Air and ground vibrations from explosions on the Earth's surface

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Disclaimer

Abstract

Most equations used to predict the ground motion produced by explosions were developed using confined blasts that were detonated with the intention of breaking rock for mining or tunnelling. Ground motion is usually recorded by geophones or seismometers. The air blast produced by open-pit blasts and explosions on the surface can pose a significant risk, thus microphones and pressure gauges are often also used to monitor the effects of the explosion. The aim is to determine whether or not the predictive equations developed for confined explosions can be used to predict the effects from explosions placed on the surface, with appropriate adjustments to the various coefficients.

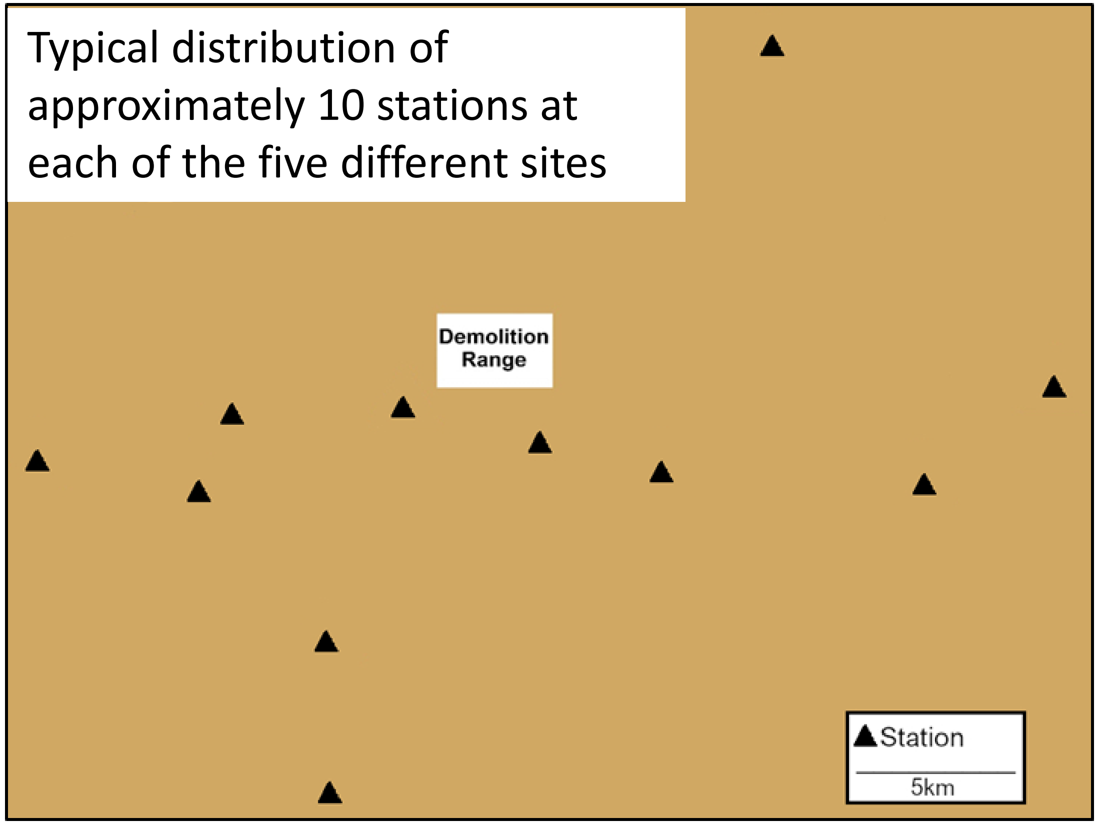
Three predictive equations developed for buried explosions were tested and it was shown that the United States Bureau of Mines peak particle velocity (PPV) predictive equation is the most reliable. In addition, a predictive equation using the secondary atmospheric shock wave phenomenon also produced good results and is easier to measure. These equations may be utilised both for demolition sites, where old and potentially unstable explosives and obsolete equipment are destroyed on the surface of the ground, and for assisting in forensic seismology to determine the details of an unexpected and unknown explosion.

Aim

- Determine if the predictive equations developed for confined explosions can be used to predict the effects from explosions placed on the surface, with appropriate adjustments to the various coefficients.
- Also, any other predictive equations that produce good results.

How was the data obtained?

