# NEAR-FIELD PULSE-TYPE MOTION OF SMALL EVENTS IN DEEP GOLD MINES: OBSERVATIONS, RESPONSE SPECTRA AND DRIFT SPECTRA

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## ABSTRACT:

Strong pulse-type motions are observed in the near source region of large earthquakes; however, there is a lack of waveforms collected from small earthquakes at very close distances recorded underground in mines. The results presented in this paper are relevant for structures of with the height of a few meters, placed in an underground excavation. The strong ground motion sensor was installed in a deep gold mine at the surface of a seismic active stope. The strongest monitored horizontal ground motion was caused by an event of magnitude 2 at a distance of 90 m with PGA 103 m/s$^2$ and PGV 0.365 m/s, and the final displacement was 6.2 mm. The drift response technique based on a continuous shear beam model is employed here to estimate the drift response subjected the near-field earthquakes. The main features of velocity response spectra and drift spectra are similar, which is an indication that the larger damage comes from the large velocity peaks. The strong ground motions with PGA larger than 10 g cause drifts of 50%, which are unobserved at the earth's surface. Drift larger than several percents could cause non elastic deformation. The damping constant of a structure has to be increased significantly to decrease a value of the drift. The weak underground motion has spectral characteristics similar to the strong ground motion observed on the earth's surface; the drift spectrum has a maximum value less than 1% in frequency range relevant to a high underground structure.

**KEYWORDS:** pulse-type ground motion, drift spectrum, response spectrum

## 1. INTRODUCTION

The near-field ground motions are strongly affected by the fault geometry and rupture mechanism. The strong ground motions recorded in the near-field are often characterized by distinct low frequency pulses in the acceleration time histories and coherent pulses in the velocity and displacement time histories. These motions have been observed to cause structural damage. Already some structural design codes require that the pulse-type accelerograms be incorporated into the process of modelling structure response in order that the drift demands are appropriately determined.

The time history of ground motion in the near field is qualitatively quite different from that of the far-field earthquake ground motion. When input is the far-field ground motion, the seismic design for structures is specified in terms of a response spectrum based on a single-degree-of-freedom linear system. The response spectrum is an adequate measure of demand for the far-field ground motion that could be modelled using modulated, broad-band random function of time (e.g. Boore, 1983). The response spectrum generally provides a good estimate of the global displacement and acceleration demand of far-field ground motion on structure. However, it does not provide accurate information on the local shape or internal deformation of the response of the structure. Pulse like ground motion will propagate through the structure as waves, causing large, localized deformation that occurs before a resonant mode response can build up (Iwan, 1997). Therefore, the response spectrum alone is not a sufficient representation of near field ground motion features. It does not adequately represent the demand for a high rate of energy absorption presented by near fault pulses.

## 2. DRIFT SPECTRUM

A large local displacement demand imposed on structure by the near-field pulse is modelled with the drift spectrum. Iwan (1997) proposed the drift spectrum as a new measure of earthquake demand suitable for pulse like ground motion. The response of a continuous shear beam under horizontal seismic excitations is proposed to model a structure vibration exposed to a near-field pulse ground motion. The drift spectrum is defined as the maximum value of the shear strain $\partial u(x,t)/\partial x$ of the shear beam, where u(x,t) is the displacement of the structure relative to the base, x is the arbitrary height above the base beam and t is the time (Iwan, 1997). The beam is subjected to a ground level displacement of the horizontal ground motion, z(t). The maximum of the shear strain at the dimensionless height β is given by:

$$\begin{aligned} D(T,\zeta,\beta) &= \max_{\forall t} \ |\partial u(x,t)/\partial x|_x \\ &= \max_{\forall t} \ \frac{1}{c} \ | \ e^{-\pi\beta\zeta/2}\left[ v(t-\beta T/4) + \frac{2\pi\zeta}{T} z(t-\beta T/4) \right] \\ &+ \sum_{n=1}^{N\le 2t/T-\beta/2} (-1)^n e^{-(n\pi+\beta/2)\zeta} \left[ v(t-nT/2-\beta T/4) + \frac{2\pi\zeta}{T} z(t-nT/2-\beta T/4) \right] \\ &+ \sum_{n=1}^{N\le 2t/T+\beta/2} (-1)^n e^{-(n\pi+\beta/2)\zeta} \left[ v(t-nT/2-\beta T/4) + \frac{2\pi\zeta}{T} z(t-nT/2-\beta T/4) \right] \ | \end{aligned} \tag{2.1}$$

