Abstract
This paper compares response of large urban structures to small charge weight, ultra-high frequency rock blast excitation from contiguous excavation to that of houses to more distant, larger charge weight blasts. Time correlated responses were measured for both structures at the corners, top and bottom of the structures as well as in the foundation rock below the bottom. The comparison allowed the following conclusions: Close-in blasting with direct rock to building wave transmission imposes short wave length excitation which fails to excite the large, massive structures synchronously whereas the more distant blasts do synchronously excite houses. The larger urban structures respond predominantly in wave transmission mode where there is a noticeable difference in time, frequency, phase and amplitude of motions measured at the bottom and top corners of the structure. Excitation motions along the base of the larger urban structures also differs in time, frequency, phase and amplitude. The short wave length of the excitation motions leads to attenuation of the peak particle velocity along the base. Ultra-high excitation frequencies, which are much higher than the expected structural natural frequencies, lead to deamplification for all events for the large urban structures.
**Introduction**

This paper presents unique measurements of time correlated attenuation and delays in first arrival times along large urban structures. Transmission of motion up through urban structures during response to contiguous blasting has been observed before (Dowding et al, 2016 &15 and Aimone-Martin et al 2015). This article provides further insight into blast induced response and excitation along the base of larger urban structures because of the multiple locations of measured response along the structures.

These multiple time correlated responses show that urban structures do not respond synchronously as do smaller residential structures upon which much blasting literature is based (Siskind, et al, 1980). Current regulations often only require that the excitation motions be measured at one (or several) location(s) with no requirement for time correlation of the measurements. Building response is then most likely to be considered in phase and similar to that measured by the Siskind work with smaller residential structures and longer wave length excitation. Because there is no requirement to measure excitation at multiple points and/or building response, compliance measurements provide little new information about the nature of larger building response to ultra-high frequency excitation.

Implications of the non-synchronous or wave propagation response of urban structures observed in this study is illustrated in Figure 1 by scaled comparison of response of this urban structure to high frequency excitation with that of houses to lower frequency excitation. The house and its response is illustrated in the boxed inset on the lower right. Scaled photographs of both structures underscore the relatively massive nature of urban structures—by weight and size. All information regarding the smaller “house” example is enclosed in its own box. Blue circles below the excitation time histories compare the amount of explosives detonated in any instant and the distance between blast and structure.

Excitation motions, measured at each structure at the yellow dots, is shown by the adjacent time histories; urban to the left and house to the right. Time and amplitude scales are equal for both time histories. Response at the red dots shows that despite urban excitation amplitudes twice those at the house, urban response was de-amplified to only 20% of the excitation, while house response was amplified to 2.4 times that of the excitation. This difference is in part the result of higher frequency (333 cycles per second, cps or Hz) urban excitation compared to the lower, 5 cps, house excitation. Urban de-amplification also results from the non-uniform or non-synchronous urban response compared to the house. Arrival times of the motions differ greatly for the urban structure as shown by the difference in arrival times of the motions at yellow, green and red dots. For the house the peaks of the yellow, green and red coincide. The difference in arrival and response times for urban structures demonstrates that the energy of the urban high frequency excitation is insufficient to produce whole body response of the massive urban structure.

**Site Geology and Blasting Practice**

This study was conducted in a dense urban location in New York City where blasting was required not just adjacent to buildings but contiguous to them as illustrated in Figure 2. Both of the buildings are over 100 years old and are landmarked structures. They are 4- to 6-story unreinforced brick masonry buildings, built 1890 and 1920, and are typical of those structures built New York City at that time. They both have basements.
Figure 1  Scaled Comparison of Response of a Large Urban Structure to Excitation from Contiguous Rock Blasting with that of a Residential Structure to Surface Coal Mine Blasting Showing Large Differences in Response
The rock supporting these structures is a mica schist whose foliation dips into the excavations from beneath the structures. Vertical rock faces are supported by rock bolts that are 3 to 9 m (10 to 30 ft) long. Measured propagation velocities confirm the relative stiffness of the rock mass.