Typical installation of seismometer, digitiser and batteries



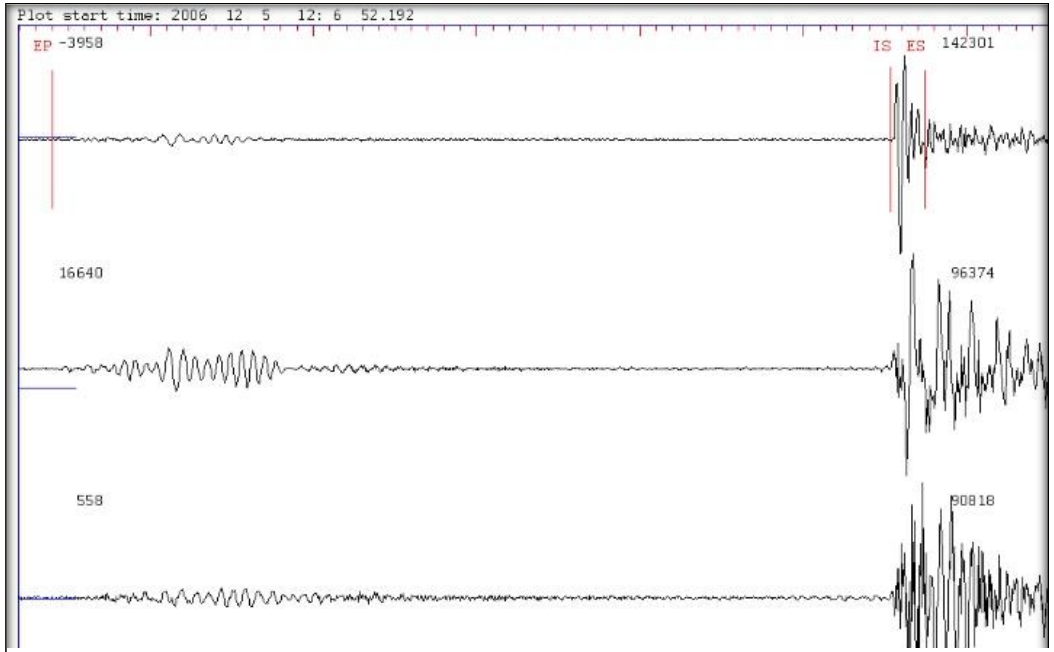
Typical distribution of approximately 10 stations at each of the five different sites

Typical installation of seismometer and digitiser

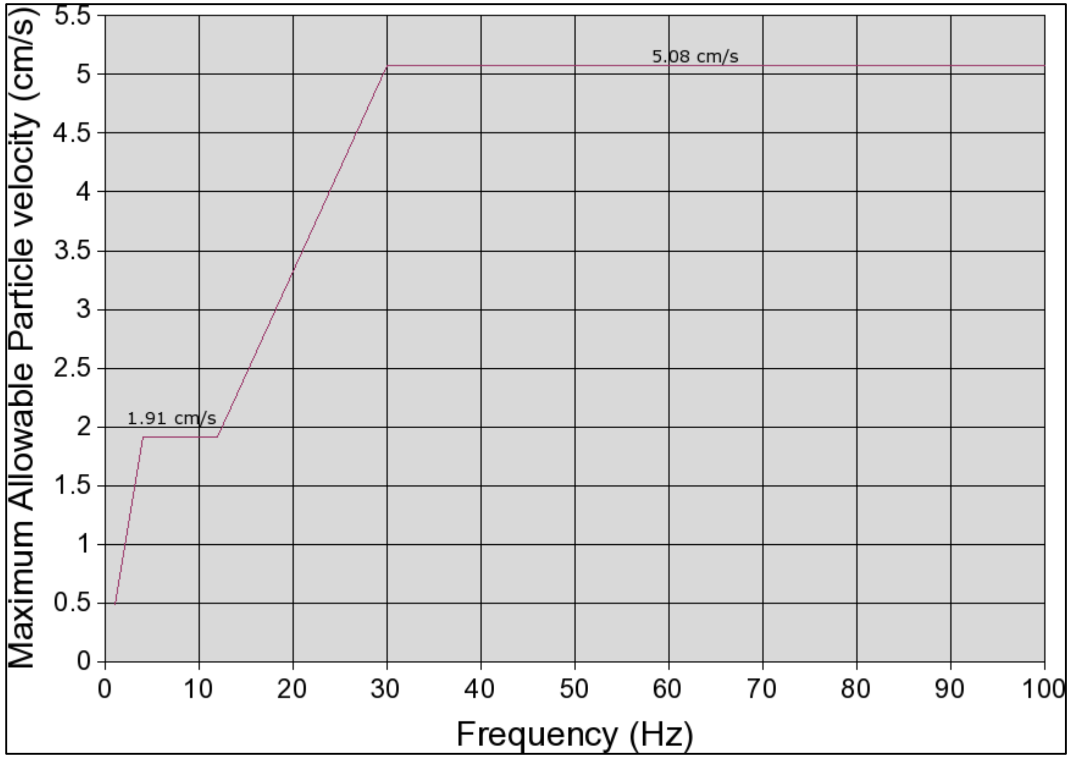
Seismometers installed around the demolition range at five different demolition sites across the country each with different geologies.

Data analysis

The data from each explosion was analysed and compared against the USBM regulations and then recorded with the mass of the explosives used and the distance between the stations and the demolition site.



Example of the signal registered on all three components of a station 2.14km from the demolition range.
"P" indicates the P-wave arrival, "MS" the main shock and "SS" the secondary shock.



Graph of PPV limits modified from the United States Code of Federal Regulations (30 CFR part 816.67 of 1998).