where c is the wave velocity in structure, ζ is the critical damping in the first mode, T is the fundamental period, x is equal to the product of β and H, H is the height of the shear beam, β varies from 0 to 1 and v(t) is the velocity of the horizontal ground motion. By analogy to the response spectrum the drift spectrum is a measure of the demand of the excitation. Iwan's model captures the shear wave propagation effect in a structure caused by a short duration strong pulse, while the response spectrum displacement provides only a measure of overall displacement demands. When structures are subjected to a near field ground motion, the oscillatory response may not occur before the pulse propagating through the structure as waves cause large local deformation.

The drift spectrum can be formulated with modal analysis by including the higher modes. Chopra and Chintanapakdee (2001) show that a SDOF system with a few modes will match the drift spectrum developed by Iwan (1997). The fundamental mode mobilized approximately 80 percent of the total mass of the idealized shear beam (Akkar and Gülkan, 2002). In a series of research works, Akkar and Gülkan focused on the first mode only (Gülkan and Akkar, 2003). The generalized interstory drift spectrum for a realistic building model was presented recently by Miranda and Akkar (2006) using modal analysis. Inspired by the above papers and using Chopra's (1995) notations for model analysis, the drift spectrum for a uniform underground structure is presented. Displacement for ith mode is given by:

$$u_i(t,x) \quad = \quad \Gamma_i \quad \Phi_i(x) \quad D_i(t) \tag{2.2}$$

where $\Gamma_i$ is the model participation factor of the ith mode, $\phi_i$ (x) is the shape function of the ith mode, $D_i$ (t) is the relative displacement of a SDOF system, with period, T, and damping ratio, ζ, in the first mode. As in this paper only the fundamental mode is used, so the modal index can be dropped. The first mode participation factor for the shear beam is $\Gamma = 4/\pi$ and the shape function can be expressed as $\phi(x) = \sin(2\pi x/H)$ (Chopra, 1995). The peak amplitude of relative displacement D (t) for specific period T and damping ratio ζ is named displacement response spectra, $S_d(T, \zeta)$. Therefore the maximum displacement for the shear beam structure becomes

$$u_{\max}(T,\zeta,x) \quad = \quad \frac{4}{\pi} \quad \sin(\frac{\pi x}{4H}) \quad S_d(T,\zeta) \tag{2.3}$$

Displacement shape function, ϕ (x), has that the largest drift in the fundamental mode occurs at the top, where x is equal to H. The height above base, x, can be replaced with β H. Lateral motion u(x,t) within the shear beam is propagated with velocity c, consequently, H can be replaced with Tc/4. As a result, the shear strain can be defined as later displacement divided by the height:

$$D(T,\zeta,\beta) = \frac{u_{\max}(T,\zeta,x)}{x} = \frac{16}{\pi} \sin(\pi\,\beta/2) \frac{1}{Tc\beta} S_d(T,\varsigma) \qquad (2.4)$$

The displacement response spectra, $S_d(T, \zeta)$, represent global displacement, while drift spectrum defined with Eqn 2.4. represents an average shear strain over height x.

## 3. EXPERIMENT AND DATA DESCRIPTION

In South Africa hard rock mining sometimes causes unstable fracturing. These mining operations are generally performed using a long-wall stopping technique. The rock around the stope appears to be one of the most heterogeneous regions in the mine, as a fractured rock zone is progressively generated ahead of the advancing stope face. Figure 1 illustrates the fracture pattern which forms ahead and behind a typical stope face in a deep gold mine. The shear fractures form ahead of the stope face, where the shear stresses are relatively high. The concentration of the seismic events induced by mining is largest in the front of a stope face and around geological features such as faults and dykes. Source mechanisms of seismic events in Deep South African gold mines have shear failure similar to tectonic earthquakes. The double-couple model has been applied to explain the mechanisms of larger, mine related seismic events.

