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Rock blasting — peak particle velocity against distance

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Abstract

The potential damage which could be induced by blasting in rock is normally evaluated with reference to the peak particle velocity (PPV). It is well-known that closer distances lead to higher PPV values. In some cases, due to muck handling logistics, the ramps forming the access result in different elevations across the different parts of a very deep excavation. Deep excavation access ramps and the completed base excavation ready to receive the concrete casting can be in close proximity to each other. In order to meet the construction schedule, the base slab has to be concreted while blasting works are still on-going at the access ramps. Hence, an optimised blasting programme is required to assure that construction progress is not unreasonably compromised, while vibration is kept under control. This paper first discusses the effectiveness of trenches to reduce vibration based on the findings reported in the literature, showing that this solution could be difficult to implement in practice because a very deep trench is required especially for hard rocks. Therefore, in most rock blasting programs, a more practical solution is to establish the distance beyond which PPV measurements are acceptable. This paper presents the data obtained from field measurements obtained from the excavation of an underground station in limestone rock. The vibrations were monitored from three permanent tunnel rings which are adjoining the boundaries of the underground station box, for which blasting was still on-going. An attempt is made to approximate the PPV with distance, and at the same time considering other factors such as the explosive charge weights in each delay, height of the free face, drill depth, drill spacing and number of holes.

1 Introduction

To carry out excavations in rock, the blast design must ensure adequate fragmentation of the rock, otherwise secondary breakage is required. Excavations using a hydraulic breaker or other mechanical methods are time consuming. Therefore, blasting using explosives is often the preferred method of rock excavation. However, blasting causes vibration in the ground which could induce damage to nearby existing buildings and structures. Vibration is normally quantified by the peak particle velocity (PPV), and this is typically measured at structures for which vibration induced damage has to be minimised. Vibration can be a major concern where the distance between the structure of concern and the blasting source are close to each other. In these circumstances the induced vibration could be controlled by either reducing the amount of explosives or by introducing man-made features in the ground such as a 'free-face' or 'relief-holes' which are known to be capable of diminishing the magnitude of vibration. It is also known that limiting the drill depth and spacing could reduce the magnitudes of vibration.

2 Motivation of investigation and preliminary desk study on the effectiveness of trenches

In the construction of Mass Rapid Transit underground station projects in rock, the understanding of vibration becomes even more important. The reason for this is that the permanent tunnel lining is located at the edge of the station box (see Figure 1); the mine-through option was adopted for the lower tunnel to improve the overall tunnel schedule to reduce the launching risk at the initially proposed launch shaft. Due to muck handling logistics, the ramps forming the access result in different elevations across the different parts of the excavation (Figure 1). To achieve the required permanent works programme, some parts of the excavation were excavated to final excavation level earlier. Rock excavation using a surface miner (a machine on a crawler with a cutting drum rotating against the travel direction to cut and crush rock mechanically) was also used at this station. Reasonable progress was achieved; however, the maintenance and operation cost was very high and was only effective when the working area is sizable. The surface miner was decommissioned when the excavation was more restricted, and drill and blast was commissioned for further excavation. This means that, during the construction of the underground station, the casting of the base-slab could be affected by adjacent blasting. The need for a better understanding of the induced vibration due to blasting is critical so that the progress of excavation is not unduly compromised while at the same time still satisfying the permissible PPV measured at the concerned structure.

At the beginning of our project, which is founded on the Kuala Lumpur Limestone formation, a desk study was undertaken to explore the efficacy of trenches in reducing blast induced vibrations. From our literature review, the results of Beskos et al. (1986), Ashref and Al-Hussaini (1991) and Alzawi and Hesham El Naggar (2011) suggested that the trench depth has to be at least half of the wavelength of the Rayleigh waves to achieve a reliable and sufficiently significant amplitude reduction. The measured vibration frequency due to blasting was determined to be approximately 15-50 Hz. From nearby seismic refraction surveys at the site, the p-wave velocity was estimated to in the range of 2,500 to 4,000 m/s for the rocks at our site with different degrees of fracturing. Therefore, the Rayleigh wavelength induced by vibration is expected to be greater than 25 m. For practical purposes, it was deemed operationally feasible to create a 4 m deep open trench. The trench depth to Rayleigh wavelength ratio of approximately 0.16 would result in an amplitude reduction of 0.75 (optimistic estimate according to Figure 2 and operational blasting parameters). Therefore, the aforementioned finding suggests that creating trenches is unlikely to exhaustively reduce the effect of blasting and accommodate the required base-slab casting programme (in terms of the minimum distance away from blasting). This led to the adoption of a more rigorous analysis of establishing the measured PPV with distance from the on-going blasting.