Predictive equations for ground motions

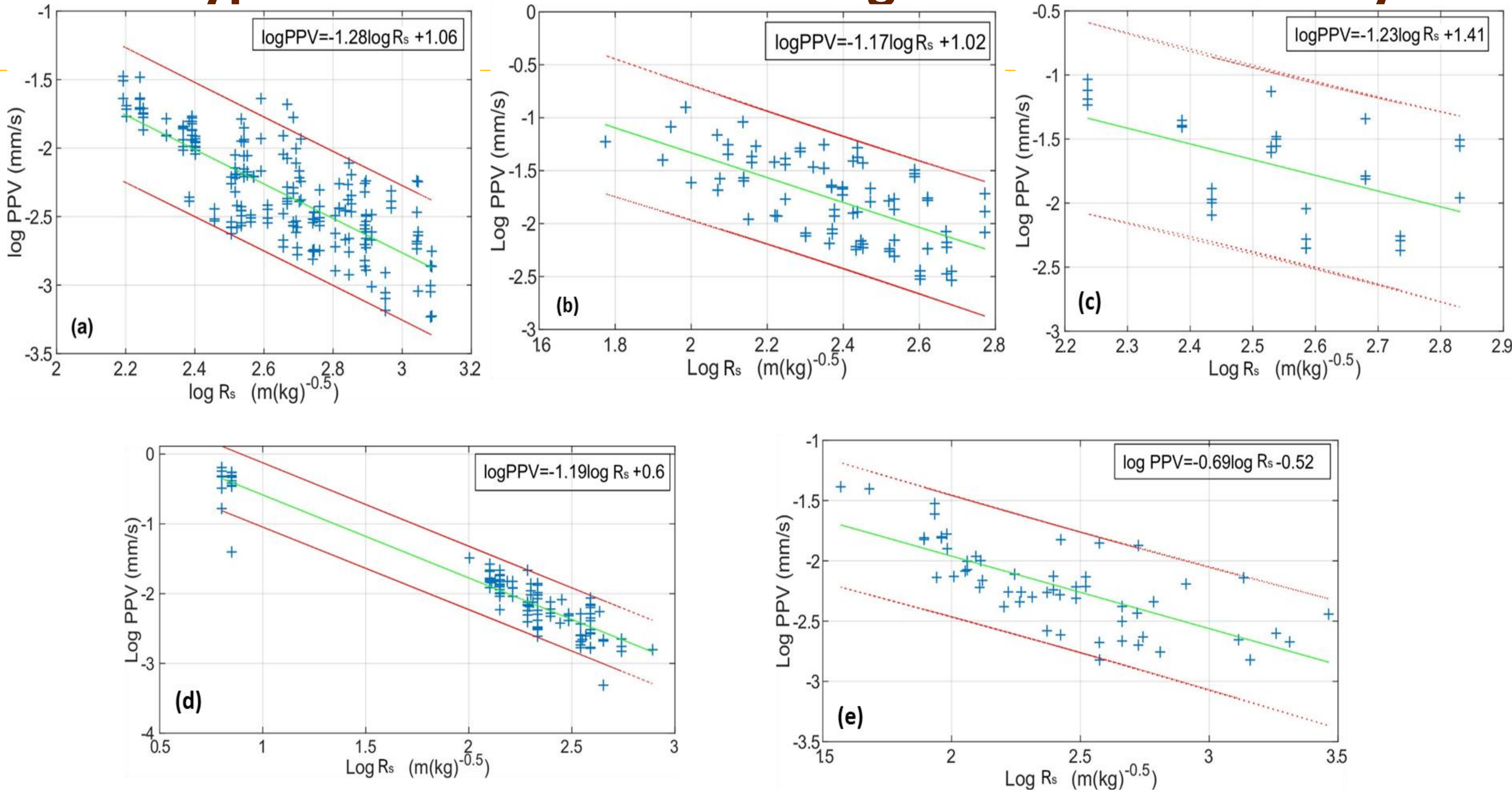
PPV predictive equations used in the studies by Ozer (2008), Ozer et al. (2008), Puri and Prakash (1991).

	USBM	Ambraseys-Hendron	Langefors-Kihlstrom
PPV prediction equation	$PPV(mm/s)=K(R_s)^{-\beta}$ ($\log PPV=-\beta\log R_s+\log K$)	$PPV(mm/s)=K(R_{s\ A})^{-\beta}$ ($\log PPV=-\beta\log R_{s\ A}+\log K$)	$PPV(mm/s)=K(R_{s\ L})^{\beta}$ ($\log PPV=\beta\log R_{s\ L}+\log K$)
R_s equation	$R_s = R/(W_d)^{0.5}$	$R_{s\ A} = R/(W_d)^{0.3}$	$R_{s\ L}=(W_d/(R)^{0.6})^{0.5}$

Where:
PPV = peak particle velocity (mm/s)
R_s = scaled distance
$R_{s\ A}$ = scaled distance for Ambraseys-Hendron equation
$R_{s\ L}$ = scaled distance for Langefors-Kihlstrom equation
K = the ground transmission coefficient
β = the specific geological constant
R = distance from explosion to station (m)
W_d = maximum charge per explosion (kg)