Research is focused on the study of strong ground motion in the stope area. Several experiments were conducted to monitor the motion of support under seismic loads (Cichowicz, 2001, 2002). The waveforms of strong ground motion are required in order to design the optimal stope support in seismically active areas. At a depth of 2500 m several strong ground motion sensors were installed at the surface of underground excavations. The monitoring of the ground motion was conducted at several sites near a stope face. During the experiment the instrument followed the advancing of the stope face in order to be at the right time and place. Data provides a new insight into the near-field ground motion recorded underground. The ground motion on the surface of excavations may be amplified relatively to the ground motion in solid rock, owning to the free surface effect, surface waves and local site effects (Cichowicz *et al.*, 1999, Cichowicz *et al.*, 2000, Milev and Spottiswood, 2005).

Examples of strong and weak ground motion recorded underground on the surface of excavations are shown in Figure 2. The strong ground motion caused by an event of magnitude 2, recorded at 90 m from the seismic source has PGA= 103 m/s$^2$, and PGV = 0.365 m/s. The velocity trace is dominated by two pulses - one up and the second down and this is converted to one strong pulse in displacement. The seismic event associated with a weak ground motion was not located, as it was only recorded by one station. This accelerogram has a simple structure, with a relatively small value of PGA = 7.6 m/s$^2$ and the velocity trace is dominated by one pulse.

## 4. RESPONSE AND DRIFT SPECTRA

The terms “strong ground motion” and “weak ground motion” are used to classify the observed records. The strong ground motion is used to describe seismograms characterized by few oscillations and a dominant pulse with a strong component of low frequency. The near fault pulse-type ground motions can be represented by oneor more simplified pulses. The spectrum of strong ground motion is usually broadband, so a high frequency signal is present as well. The weak ground motions have, by definition, a smaller signal amplitude than strong ground motion, and for a small seismic source has a strong component of high frequency.

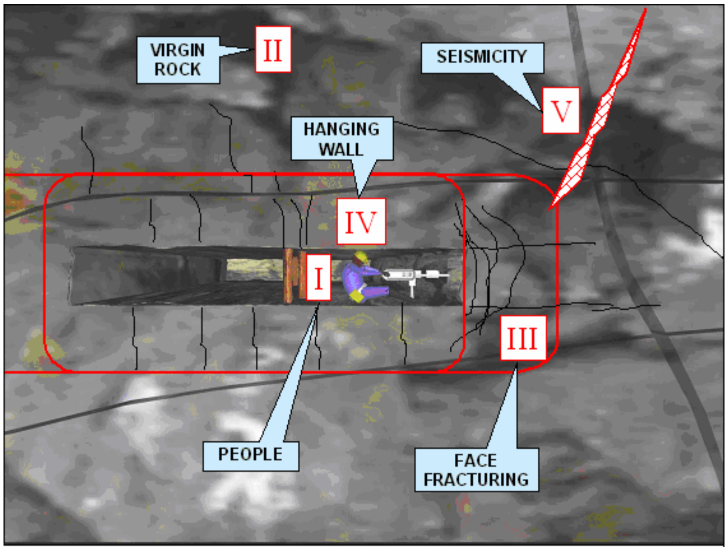

Figure 1 Cross section of an underground stope and surrounding hard rock (figure courtesy of S. Spottiswoode, used with permission). The various zones shown above associated with the underground mining environment are described as follows: Zone I is the excavation where mining takes place, Zone II is the virgin rock, Zone III is the highly fractured zone ahead of the stope face that could extend to 20 m, Zone IV is the hangingwall, Zone V is the seismogenic region in the stope.

