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Near-field ground motion modal versus wave propagation analysis

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Abstract. The response spectrum generally provides a good estimate of the global displacement and acceleration demand of far-field ground motion on a structure. However, it does not provide accurate information on the local shape or internal deformation of the response of the structure. Near-field pulse-like ground motion will propagate through the structure as waves, causing large, localized deformation. Therefore, the response spectrum alone is not a sufficient representation of near-field ground motion features. Results show that the drift-response technique based on a continuous shear-beam model has to be employed here to estimate structure-demand parameters when structure is exposed to the pulse like ground motion. Conduced modeling shows limited applicability of the drift spectrum based on the SDOF approximation. The SDOF drift spectrum approximation can only be applied to structures with smaller natural periods than the dominant period of the ground motion. For periods larger than the dominant period of ground motion the SDOF drift spectra model significantly underestimates maximum deformation. 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 that were recorded underground in mines. The results presented in this paper are relevant for structures with a height of a few meters, placed in an underground excavation. The strong ground motion sensors recorded mine-induced earthquakes in a deep gold mine, South Africa. The strongest monitored horizontal ground motion was caused by an event of magnitude 2 at a distance of 90 m with PGA 123 m/s^2, causing drifts of 0.25%–0.35%. 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 0.02%.

Keywords: Pulse-type ground motion, drift spectrum, response spectrum

1. Introduction

The strong ground motions recorded in the near-field are characterized by distinct low frequency pulses in the acceleration time histories and coherent pulses in the velocity 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 modeling 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 (SDOF) linear system. The SDOF system provides an estimate of the maximum global amplitude; however, the displacement response spectrum does not provide information on the local shape or internal deformation. The response spectrum is an adequate measure of demand for the far-field ground motion that could be modeled using a modulated, broad-band random function of time [1]. 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 [2]. Therefore, the response spectrum alone

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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.

There are two objectives of this paper. The first one is to evaluate the range of applicability of the models used to estimate structure drift. The second one is to utilize recordings from the extremely strong ground motion observed underground in a modeling process. Typically, data bases of strong ground motions used for modeling the structure responses include seismic recordings of large earthquakes. There is a lack of recordings of relatively small earthquakes detected at very small distances from the seismic source. Such records have a large high frequency content and a very large amplitude of acceleration.

2. Drift spectrum

A large local displacement demand imposed on a structure by the near-field pulse is modeled with the drift spectrum. Iwan [2] proposed the drift spectrum as a 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 [2]. The major contribution to drift comes from the ground velocity, ν(t), not from ground displacement therefore displacement contribution is removed from the original Iwan's equation. The maximum of the shear strain at the dimensionless height β is given by:

$$\begin{aligned} D_{sb}\ (T,\zeta,\beta) &= \max_{\forall t} |\partial u(x,t)/\partial x|_x \\ &= \max_{\forall t} \frac{1}{c} \left| e^{-\pi\beta\zeta/2} v(t-\beta T/4) + \sum_{n=1}^{N\leqslant 2t/T-\beta/2} (-1)^n e^{-(n\pi+\beta/2)\zeta} v(t\ - nT/2 - \beta T/4) \right. \\ &\quad \left. + \sum_{n=1}^{N\leqslant 2t/T+\beta/2} (-1)^n e^{-(n\pi+\beta/2)\zeta} v(t\ - nT/2 + \beta T/4) \right| \end{aligned} \tag{1}$$

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 ν(t) is the velocity of the horizontal ground motion. The plot of D_{sb} (T, ζ, β) constitutes the drift spectrum.

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 [3] show that a SDOF system with a few modes will match the drift spectrum developed by [2]. The fundamental mode mobilized approximately 80 percent of the total mass of the idealized shear beam [4]. In a series of research works, Akkar and Gülkan focused on the first mode only [5]. The generalized interstory drift spectrum for a realistic building model was presented recently by Miranda and Akkar [6] using modal analysis. Inspired by the information in the above papers and using Chopra's [7] notations for model analysis, the drift spectrum for a uniform underground structure is presented. Displacement for i-th mode is given by:

$$u_i(t,x) = \Gamma_i \Phi_i(x) D_i(t) \tag{2}$$

where Γ_i is the model of participation factor of the i-th mode, Φ_i (x) is the shape function of the i-th 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, therefore 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 $\Phi(x) = \sin(2\pi x/H)$ [7]. The peak