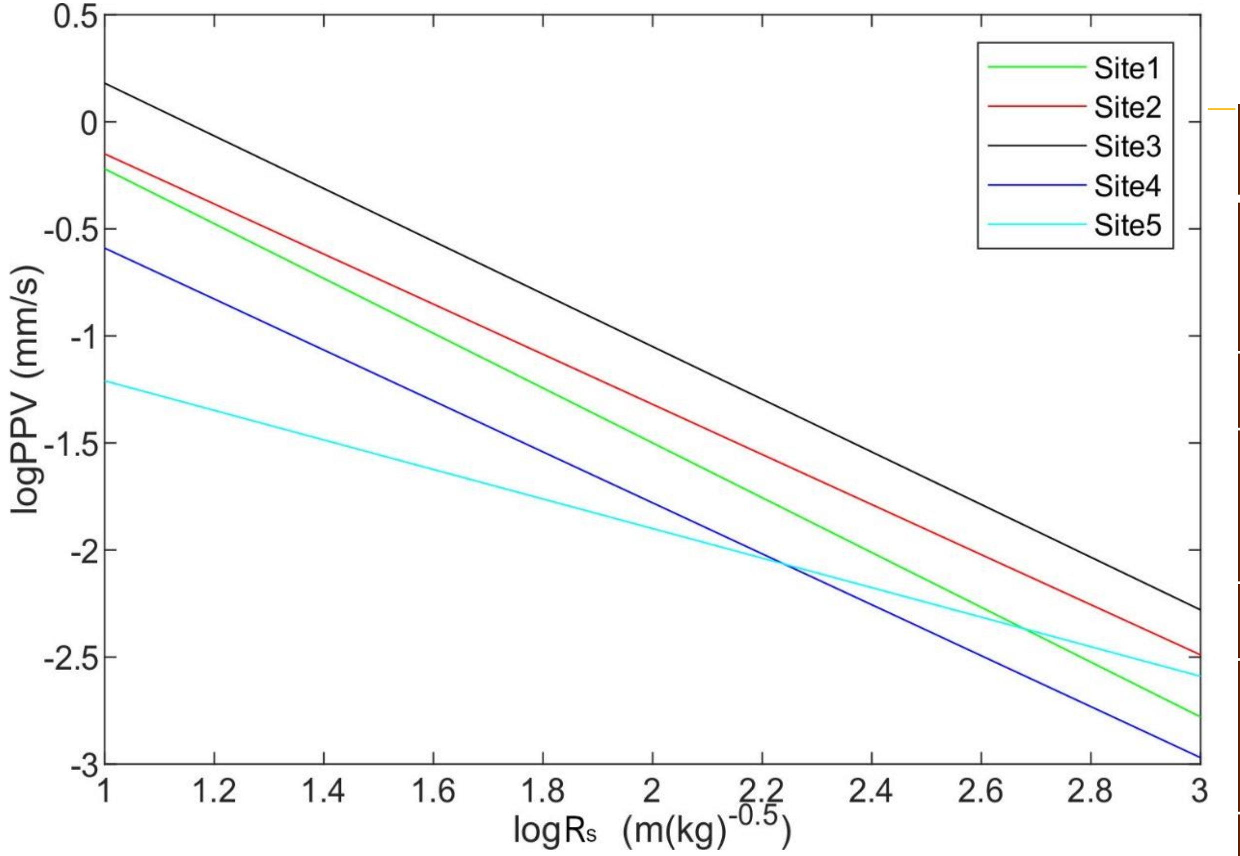
- Extensive literature describing prediction equations for the vibrations induced by blasting in open pit mines and during tunnelling (at close distances) (Aloui et al. (2016); Bongiovanni et al. (1991); Khandelwal and Singh (2007); Kahriman (2002); Ozer (2008); Ozer et al. (2008); Milev et al (2016); and Puri and Prakash (1991)). However, the majority of the authors used these three PPV-based predictor equations.
- The most common approach being to plot the variation of PPV with scaled distance (R_s)

Typical results obtained for ground motion study



The relation between PPV and R_s for all 5 sites using the USBM equation. The green lines represent the best fit using the least squared method, and the red lines represent the 95% confidence range. The "+"symbol represents the recorded PPV. ((a) = Site 1 (b) = Site 2, (c) = Site 3, (d) = Site 4, (e) = Site 5). The gap in the data for Site 4 is due to the lack of stations within that range from the explosion.