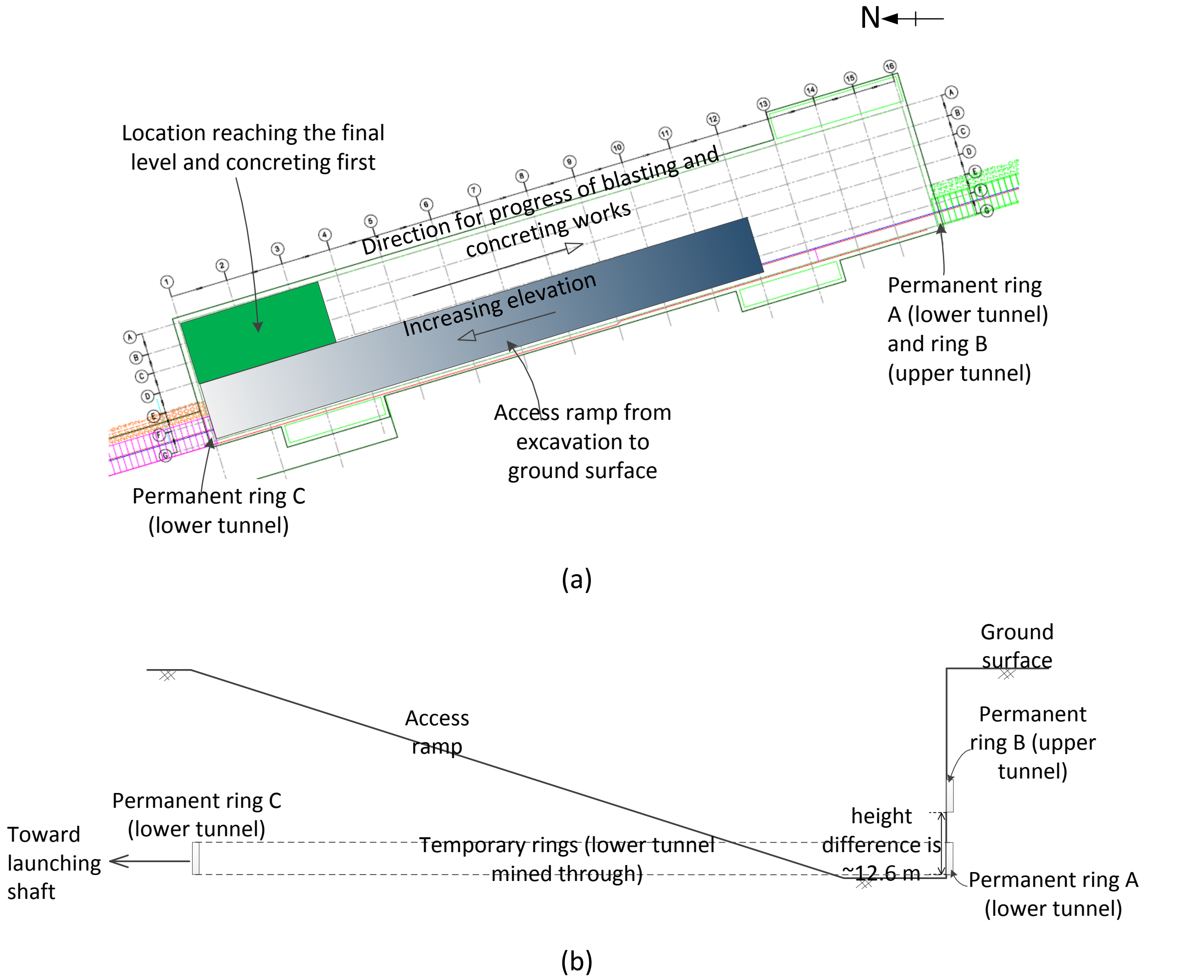


Figure 1 Excavation and location of monitored permanent tunnel rings: (a) layout plan; and (b) cross-section view