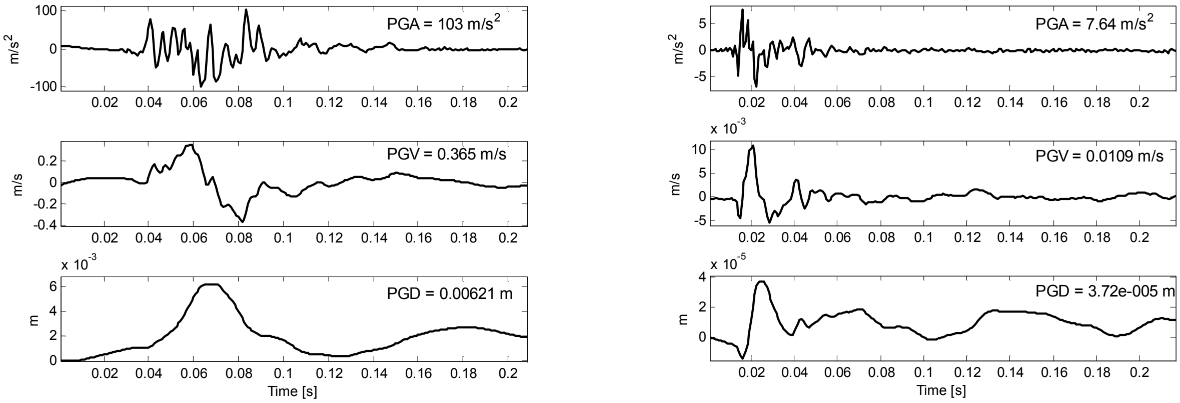

Figure 2 (Left) An example of a strong ground motion. Seismic event with magnitude 2 is located 90 m from strong ground motion sensor. Horizontal component of the accelerogram is converted to velocity and displacement with PGA = 103 m/s$^2$, PGV = 0.365 m/s and PGD = 0.0062 m. (Right) An example of a weak ground motion with PGA = 7.64m//s$^2$, PGV = 0.01 m/s and PGD = 0.000037 m.

The strong ground motion of the acceleration response spectrum, the velocity response spectrum, the displacement response spectrum and the drift spectrum are shown in Figure 3. The spectra are calculated with damping constant equal to 10%. The acceleration response spectrum has distinct peaks below 0.02 sec, and these high frequency peaks do not affect structure underground. The heights of the underground structure can vary from 1 to 6 m, so the periods from 0.03 to 0.16 sec for shear wave velocity c = 150 m/s are of interest for engineering applications. The wave speed in the reinforced, concrete structure typically varies from 100 to 200 m/s (Iwan, 1997). The shape of the velocity response spectrum is dominated by one broad pulse with a maximum around 0.04 sec (25 Hz). The values of the displacement spectrum steadily increase with the increase of the period.

The drift spectrum was obtained for five different elevations above base of the structure: 0.2H, 0.4H, 0.6H, 0.8H and 1.0H. The drift spectrum has a maximum at the base of the structure and has similar features as velocity response spectrum. In periods ranging from 0.03 to 0.16 sec the drift spectrum varied from 0.5 to 0.2 (see Figure 3). The largest drift is observed at the bottom of the structure and at the high frequencies. Drift spectrum predicts demands imposed by a strong pulse-type motion to an extent not anticipated by the displacement response spectra.

It is unlikely, that a structure exposed to a large drift will be deformed elastically. Therefore, the drift spectrum obtained for the strong ground motion should be corrected for ductility by introducing inelastic to elastic displacement factors (Gülkan and Akkar, 2003), or by modifying the natural vibration period. However, a modification of viscous damping of the equivalent linear system is the most common practice and is achieved by adding an extra term responsible for the ductility of a structure. The increase in the damping could be as large as 40% (Chopra and Goel, 2000).

An example of the analysis of weak ground motion is shown in Figure 4. Typically weak ground motion is observed in a far field. In this case, the weak ground motion is caused by a small event, so the spectra are dominated by high frequency peaks. Their shapes are similar to those of strong ground motion; however, all peaks have shifted towards higher frequencies, as was expected. The drift spectrum in the periods of engineering interest is lower than 1% and this value is similar to drift observed at the surface caused by natural earthquakes.