Results: USBM was consistently the better equation

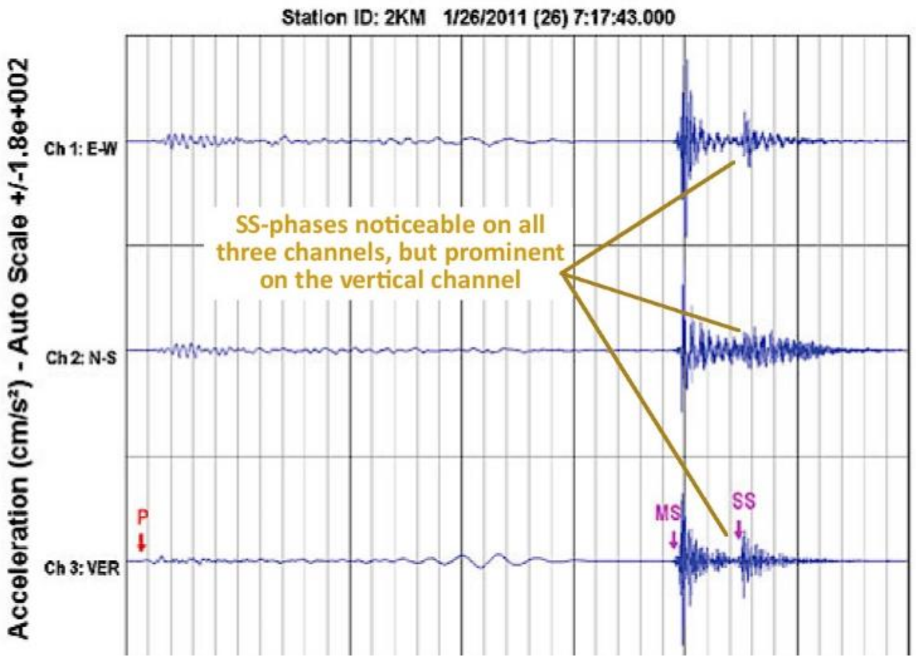


		Site 1	Site 2	Site 3	Site 4	Site 5
USBM	K	11.4	10.4	25.5	4.02	0.3
PPV = K(R_s)$^{-\beta}$	β	1.3	1.2	1.2	1.2	0.7
*** R^2**		0. 61	0.41	0.28	0.90	0.58
Ambraseys	K	562.3	220.3	240.2	9.79	3.75
PPV=K($R_{s\ A}$)$^{-\beta}$	β	1.7	1.5	1.5	1.2	0.9
*** R^2**		0.58	0.45	0.29	0.89	0.57
Langefors	K	0.01	0.01	0.04	0.003	0.003
PPV=K($R_{s\ L}$)$^{\beta}$	β	0.9	1.2	1.2	3.4	0.7
*** R^2**		0.27	0.39	0.15	0.81	0.43

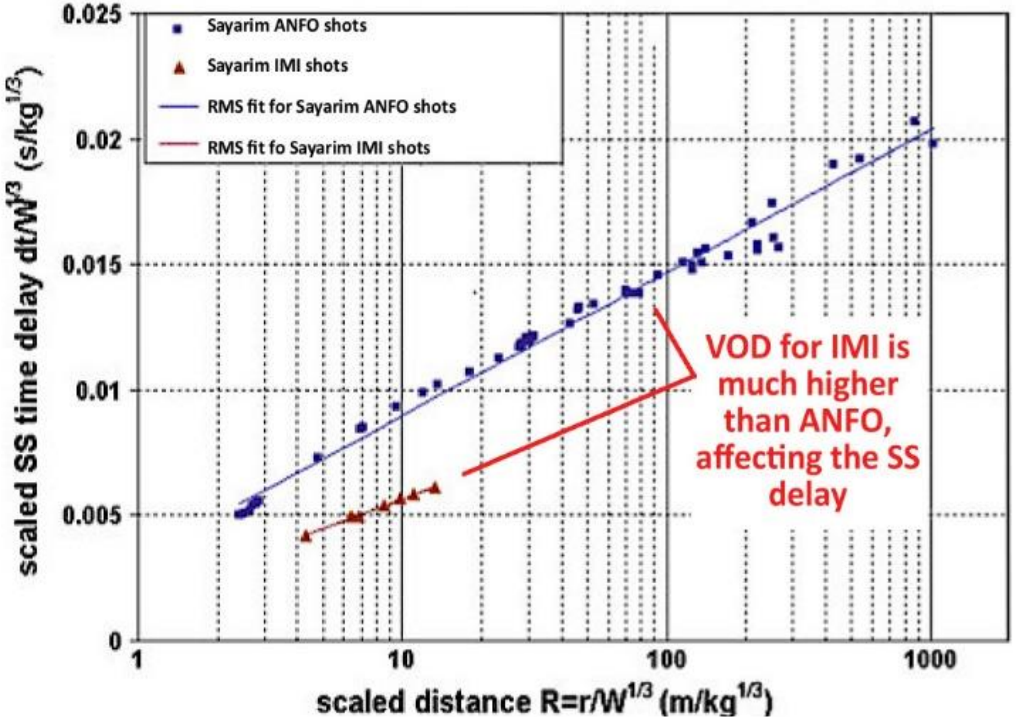
* R^2 = coefficient of determination

- Site 4 on granitic rock produced the best results.
- USBM produced geological constants (β) of 1.2 which are considered satisfactory by a number of authors (Atkinson, 2004; Atkinson and Mereu, 1992; Ford *et al.*, 2014).