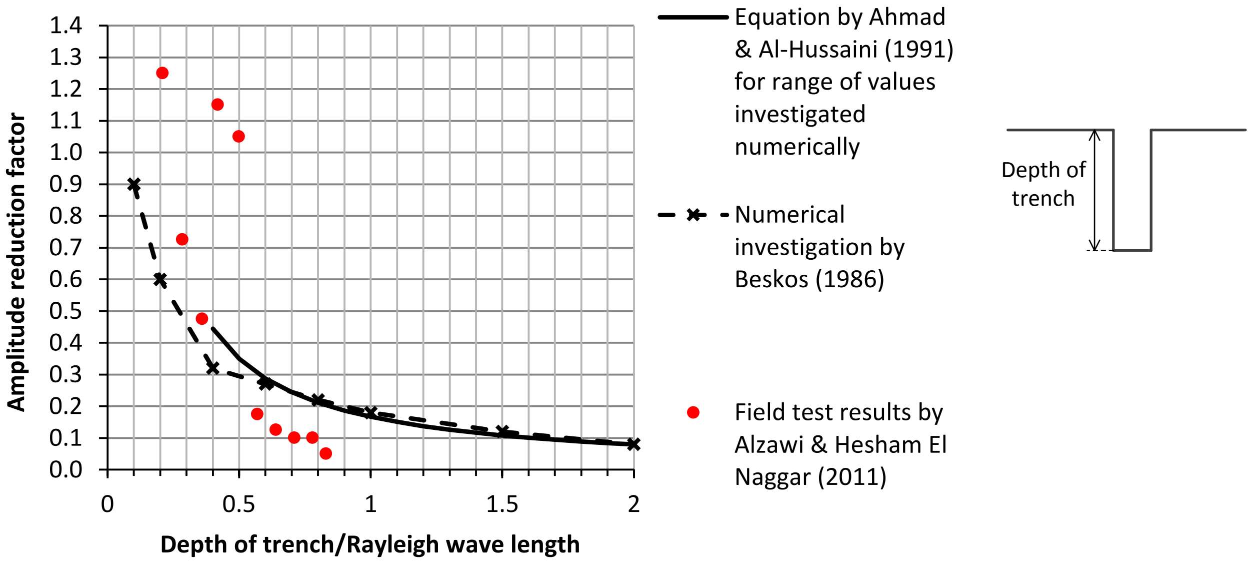


Figure 2 Summary of desk study on the effectiveness of open trenches to reduce vibration

Note that the amplitude reduction factor should be limited to 1.0. Note also that Alzawi and Hesham El Naggar (2011) presented their field test data with amplitude reduction factor of greater than 1.0 because the data is believed to be a scatter around 1.0.

3 PPV measurements and the relationship with other blasting parameters

An investigation of blast induced vibrations was undertaken to understand the way by which blasting could be optimised, and to estimate the minimum distance beyond which the PPV magnitudes are within the permissible limits for reinforced concrete structures. The investigation was aimed primarily at establishing a site-specific empirical PPV against distance relationship. The site layout plan is shown in Figure 1(a). The permanent rings of the stacked tunnels had already been built when the study was undertaken. The points of measurement are at the invert of the first permanent rings adjoining the station box at which blasting is still on-going. Three tunnel rings were monitored, namely Rings A and C from the lower tunnel (each from both ends of the station), and Ring B from the upper tunnel (see Figure 1(b)). The mine-through option was adopted for the lower tunnel to improve the overall tunnel schedule and to reduce the launching risk at the initially proposed launch shaft. The upper tunnel punched out from the station box at the Southern end at Gridline 16 (Figure 1). At the Northern end (further away beyond Gridline 1), the drill and blast method was adopted to construct the upper tunnel.