Contiguous blasting produced excitation ground motions of unusually high amplitude and dominant frequencies. Rock was fragmented with the close-in blasting techniques that included line drilling. Holes were detonated with 25 and 17 ms surface delays with 500 ms in-hole delays. Blasts typically included 20-50 holes with 2 to 10 rows. They were arranged in a spacing and burden pattern of less than 60 cm x 60 cm (2 ft x 2 ft). There was usually at least one free vertical face, and often two. Blast holes are charged with 2 cartridge based emulsion with 2.4 to 3 kg/delay (5.25 to 6.5 lbs/delay). Blasts monitored in this study were detonated within 9 horizontal meters (30 ft) of the north corner of building 1. Because of regulatory limitation of blast-induced vibration, the number of holes per volume of fragmented rock is often high, hole diameter is small, and in-hole delays are used.

**Transducer Description and Installation**

Buildings and rock were instrumented with seismographs that were connected in series to provide a common time base that was accurate within one sample interval of 0.0005 sec. LARCOR Mini Seis II four channel seismographs deployed in this investigation and associated velocity geophone transducers meet the International Society of Explosive Engineers (ISEE) standards.

Two horizontal transducers were located at the street level, B, and roof top, A of the north, N, and south, S, corners of the west wall nearest the excavation as shown in Figure 2 (left). One was oriented parallel (denoted radial or R) and the other perpendicular (denoted transverse of T) to the wall west building wall. The lower (B) geophones were bolted on brackets which in turn were bolted into the mortar between bricks on the building about 1 m (3-4 ft) above street level. The upper (A) transducers were also bolted to brackets and bolted into the mortar on the inside of the parapet wall just above roof mastic. For blasts close to the north corner of building 1, the majority of blasts in this study, the north seismograph would trigger the south seismograph.

In addition triaxial sensor with three velocity transducers was installed in the rock (G) beneath the north corner with the radial parallel and the transverse perpendicular to the west wall. It was time correlated to structure measurements as described above, and would trigger the nearest corner seismograph, N in the cases described in this study. Construction interaction prevented installation of rock transducers altogether at the south end. Only the horizontal rock motions were evaluated or reported herein.

Building 2 was instrumented in a manner similar to that of building 1 as shown in Figure 2 (right). The upper north geophone, NA, was bolted to the inside of the upper tower portion instead of the parapet. Two single-axis transducers were also deployed in the basement of building 2. One was mounted to the inside of the basement west wall at mid height, 9 m (30 ft) north of the south corner with its horizontally sensitive axis perpendicular to the wall. A second, vertically-oriented transducer was mounted to the underside to the basement ceiling (first floor) also 9 m north of the south wall.

**Blast-Induced Vibration Amplitudes and Dominant Frequencies**

Figure 3 compares the values of peak particle velocity in rock against scaled distance for four blasts adjacent to the north corner of building 1 (left 4 circles) with expected values (lines) given by Oriard (1972). The right two circles are values for rock (SD = 11) and lower building (SD = 14) for the same blast, a.
Figure 2. Photographs of the construction site showing building dimensions, foundation details, and transducer locations for building 1 (left) and 2 (right). [1 m = 3.28 ft]

Figure 3. Comparison of square root scaled distance attenuation as measured in the ground (black circles) to Oriard’s (1972) expected values for typical practice (lines shown for lower bound, upper bound, and upper bound for highly confined blasts) [25.4 mm/s = 1 in/s, 1 m/kg$^{1/2}$ = 2.3 ft/lb$^{1/2}$]
The lines on the plot are lower and upper bounds of Oriard’s expected values as well as upper bound of expected values for highly confined blasts. Four of the five plotted points from this study fall within the normal bounds of expected values, and all five fall below the upper bound for confined blasts. As these blasts are have a tendency to be confined, these data are in the expected range given by Oriard and are not unusual.