Predictive equations for atmospheric signals



Waveforms recorded by a 3-component accelerometer modified from Gitterman (2013). P – Primary seismic wave, MS – Main shock and SS – Secondary shock

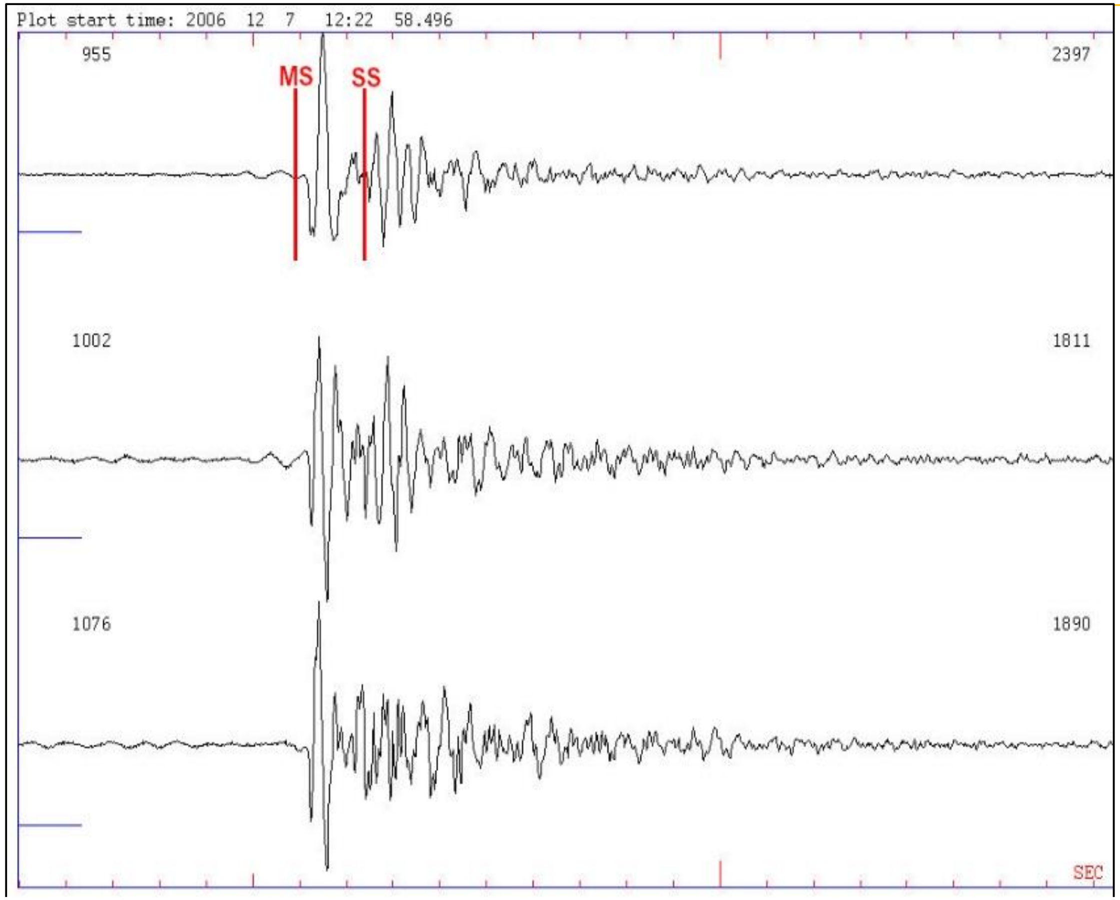


Comparison of different types of explosives (ANFO and IMI) and the effect on the SS delay, modified from Gitterman (2013).

Bonner et al. (2013), Gitterman and Hofstetter (2012) and Gitterman (2013) used data obtained from seismometers to develop a unique empirical **scaled relationship for the secondary shock (SS) delay** for ANFO (ammonium nitrate/fuel oil which is a widely used bulk industrial explosive) charges and distances. The Secondary shock (SS) delay (Gitterman (2013)) occurs when the air blast wave for an explosion source displays a number of recurrent shocks of smaller magnitudes and at different times.

A higher pressure shock front travels faster, therefore the time delay between the main shock (MS) and the SS phase increases with distance, as well as with the amount of explosive.