3.1 Comparison of measurements against solutions in published literature and the establishment of upper bound predictions

Numerous equations have been proposed in published literature concerning the relationship between PPV, the distance, *D*, and the charge weight per delay, *Q*. For example papers by United States Bureau of Mines (1959), Ambraseys and Hendron (1968), Langefors and Kilhstrom (1978), the Indian Standard (1973), The Government of the Hong Kong Special Administrative Region (1998) in Hong Kong, Badal (2007), to name a few. Most of the proposed solutions can be simplified to:

$$PPV = k\left(\frac{D}{Q^b}\right)^n \tag{1}$$

It is understood that the numerous forms of published equations arise from the wide scatter of data from field studies. Badal (2007) has recommended a value for b of 0.5 be adopted, which is consistent with the work of United States Bureau of Mines (1959), Langerfors-Kihlstrom (1978) and in Hong Kong (implied in The Government of the Hong Kong Special Administrative Region (1998)), whereas the parameters k and n should be determined from trial blasting at the site, using a log-log relationship:

$$\log PPV = \log k + n\log\left(\frac{D}{\sqrt{Q}}\right) \tag{2}$$

The value of b = 0.5 was adopted in the study presented in this paper. The results of the investigation are shown in Figure 3(a) and (b). From Figure 3(a), we can see that (i) the PPV measurements in the y-axis are very sensitive to scaled distance in the x-axis, (ii) the red crosses show smaller magnitudes of PPV for the same scaled distance in the x-axis due to the influence of free face (see Figure 1(b) for the location of the tunnel ring), and (iii) the large scatter of data.

For engineering purposes, i.e. to satisfy the permissible PPV values, there is merit in drawing an upper bound line for the scatter because the mean will perform poorly in practice. BS 6472-2 (2008) has recommended using the 90% confidence interval. In this paper, the line was drawn based on engineering judgement. However, in Figure 3(b), one of data points was found to exist significantly outside the upper bound limit. A more detailed investigation revealed that the drilling depths for the holes were greater.

The study shows that Equation 1 could be adopted in practice through relevant site calibration. The influence of the free face and other blasting parameters such as drill depth, spacing and number of holes are not captured.