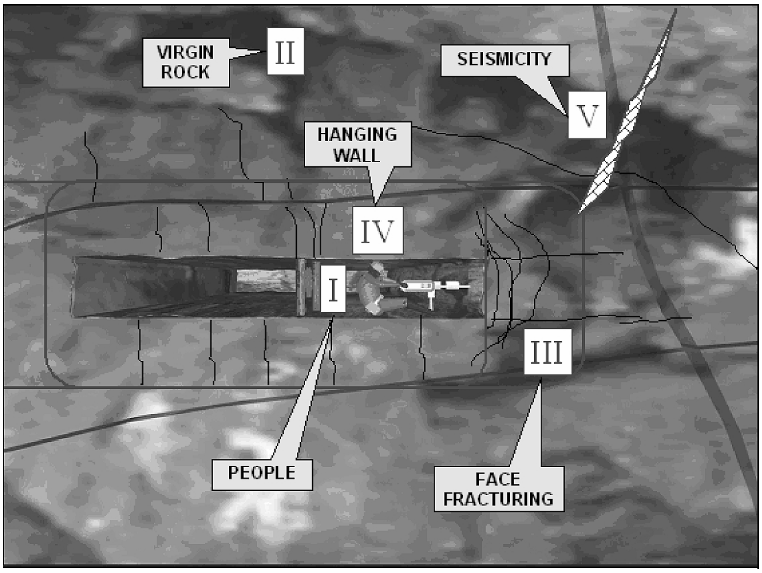

Fig. 1. Cross-section of an underground stope and surrounding hard rock (figure courtesy of S. Spottiswoode, used with permission). The various zones shown above associated with the underground mining environment are described as follows: Zone I is the excavation where mining takes place, Zone II is 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.

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

$$u_{\max}(T,\zeta,x) = \frac{4}{\pi}\sin\left(\frac{\pi x}{4H}\right) S_d(T,\zeta) \tag{3}$$

Displacement shape function, $\Phi(x)$, has that the largest drift in the fundamental mode that occurs at the top, where x is equal to H. The height above base, x, can be replaced with βH. 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:

$$D_{SDOF}(T,\zeta,\beta) = \frac{u_{\max}(T,\zeta,x)}{x} = \frac{16}{\pi}\ \sin(\pi\ \beta/2)\ \frac{1}{Tc\beta} S_d(T,\varsigma). \tag{4}$$

The displacement response spectra, $S_d(T,\zeta)$, represent global displacement, while drift spectrum defined with Eq. (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 stoping 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 [8,9]. The waveforms of strong ground motion are required in