Data analysis of atmospheric signals



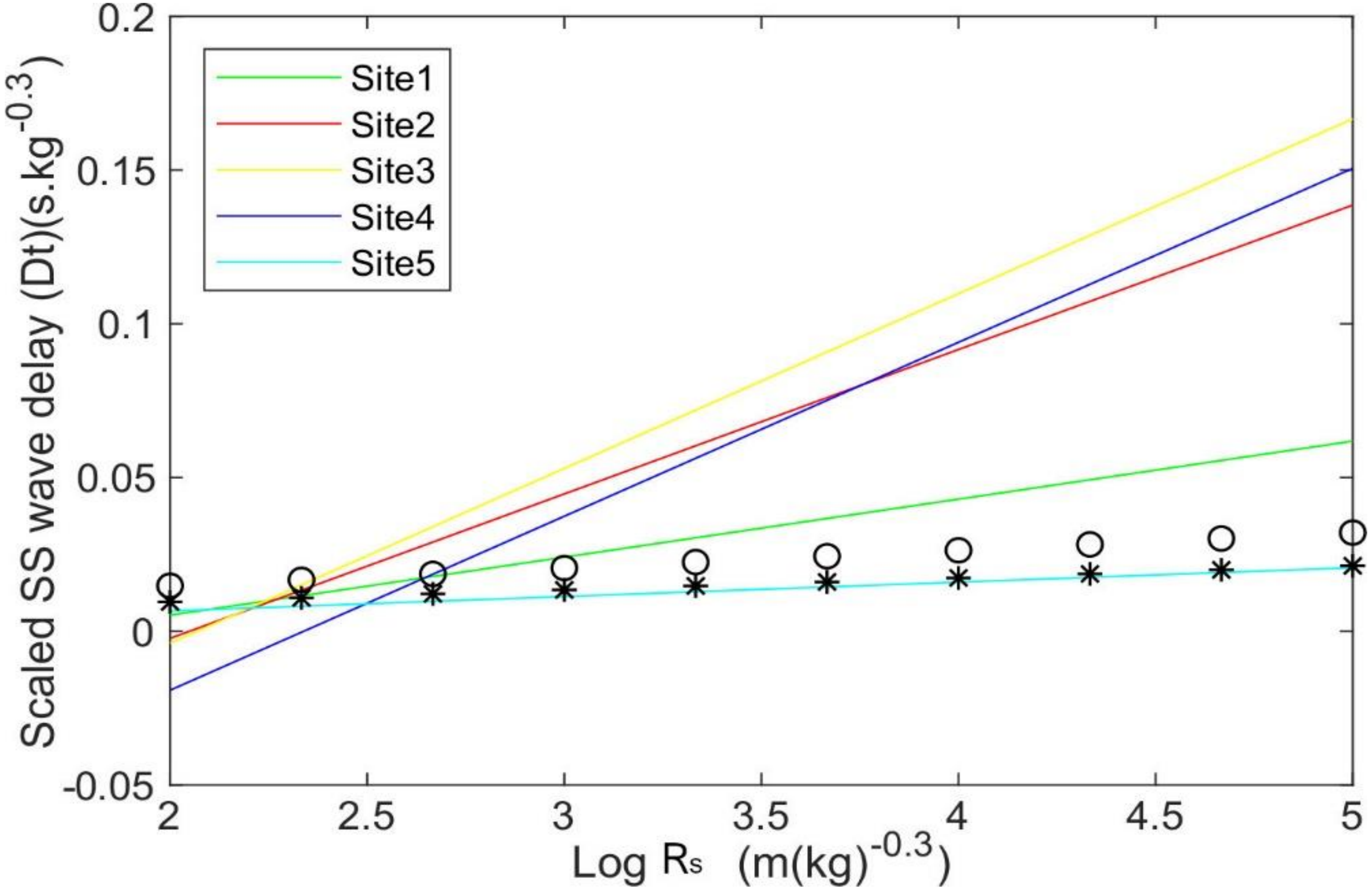
An example of the signal registered on all three components at a station 4.89km from the demolition range. The P-wave arrival was not recorded but the main shock ("MS") and secondary shock ("SS") were recorded.

- Some explosions did not record the ground motions clearly, but only the atmospheric signals. Thus, the data could be utilised

The equations developed by Bonner *et al.* (2013), Gitterman and Hofstetter (2012) and Gitterman (2013).

$Dt=\Delta t/Wd^{0.33}$	$R_s=R/Wd^{0.33}$
Where:	Where:
Dt is the scaled SS time delay	R_s is the scaled distance
Δt is the measured delay in seconds	R is the distance in metres from the explosion to the station
Wd is the amount of explosive in kg	Wd is the amount of explosive in kg

Results for each site for the atmospheric signals



The relation between scaled SS wave delay (Dt) and log R_s for all five sites. The coefficients calculated for each site are listed in Table V. The results from Gitterman (2013) is added for comparison (o indicates the results for the ANFO shots and * indicates the results from the IMI shots)

Site	Equation	* R^2	Season
1	Dt=0.018865log R_s -0.032479	1.00	Autumn
2	Dt=0.046972log R_s -0.096245	0.9996	Spring
3	Dt=0.056846log R_s -0.11758	0.9998	Summer
4	Dt=0.05658log R_s -0.13233	0.9997	Spring
5	Dt=0.0046869log R_s -0.002762	1.00	Summer

