create the model are equal to the average bulk charge weight per delay, as calculated from the explosives receipts.

Figure 4 - Minimum Charge per Delay and Test Blasts models plotted together
Figure 4 shows a bi-logarithmic plot incorporating both the test blast and tunnel blast data, using the min MIC in the SD calculation. Best fit lines have been added to both sets of data. The derived relationship for the min MIC model is summarised below:

- **Derived relationship:**
  \[ PPV = 632716(SD)^{-2.916} \]

- **Standard error** = 0.2828284
- **Correlation coefficient** = -0.919783

The standard error and correlation coefficient indicate a high negative correlation with an acceptable amount of scatter. The gradient for the min MIC best fit line is very close to that of the max MIC best fit line, as confirmed the ‘b’ values in the derived relationships, the standard error and correlation coefficients are also very similar. These similarities come as no real surprise, as on the whole, the max MIC was exactly ten times greater than the min MIC. The gradient of both the min MIC and max MIC best fit lines are steeper than that of the test blast best fit line. In the min MIC model (figure 4), it can be seen that the tunnel blast data lies much closer to the test blast best fit line when compared to the max MIC model (figure 3), however one must remember that both axis are logarithmic. The improved fit of the min MIC data to the test blast best fit indicates that the min MIC provides the best approximation to the actual MIC. However the fact that all the data points in the min MIC are positioned above the test blast line suggests that there was at least some wave reinforcement occurring. In an attempt to quantify the extent to which the blast holes were interacting, MIC ratio lines were added to the min MIC model as shown in figure 5. In figure 5 the MIC ratio lines have been projected from the test blast best fit line, by increasing the MIC used to predict the PPV by multiples of 2, 3, 4, 5, & 10. The MIC ratio lines indicate the factor which the MIC would have to be multiplied in order to fit a data point to the test blast line, i.e. if a data point is situated exactly on theMIC×5 line then the MIC value used to calculate the scaled distance would have to be multiplied by 5 to reposition the data point on the test blast line.

The positions of the tunnel blast data points relative to the MIC ratio lines are summarised below:

- 100% of data points situated above Test Blast Line
- 48.8% of data points situated above the MIC×2 line
- 20.9% of data points situated above the MIC×3 line
- 7% of data points situated above MIC×4 line
- 4.7% of data points situated above MIC×5 line
Just over half the data points lie between the test blast line (MIC×1) and the MIC×2 line.

**Detailed Regression Analysis**

Seismograph recordings from tunnel blasting contain far more information than can be expressed using a single PPV value. In using a single PPV value, standard regression analysis does not recognise the manner in which individual components of a tunnel round contribute to ground vibrations.

The purpose of performing the detailed regression analysis was to determine which components of the tunnel blast generated the recorded PPV values, and to investigate whether PPV prediction could be improved by using SD models derived for selected components of a tunnel round.

The method devised involved breaking up each individual seismograph recording and extracting resultant PPV values associated with every detonator delay period used within a tunnel blast. Thereby dividing each recorded tunnel blast event into a series of sub-events that could be further analysed using a bespoke blasting database.

Once the PPV values had been extracted for each period number, it was possible to identify which period number caused the PPV in each seismograph recording. Figure 6 shows the frequency with which the recorded event PPV values fell within the time slots.
designated to the 24 period numbers.

![Delay Period Attributable to PPV](image)

**Figure 6. PPV frequency against period number**

An examination of Figure 6 indicates that

- 5 cut blasts were responsible for the maximum PPV for a given blast;
- 27 Bulk Blasts were responsible for the maximum PPV for a given blast;
- 4 lift blasts were responsible for the maximum PPV for a given blast;
- 8 trim blasts were responsible for the maximum PPV for a given blast;
- None of periods 2, 3, 4, 5, 6, 7, 8 and 9 [which were all individual holes] gave rise to a maximum PPV values recorded.
- rather surprisingly neither did period numbers 14, 16 nor 50
- only period 1 within the cut is identified as causing the maximum PPV for a given blast;

The highest PPV values appear to have been generated by the Lift and Bulk components of the tunnel round, which is not surprising as the Lift and Bulk had the greatest charge per delay. What is more surprising is that three of the PPV values attributed to the period number 1 delay are situated above the MIC×2 ratio line. If anything these data points ought to be the closest to the test blast line. One possible explanation for the high PPVs associated with period number 1 is that sympathetic detonation occurred within the closely spaced holes of the cut, initiated by the first hole. This was confirmed by
inspection of the actual blasts vibration traces.

**Conclusion**

Seismograph recordings of tunnel blasts contain a vast amount of information that cannot possibly be expressed using a single value. This project has established a method of analysis that can unlock this information for predictive purposes. By permitting the extraction of sub-event PPV values derived for individual period numbers or groups of period numbers, the method has the potential to vastly improve PPV prediction from tunnel blasting. The method established could also help diagnose blasting problems and help target blast design modifications, resulting in improved efficiency and excavation rates.

As a result of the analysis undertaken during this project the following conclusions can be made:

- Not all the detonators were firing exactly at the nominal times in the tunnel rounds. However some of the holes must have detonated within a sufficiently short time of one another to have produced the recorded PPV values.
- The maximum charge per hole was the most suitable MIC value for use in the calculation of SD for the tunnel blast data.
- The MIC ratio lines indicated that as many as five holes may have detonated simultaneously to give rise to the recorded PPV values. The use of MIC ratio along with the coded data identified the occurrence of sympathetic initiated by the first hole in the burn cut. This was confirmed by visual examination of the of the resultant particle velocity plots of the relevant events.

**Future work**

It is clear from the results obtained that, for every blast monitored, all the maximum PPV levels were above the test blast line, inferring either a greater or less degree of constructive interference between at least two blast holes. That being so, the application of electronic detonators, where the actual firing times can be precisely defined to ensure that no two holes are fired simultaneously, could be of great benefit when driving hard rock tunnels in urban areas. A project is currently being carried to by the Blasting and Environmental Research at the University of Leeds determine if this is a practical proposition.
References