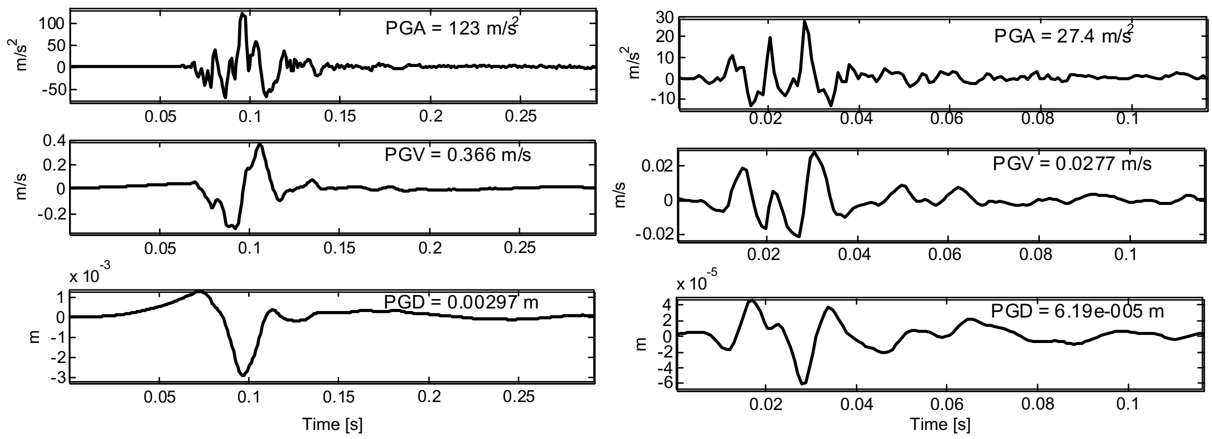

Fig. 2. (Left) An example of a strong ground motion. Seismic event with magnitude 2 is located 90 m from strong ground motion sensor. Horizontal component of the accelerogram is converted to velocity and displacement with PGA $=$ 123 m/s^2, PGV $=$ 0.366 m/s and PGD $=$ 0.00297 m. (Right) An example of a weak ground motion with PGA $=$ 27.4m/s^2, PGV $=$ 0.0277 m/s and PGD $=$ 0.000062 m.

order to design the optimal stope support in seismically active areas. At a depth of 2 500 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 provide 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 [9–12].

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 one or more simplified pulses. The spectrum of strong ground motion is usually broadband; therefore a high frequency signal is present as well. The weak ground motion has smaller signal amplitude than the strong ground motion, and, for a small seismic source, has a strong component of high frequency.

Examples of strong and weak ground motion recorded underground on the surface of excavations are shown in Fig. 2. The strong ground motion caused by an event of magnitude 2, recorded at 90 m from the seismic source has PGA $=$ 123 m/s^2, and PGV $=$ 0.366 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 $=$ 27.4 m/s^2 and the velocity trace is dominated by one pulse.

4. Calculation of drift demand spectra

The wave speed in the reinforced, concrete structure typically varies from 100 to 200 m/s [2]. The heights of the underground structure can vary from 1 to 10 m, therefore the periods from 0.03 to 0.27 sec for shear wave velocity $c =$ 150 m/s are of interest for engineering applications.

An example of the analysis of weak ground motion is shown in Fig. 3. The related waveforms are displayed on the right side of Fig. 2. Typically, a weak ground motion is observed in a far field; however, in this case, the weak ground motion is caused by a small event at a very close distance, so the spectra are dominated by high frequency peaks. The SDOF spectrum given by Eq. (4) and the drift spectrum of the shear beam defined by Eq. (1) are shown in Fig. 3. The spectra are calculated with damping constant equal to 10%. The dominant period of ground motion, T_p, is about 0.02 sec. Both drift spectra have distinct peaks below 0.02 sec, and these high frequency peaks do not affect the structure underground. Horizontal orange arrows indicate the range of natural frequencies of possible structures placed underground. The shapes of two models are very similar for periods lower than dominant ground

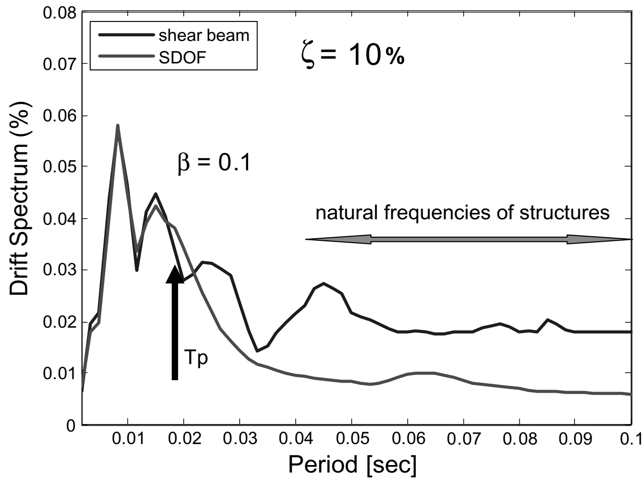

Fig. 3. Drift Spectrum for the SDOF and the uniform shear-beam models. The associated waveforms are displayed on the right side of Fig. 2. SDOF drift spectra significantly underestimate maximum deformation for the period range larger than T_p.