Particle velocity time histories of rock to rock motions reveals ultra-high excitation frequencies with separated, singular pulse excitation evident in the rock motions shown in Figure 1. Figure 4 compares 5% damped spectra of three blast induced ground motions; that from the 06/02, “a”, event, shown in Figure 1, a close tunnel blast (A) and large, distant quarry blast (B). Blast “a” generated a radial peak particle velocity of 51 mm/s (2 in/s) in the rock from a 2.4 kg (5.25 lb) blast some 9+ m from building 1. Blast A generated a PPV of 61 mm/s (2.4 in/s) 12m (40 ft) away from a 0 to 9 ms delayed tunnel blast with a maximum charge in any single delay of 1.7 kg (3.7 lb). Blast B generated a PPV of 43 mm/s (1.7 in/s) 72m (236 ft) away from a single 91 kg (200lb) charge detonated in a typical bench in a limestone quarry (Dowding, 1996).

Principal pulse frequencies for the radial and transverse components of all ground motion time histories recorded during this study range from 333 to 500 Hz at building 1 and 140 to 500 Hz at the more distant building 2. These ultra-high principal peak excitation frequencies are one of the important unique features of this study. Implications of these ultra-high frequency motions will be discussed in the following sections.

**Structure Response to Ultra High Frequency Excitation from Close-in Blasting**

Rock excitation motions arrive with high peak particle velocities (PPV’s up to 200 mm/s – 7.8 in/s) and ultra-high frequencies (250-500Hz). These pulses are quickly attenuated and filtered in the structure. For example, for blast “a” which had 51 mm/s (2 in/s) motions in the rock, the street level PPV (NB) was only 6 mm/s (0.24 in/s) and the top PPV (NA) was 7 mm/s (0.28 in/s). Dominant frequencies at the street level are higher than that at the upper structure. For instance, at building 1, mean values of radial dominant frequencies at North and South corners respectively are 108Hz and 158Hz at the street levels and 72Hz and 36Hz at the top.

Figure 5 compares amplification factors from these large urban structures and for one- and two-story residential structures (homes) reported by Siskind et al. (1980) Amplification values for the Siskind data were calculated from upper corner, A, and wall, MW, motions divided by ground motions, “Rock”. For this study amplification factors for the superstructure were calculated as velocity ratios, top(A)/rock and top(A)/bottom(B), at the comers of buildings 1 and 2. Figure 5.a compares superstructure amplification ratios with the dominant frequency excitation for both the Siskind and this study. Amplification ratios for this study are found at the extreme right in Figure 5.a as they result from excitation at high dominant frequencies. In no case is there amplification: the largest ratio is 0.92, or no amplification. The basement (wall-MW)/rock amplification factor for building 2 during the 08/05 event (filled circle) and bottom/rock amplification factor is again found on the extreme right of the wall response in Figure 5.b. Again there is no amplification, even for the basement wall, the bottom of which is in direct contact with the rock. Even though it sustains high particle velocity, its relative displacement remains low because of the high excitation frequency as discussed below.

Basement walls on the west side of these structures are the only freely responding bottom element that is in direct contact with rock. All other components respond to the filtered/attenuated building motions. Thus comparison of pulse correlated basement wall velocity response to rock PPV excitation (Wall/Rock) with that of other building elements, such as (Bottom/Rock) and (Top/Rock) is of special interest. The response of building 2 during the 08/05/2014 event provides this comparison and is shown
beneath the “W” in Figure 5.b. Basement deamplification ratio is 0.61, which can be compared to Bottom/Rock deamplification of 0.28 and Top/Rock deamplification factor 0.51.

Figure 4. Comparison of response spectra of ground motions (GR = radial-thin, solid line, GT = transverse-thin dotted line) from close-in blast event “a”, a low frequency quarry blast, (Q) and a near-by tunnel blast (T) [ 25.4 mm/s = 1 in/s]

Figure 5. Comparison of Amplification ratios vs ground vibration frequency as observed in the USBM by Siskind et al. (1980) for 1 and 2 story structures (open symbols) compared to those observed in this study for buildings 1 and 2 (filled symbols) which are 4-6 stories high. Residential, 1 to 2 story high structure response is amplified, whereas that of urban structures is deamplified.
Pseudo Velocity Response Spectra Demonstrate and Low Distortion

Considerations of energy and mass show that response of large, urban structures to ultra-high frequency excitation is likely to be lower than that predicted by standard response spectrum analysis. First consider standard single degree of freedom (SDOF) pseudo velocity responses to typical blast induced ground motions shown earlier in Figure 4.