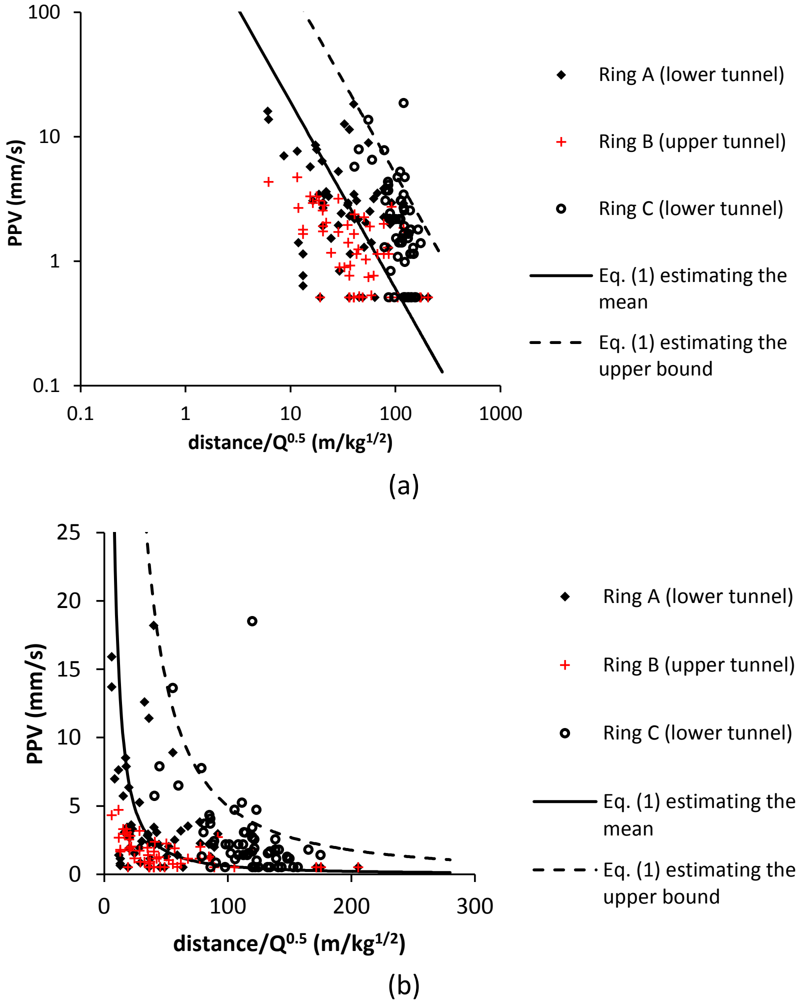


Figure 3 Measured PPV against scaled distance ($D/Q^{0.5}$) in (a) log scale and (b) normal scale

Note: kmean = 600 and kupper = 5,000 and n = -1.5 in Equation 2. Drill depth ranges between 1.3-3.5 m, drill spacing 1-1.3 m, and explosive used was Emulite.

4 Incorporating the influence of free face and other blasting parameters such as drill depth, spacing and number of holes

To incorporate the influence of the free face with height *H*, an equivalent additional distance is incorporated into the original equation so that:

$$PPV = k\left(\frac{D + cH^{1.3}}{Q^{0.5}}\right)^{n} \quad (3)$$

Where *c* is a constant which in our case is 2.0. This method of extending the travel distance can be physically justified since the wave has to travel a longer distance to bypass the free face. To further consider other parameters such as the number of drill holes, *N*, the drill spacing, *s,* and depth, *t*, the equation is further modified such that:

$$PPV = k\left(\frac{D + cH^{1.3}}{Ns^2tQ^{0.5}}\right)^n \tag{4}$$

These parameters are added to the denominator since they are related to the energy created to induce the vibration.

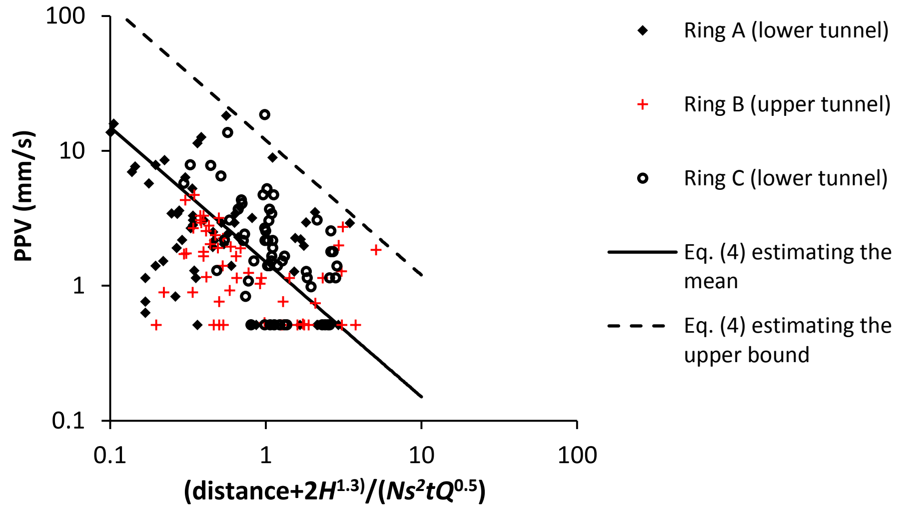
The results of these further analyses are shown in Figure 4 where the following improvements are observed:

- The PPV readings on the tunnel ring with the free face (red crosses) are now plotted further to the right along the x-axis. That is, Equation 4 will predict a smaller PPV magnitude when a free face is present.
- The outlier present in Figure 3 is now moved to the left, after considering the drill depth. The scatter of data is now more concentrated around reduced values of scaled distance.

