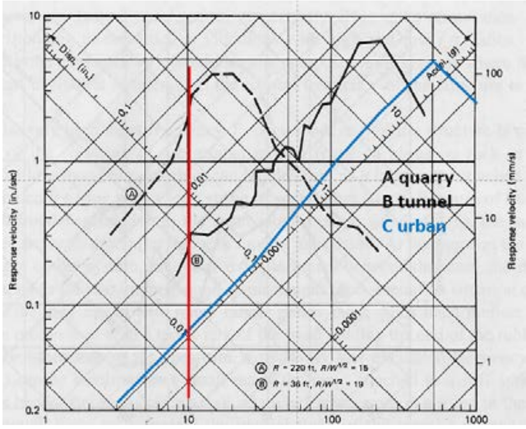
Newsletter #35

Measurements of Low Relative Displacements and Deamplification with Ultra High Frequency Excitation Validate Use of Single Degree of Freedom and Impulse Models



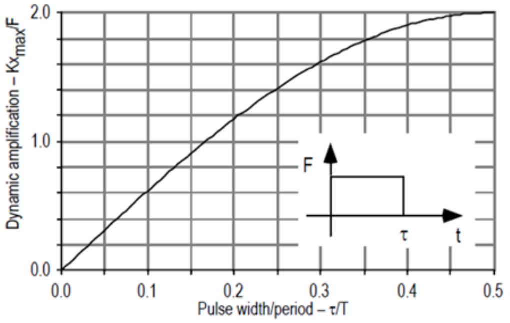


Figure 1 (left) Comparison of single degree of freedom (SDOF) response spectra for a quarry, close-in tunnel (black) and small charge, close-in urban blasts (blue) that show small expected relative displacement and thus low strain. Figure 2 (right) SDOF response showing that small pulse width, τ, ($1/f_{excitation} = 1/300$Hz) excitation of a large period, structure ($T = 1/f_{structure} = 1/3$Hz) or low ratios of τ/T or $1/f_{excitation}/1/f_{structure}$ or $f_{structure}/f_{excitation} = 3/300 = 0.01$ results in deamplification (Wright, 2012).

This newsletter describes how the measurement of small blast induced displacements and strains introduced in Newsletter 34 validate the use of frequency based models of structural response as well as observation of wave transmission rather than whole building response.

First consider single degree of freedom (SDOF) pseudo velocity response, Sv, with 5% damping to the 06/02 Urban (U) event ground motions compared to that from a large, distant quarry (Q) and close tunnel (T) blast shown in Figure 1. All spectra were calculated from ground motions with similar peak particle velocities (PPV): (2.4, 1.7 & 2.0 in/s or 61, 43, and 51 mm/s) for the T, Q and Urban events respectively. Spectra T, Q, and Urban were developed from ground motions recorded 12, 72, and 9 m from blasts with maximum charges per delay of 1.7, 91, and 2.4 kg

Even though the peak particle velocities are similar, standard response spectrum analysis of these ground motions predicts that the response of an urban structure to a close-in, small charge weight per delay blast will be 1/ 40th and 1/5th that of the quarry and close-in tunnel blasts. This difference is shown in Figure 1 above by either the pseudo velocity resposes (y axis Sv values) or the relative displacements, δ, (axis sloping 45 °up to left) for the Q, T and U events. Sv response is proportional to relative displacement for structures with the same natural frequency, f;

$$\delta = Sv/(2\pi f)$$

As can be seen at the red line for a structure with natural frequency, f, of 10 Hz, the Urban blast would be expected to induce less Sv and thus less relative displacement, δ, strain, and potential for cosmetic cracking than a typical quarry blast. The same is true for larger, multi-story structures with natural frequencies of f = 2 to 3 Hz. As explained in Chapter 5 in Construction Vibrations, structures with these low natural frequencies (2 to 3 Hz) compared to the urban blast's high excitation frequency (300+ Hz) lie on the displacement bound of the response spectrum of the close-in, small charge weight urban blast. Further explanation is presented at the end of this newsletter.

Now consider the deamplification of the rock excitation motions (yellow dot in Figure 1 of Newsletter #34) as shown by the response measured at the street level (green dot in Figure 1 of Newsletter 34). Standard texts (Wright, 2012 and Brooks & Newmark, 1953) demonstrate that short pulses with durations (1/300 = 0.0033 sec), which are significantly less than the period of the responding structure (2 Hz or T of ½ sec = 0.5 sec) produce response motions that are smaller than those by which they were excited. Figure 2 above from Wright, 2012 shows that the response of the single degree of freedom system to a step pulse with a ratio of τ/T. The single step pulse is consistent with the series of single peak pulses shown in Figure 1 of Newsletter #34. For the urban structure in this case, τ is the half period of the ultra-high frequency pulse of ½ (1/300) = 0.0033 sec, and T is the half period of the 2 Hz natural frequency urban structure sec, which is a period of ½ or 0.5 sec. Thus the τ/T ratio is 0.0033/0.5 = 0.0016 and the dynamic amplification factor is some 0.05 <<<< 1.0. In the example in Figure 1 of Newsletter #34, the ratio of peak particle velocity on the building at the street level to that at the foundation rock is s 0.2.