* R^2 = coefficient of determination

Conclusions

- Identified a number of predictive equations, which have produced **acceptable results** when examining data obtained from military **ordnance**, that included not only the explosives but the **casings/shells** as well, demolitions on the surface.
- The values for the **atmospheric shock** waves were **easier** to determine than those of the ground motion because the atmospheric shock waves are more prominent on the seismograms than those of the ground motion, due to the fact that **very little** of the energy is transmitted into the ground.
- Therefore, utilising atmospheric shock wave measurements may be **more useful** because the ground motion waves are not clearly recorded. The **secondary shock** wave delay observations **increase** both with **distance** from the explosion as well as the **amount** of explosives used.
- PPV observations, which **increase** with the **amount** of explosives used, but **decrease** with **distance**.
- The secondary shock wave delay equations may be used at sites **further** from the source of the explosion compared to the ground motion equations.
- USBM PPV predictive equation was identified as the **most reliable** equation out of the three equations examined, the predictive equation using the **secondary shock** wave phenomenon produced **better results**.

Conclusions (cont.)

The **usefulness** of the suggested prediction equations would **depend** on the quantity that requires predicting:

- When assessing how best to **mitigate the hazard** posed by a military **demolition** range, where **PPV** prediction is required, the **USBM** equation would be the better solution.

- Alternatively, when assisting in **forensic** seismology to determine the details of an **unexpected** explosion (such as the amount of explosives used), the secondary shock wave has the potential to be useful, especially if the ground motion waves are not obvious within the seismograms.

References

- Aloui, M., Bleuzen, Y., Essefi, E. and Abbes, C. (2016). Ground vibrations and air blast effects induced by blasting in open pit mines: Case of Metlaoui mining basin, Southwestern Tunisia, *J. Geol. Geophys*, 5:3. DOI: 10.4172/2381-8719.1000247
- Ambraseys, N.R. and Hendron, A.J. (1968). Dynamic behavior of rock masses. Rock mechanics in engineering practice. London: Wiley.
- Atkinson, G.M. (2004). Empirical attenuation of ground-motion spectral amplitudes in southeastern Canada and northeastern United States. *Bull. Seism. Soc. Am.*, 94, pp 1079-1095.
- Atkinson, G.M. and Mereu, R.F. (1992). The shape of ground motion attenuation curves in southeastern Canada. *Bull. Seism. Soc. Am.*, 82, pp 2014-2031.
- Bongiovanni, G., Gonelli, V., Rienzo, G. and Rinaldis, D. (1991). Experimental Studies of Vibrations caused by blasting of Tunnel excavation. *Earthquake, Blast and Impact: Measurement and Effects of Vibration,* Elsevier Applied Science, London, pp 201-210.
- Bonner, J., Waxler, R., Gitterman, Y. and Hofstetter, R. (2013). Seismo-acoustic energy partitioning at near-source and local distances from the 2011 Sayarim explosions in the Negev desert, Israel. *Bull. Seism. Soc. Am.*, 103, No. 2A, pp 741-758.
- Ford, S.R., Rodgers, A.J., Xu, H., Templeton, P.H., Foxall, W. and Reinke, R.E. (2014). Partitioning of seismoacoustic energy and estimation of yield and height-of-burst/depth-of-burial for near surface explosions. *Bull. Seism. Soc. Am.*, 104, pp 608-623.
- Gitterman, Y. (2013). Secondary shock features for large surface explosions: results from the Sayarim Military Range, Israel and other experiments. *Shock Waves*, DOI 10.1007/s00193-013-0487-y.
- Gitterman, Y. and Hofstetter, R. (2012). GT0 explosion sources for IMS infrasound calibration: Charge design and yield estimation from near-source observations. *Pure Appl. Geophys.*, DOI 10.1007/s00024-012-0575-4.
- Kahriman, A. (2002). Predictability of the ground vibration parameters induced by blasting during the tunneling. *Min. Resourc. Engin.* 11(3), pp 279-291.
- Khandelwal, M. and Singh, T.N. (2007). Evaluation of blast-induced ground vibration predictors. *Soil Dynam. and Earthq. Engin.*, 27, pp 116-125.
- Langefors, U., Kihlstrom, B., Westerberg, H. (1958). Ground vibrations in blasting. Water Power.
- Milev, A., Durrheim, R., Brovko, F., Kgarume, T., Singh, N., Lumbwe, T., Wekesa, B., Pandelany, T. and Mwila, M. (2016). Development of a South African minimum standard on ground vibration, noise, air-blast and flyrock near surface structures to be protected. SIM 14-09-01, Mine Health and Safety Council.
- Ozer, U. (2008). Environmental impacts of ground vibration induced by blasting at different rock units on the Kadikoy-Kartal metro tunnel. *Engin. Geol.*, 100, pp 82-90.
- Ozer, U., Kahriman, A. and Aksoy, M. (2008). The analysis of ground vibrations induced by bench blasting at Akyol quarry and practical blasting charts. *Environ. Geol.*, 54, pp 737-743.
- Puri, V.K. and Prakash, S. (1991). Estimation of design forces on structures near quarries from field blast tests. *Earthquake, Blast and Impact: Measurement and Effects of Vibration,* Elsevier Applied Science, London, pp 201-210.