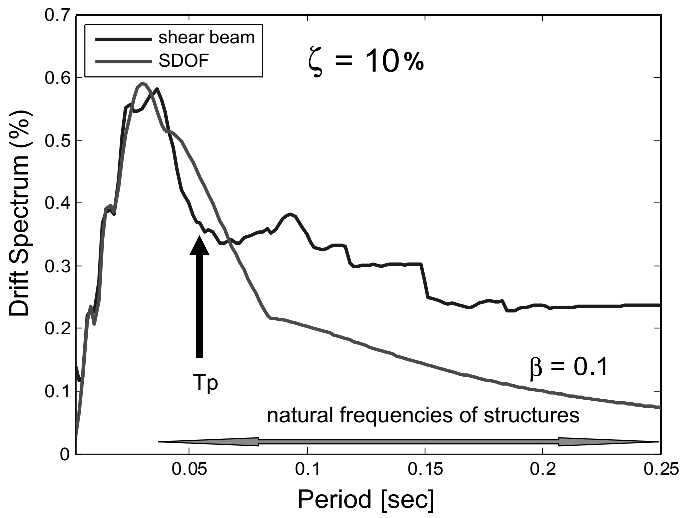

Fig. 4. Drift spectrum for the SDOF and the uniform shear-beam models. The associated waveforms are displayed on the left side of Fig. 2. SDOF drift spectra significantly underestimate maximum deformation for the period range larger than T_p.

motion period, T_p. For periods range larger than T_p a significant differences between two models are observed. This indicates that the approximation given by Eq. (4) does not adequately model a structural drift for periods larger than T_p [3] show that Iwan's drift spectrum can be replaced with multi-modal approach using several modes. However, the Eq. (4) is utilizing only the fundamental mode.

Figure 4 shows spectra for strong ground motion in similar fashion as Fig. 3. Their shapes are similar to those of weak ground motion; however, all peaks have shifted towards lower frequencies, as was expected.

5. Discussion

For periods larger than T_p the SDOF model underestimates drift demand, therefore, only shear-beam drift spectra are discussed for weak and strong ground motions.

In the periods of engineering interest, the weak ground motion (Fig. 3) has the values of the shear-beam drift spectrum (maximum strain) lower than 0.02% and this value is similar to the drift observed at the surface caused by natural earthquakes. This strain will not cause damage to a structure.

Inelastic behavior of structures is expected when near-field ground motion requires large deformation. Figure 4 shows shear strain of the order of 0.35% at a period range from 0.05 to 0.15 sec and share strain of 0.25% in the period range 0.15 to 0.25 sec. For realistic assessment of structural performance the inelastic drift limits have to be defined. An example of transforming the elastic ground story drift into inelastic one is given by Gulkan and Akkar [5]. Inelastic drift limits obtained for ductility, μ, varied from 2 to 6.

Data available for these analyses have a direct application for small structures with natural periods smaller than 0.25 sec. A question could be raised as to how a structure with a period of one second or larger behaves? A drift spectrum of weak ground motions shows a stabilizing drift for structures with natural periods larger than the dominant period of the ground motion (see Fig. 3). However, strong ground motion shows a tendency of decaying drift (see Fig. 4).

6. Conclusions

Drift spectra are suitable tool for defining the local displacement demand, particularly of near-fault ground motions. The drift spectrum, $D_{sb}(T,\zeta,\beta)$, for uniform shear beam, provides information on shape and local deformation of the structure that the displacement response spectrum, $S_d(T,\zeta)$ does not. The spectra plots emphasize the frequency dependency of drift.

Drift spectra defined for the uniform-beam model Eq. (1) and the SDOF drift spectrum approximation Eq. (4) are analyzed. Results show a limit of applicability of the drift spectrum using the SDOF approximation. Drift spectra based on the uniform shear-beam model and the SDOF model are similar at the low period range but differ at the high period range; the turning point is the period of the dominant pulse in the ground motion. The results of the presented analysis clearly show that the SDOF drift spectrum, $D_{SDOF}(T,\zeta,\beta)$, that utilizes only fundamental mode is suitable for estimation of the structural demand only for a period less than dominant period of the ground motion. The $D_{SDOF}(T,\zeta,\beta)$ drift spectra significantly underestimate maximum deformation for the period range larger than Tp.

The underground experiment provided a unique opportunity to test a structure response such as the drift spectrum under extremely large values of acceleration. Analyzed examples of ground motions are characterized with the PGA and drift demand parameters. The ground motion with the PGA 3 g has a maximum strain drift spectrum of 0.02% in the frequency range 10–20 Hz and the ground motion with the PGA 12g has maximum strain of 0.25%–0.35% for the frequency range 4–20 Hz.

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