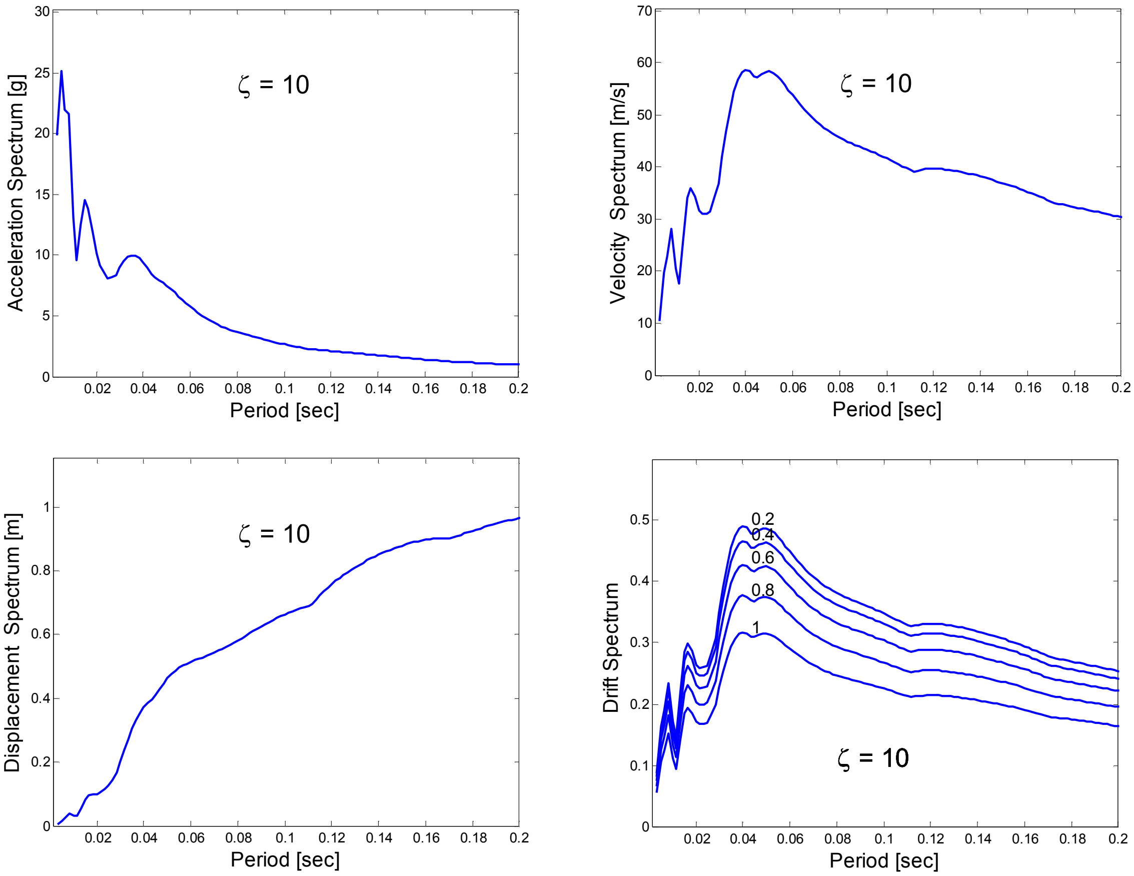

Figure 3 Acceleration, velocity, displacement and drift spectrum of strong ground motion. The associated waveforms are displayed on the left side of Figure 2.