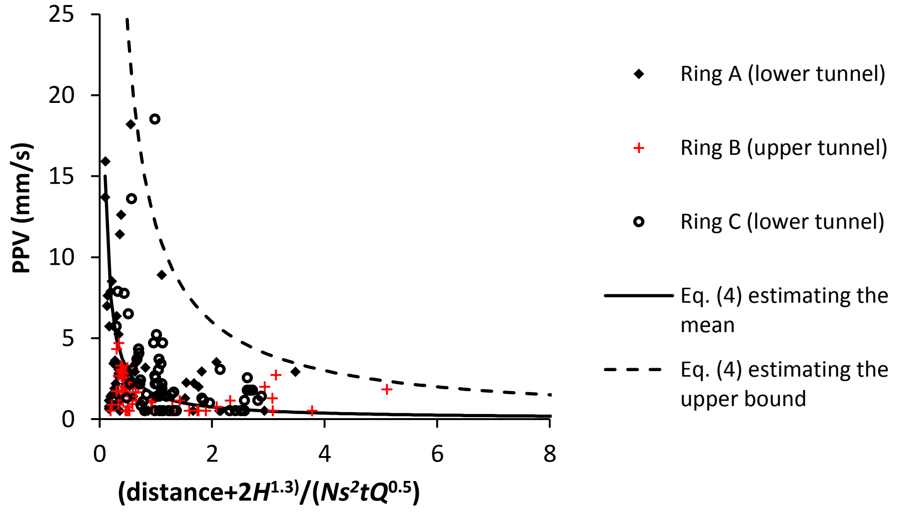
Other observations are that the data points represented as open circles in Figures 3(a) and 4(a) could be more accurately represented with a higher y-intercept. This tunnel Ring C is located at a different location compared to the other two data points. Therefore, the degree of fracturing of the rock at that location could be different. Furthermore, because the ring is completely buried underground, the surface area of the ring affected by ground vibration is greater compared to the other two rings which are exposed above the ground level at which blasting is taking place.

The PPV readings for the tunnel ring with the free face were found to follow the mean values closely and show less erratic scatter (Figure 4).

In fact, another method of interpreting the scatter is the uncertainty related to the location of the point of inflection along the x-axis, below which the PPV readings can rise very quickly. The upper bound line that is adopted serves the purpose of moving the point of inflection of the inverse function further to the right of the x-axis.



(a)



(b)

Figure 4 Measured PPV against scaled distance in (a) normal scale and (b) log scale. Dimensional consistency is not preserved in the x-axis here

Note: k_{mean} = 1.5 and k_{upper} = 12 and n = -1.0 in Equation 4. Drill depth ranges between 1.3-3.5 m, drill spacing 1-1.3 m, and explosive used was Emulite.

5 Conclusion

The motivation of studying the peak particle velocity (PPV) is explained, and a desk study of the efficacy of trenches is discussed. The desk study revealed that, for the trench depth that could be practically constructed on this site, the efficacy of trenches in reducing vibration is limited because the site was founded on hard rock and the wavelengths of the vibration are large. PPV measurements were first studied together with the distance of the blast source and charge weight per delay based on well-established empirical theory. The measured PPV readings were found to show a wide scatter, which is well-known in the literature. The method of drawing an upper bound line in a log-log plot is demonstrated to establish the bounds within which the PPV magnitudes are likely to occur.

The influence of the free face was found to be significant. An equation is proposed to incorporate this feature through the introduction of an additional equivalent distance. The influence of the number of blast holes, drill spacing and drill depth are also incorporated into the modified equation. Although scatter is still present, the trend of the data is more realistic. The proposed equation also provides a more rigorous framework for the development of future blasting programmes, which incorporate variables such as the height of free face, different blast hole spacing, depth and number of blast holes. The impact of this is challenging to gauge in practice due to the scatter of feedback and the combination of parameters interacting with each other.

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