Response of the urban structure is likely to be small for several additional reasons. First consider the mass to energy ratio. Small charges detonated near massive structures do not produce enough energy to excite all of a large massive structure. Second, large urban structures are not excited synchronously by small charges detonated in a small area of the structure. The combined effect of these two phenomena is that *r*esponse motions travel through the structure rather than excite it all at once. This wave transmission response or declining motions within the structure with increasing distance was illustrated in Figure 1 in Newsletter 34 by the delay in the arrival of perturbing motions in at the ends of a large urban structure. It will also be shown by the strain response of columns within the Grand Central Train Shed to be discussed in Newsletters 39-42.

Back to the energy to mass ratio. A thick walled masonry urban structure with a natural frequency of 2 Hz and a wall stiffness twice that of a 10 Hz wood frame structure would be some 50 times more massive given that its natural frequency is the square root of the stiffness divided be the mass. Now consider the energy of the excitation pulses. The energy of the excitation can be estimated by the peak particle velocity divided by peak acceleration or 1/f (Sucuoglu & Nurtug, 1995). For a single principal pulse event with the same displacement, a 300 Hz excitation ground motion is some 10 times less energetic than a 30 Hz ground motion event. Thus the energy to mass ratio of the close-in rock blast excitation of an urban structure is 1/500 (= 1/50 * 1/10) that of a quarry blast excitation of a residential structure. Details of these calculations are shown and the end of this newsletter.

References

Brooks, N. and Newmark, N. (1953) "Response of Simple Structures to Dynamic Loads" Structural Engineering Research Series, No. 51. Civil Engineering Studies, University of Illinois. https://www.ideals.illinois.edu/bitstream/handle/2142/13942/SRS-051.pdf?sequence=2&isAllowed=y

Sucuoglu, H. and Nurtug, A (1995) "Earthquake Ground Motion Characteristics and Seismic Energy Dissipation" Earthquake Engineering and Structural Dynamics, Vol. 24, pgs 1195-1213.

Wright, C. (2012) Introduction to Structural Impact, PDHonline Course S164, http://www.pdhonline.com/courses/s164/s164content.pdf

Details of the displacement bound of the response spectrum of the urban blast

The use of the Sv values at 10 Hz to calculate response of a large, 2 to 3 Hz structure requires some explanation. First, the estimate of the natural frequencies come from the observation that structures have natural periods, T, of approximately 1/10 sec per story Thus a five story structure would have a natural frequency, f , (= 1/T) or 1/ (5*0.1) = 2 Hz. While these large urban structures have lower natural frequencies (2 to 3 Hz) than 10 Hz residential structure they sustain approximately the same relative displacements because 10 and 2 to 3 Hz lie along the constant relative displacement bound of the response spectrum. As explained in Chapter 5 of Construction Vibrations relative displacements are roughly similar because the dominant excitation frequencies (~300 Hz) are so much greater than natural frequencies of 1 to 5 story buildings, 10 to 2 Hz. Along the displacement bound the massive structures do not react until after the peak motion has passed. At the extreme the moment the peak motion impinges on the system the relative displacement becomes equal to the maximum ground displacement. While the urban response spectrum in Figure 1, shows that a 3 Hz urban structure Sv response to the urban blast (U) is lower than that at 10 Hz, the relative displacement is roughly similar to that at 10 Hz. It is similar because the relative displacement is equal to Sv/(2πf). Even though the Sv declines from 0.6 to 0.2 mm/s, f declines in tandem from 10 to 3 Hz.

Details of mass and energy calculations

Large urban structures, such as those in this study weigh a great deal more than residential structures. First consider the difference in weight or mass implicit in the difference in natural frequencies or periods. A masonry urban structure, u, with a natural frequency of 2 Hz would be some 50 times more massive than a 10 Hz wooden residential structure, r, if its walls were twice as stiff (k = stiffness) as the wooden home (ku = 2kr). This ratio is a consequence of the observation that the natural frequency of a single degree of freedom system is equal to the square root of the stiffness, k, divided be the mass, m, or (√(k/m)). Thus

$$2/10 = \sqrt{(2kr/mu)}/\sqrt{(kr/mr)} = \sqrt{2}*\sqrt{(mr/mu)} = 1.4\sqrt{(mr/mu)} \Rightarrow (2/10(1/1.4)) = \sqrt{(mr/mu)} = 0.1429 \text{ or } mu/mr = 50$$

Estimates of the mass or weight of the urban structure in this case study from weights of building components show it to be more than 30 times that of a typical residential structure. Thus the estimate of masses from their natural frequencies seems to be reasonable.

Now consider the ratio of the building mass to the impulsive energy imposed by an adjacent explosive detonation. Masses or weights were calculated above, so let's move on to the impulsive excitation energy. Begin with the assumption that the energy of the excitation is proportional to the peak particle velocity divided by peak acceleration (Sucuoglu & Nurtug, 1995). For a single principal pulse event with the same displacement, d, a 300 Hz excitation of an urban structure is some 10 times less energetic than a 30 Hz excitation of a residential structure.

$$(Vel/Accel)_{urban} = (2\pi fd)/(4\pi^2 f^2 d) = 1/(2\pi 300d) \text{ and } (Vel/Accel_{)residential} = 1/(2\pi 30d) \Rightarrow (V/A)u/(V/A)r = Eu/Er = 30/300 = 1/10$$

Thus the energy to mass ratio of the close-in rock blast excitation of an urban structure (Eu/mu) is 1/500 that of a quarry blast excitation of a residential structure (Er/mr). The mass ratio, mu/mr, was 50 and the energy ratio, Eu/Er, was 1/10. Accordingly (Eu/Er)/(Mu/Mr) = (Eu/Mu)/(Er/Mr) = (1/10)/50 = 1/500.