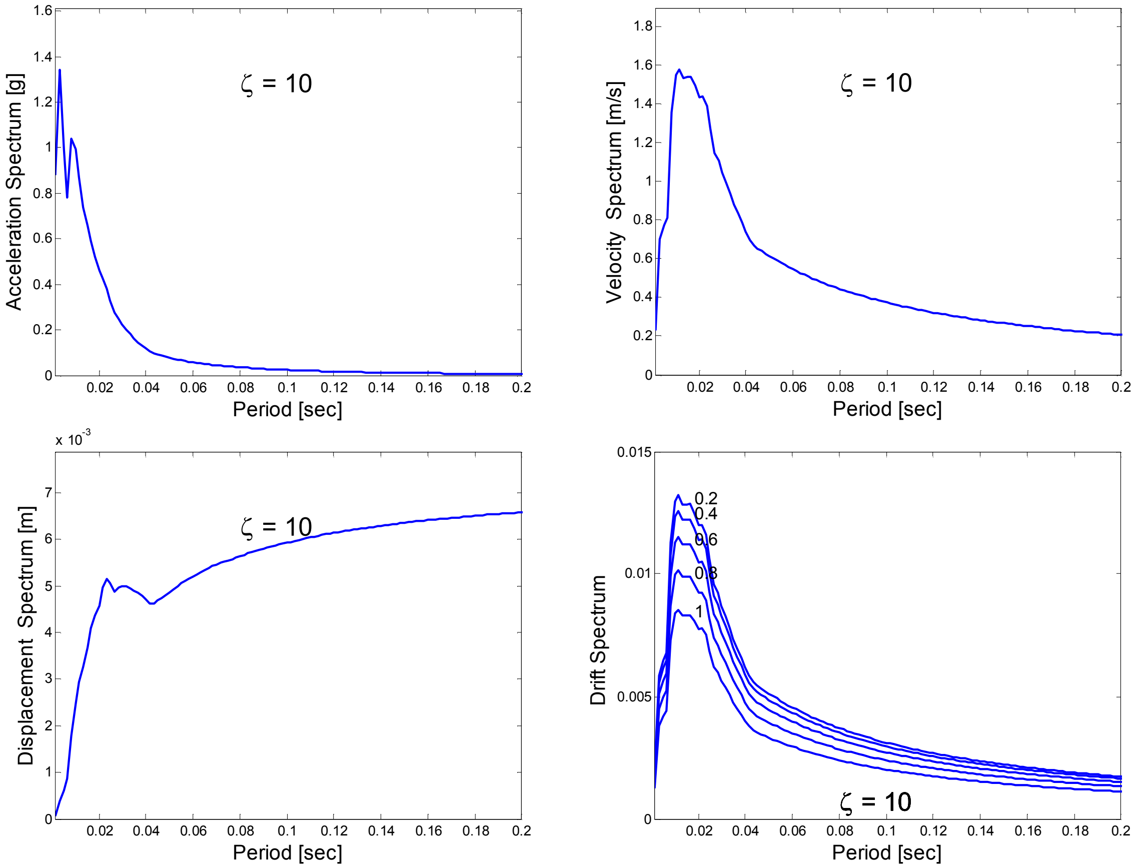

Figure 4 Acceleration, velocity, displacement and drift spectrum of the weak ground motion. The associated waveforms are displayed on the right side of Figure 2.

## 5. CONCLUSIONS

Structures exposed to pulse-type ground motion must be specified in terms of drift spectrum. The drift response technique based on a continuous shear beam model is employed to estimate the drift response. Data collected from surface of underground excavations show that the drift spectra have features similar to velocity response spectra. The drift spectrum predicts demands imposed by a strong pulse-type motion to an extent not anticipated by the displacement response spectra. The strong ground motion characterized by intensity larger than 10 g, causes a drift of 50%, which is unobserved at the earth's surface. This value of drift will cause inelastic deformation of underground structures of height varying from 1 to 6 m and a damping constant in the range from 5 to 10%. In order to avoid analysis of the inelastic system the damping constant of structures has to be increased significantly to decrease the value of the drift. The equivalent viscous damping is increased by adding an additional term responsible for the ductility of a structure and it could be as large as 40%. The weak underground motion has spectral characteristics similar to strong ground motion observed on the earth's surface with drift lower than 1%.

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