Even though the peak particle velocities are similar, standard response spectrum analysis predicts that a 10 Hz structure will sustain a pseudo response velocity that is 60 and 6 times larger for the quarry and tunnel blasts than for the high excitation frequency blast “a”. Since the pseudo velocity is proportional to relative displacement for structures with the same natural frequency (10 Hz in this case), event “a” would be expected to induce far less relative displacement, strain, and cosmetic cracking when compared to the response of a typical single story residential structure.

Consider that these particular urban structures are far more massive because of their size and masonry construction. Their super structures can be expected to have periods, \( T \), of 1/10 sec per story, where a five story structure would have a natural frequency (1/T) of \( 1/(5 \times 0.1) = 2 \) Hz. The 2 Hz response to event “a” is 1/5th that of the 10 Hz response and an urban structure would likely sustain 1/5th the relative displacement, strain and cosmetic cracking potential. Calculations of strains in these structures is discussed in Dowding et al (2016) and other urban structures in Aimone et al (2015).

Influences of Ratios of Mass to Excitation Energy, Non-Synchronous Excitation, and Size

First consider the mass to energy ratios of large urban structures and houses. First compare masses or weights. A masonry urban structure with a natural frequency of 2 Hz would be some 50 times more massive than a 10 Hz wooden residential structure if its walls were twice as stiff as the wooden home. 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 divided by the mass. 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 may be conservative.

Now compare the energy of the excitation pulses. Sucuoglu & Nurtug (1995) indicate that relative energy provided by single pulses is proportional to the peak particle velocity divided by peak acceleration. For a single principal pulse event with the same displacement, a 300 Hz excitation of an urban structure is some 10 times less energetic than a 30 Hz excitation of a residential structure.

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.

Now consider non synchronous excitation. SDOF analysis carries with it an implicit assumption that the entire building is AND can be entirely excited uniformly along the base. This assumption accompanies the use of the SDOF model because there is only one point of excitation. These urban structures have a larger foot print (65 x 20 m) (210 x 65 ft) compared to a residence (8 x 10 m) (25 x 50 ft) and are excited by motions with pulses ( = ½ a wave length) that have a length of only 10 m (33 ft) (= c/f x 1/2 = propagation velocity divided by dominant frequency times 1/2= 6000 m/s/300 Hz x 1/2). The widths and lengths of the north and south of buildings are ~ 2 to 6 pulse lengths. Thus the same pulse cannot excite the entire large urban structure simultaneously. On the other hand, a 20 Hz, surface wave with a propagation velocity of 1000 m/s (3280 ft/s) will have a pulse length 25 m (80 ft) (c/f x ½ =
1000 m/s/20 Hz x ½). The house width is only 1/3 to ½ the wave length. Thus it is more likely for a house to be synchronously excited by a distant quarry or mine blast than an urban structure from an immediately adjacent blast, as shown by the comparison in Figure 1.

Thus there are two reasons to suspect that close in blast perturbation of a large urban structure will produce less distortion than predicted by a frequency based peak particle velocity criteria. First, an urban structure is not excited in phase or synchronously as shown in Figure 1. Second the energy to mass ratio described above is smaller than that associated with observations of amplification and cosmetic cracking in the USBM Siskind et al (1980) study.

**Comparison of Time Correlated Time Histories Illustrates Wave Transmission**

Time correlated comparison of rock excitation and building response shown in Figure 1 demonstrates that the buildings do not respond in phase or synchronously. Nonsynchronous in this context means that motions at opposite ends of the top of the building or between the top and street level are not in phase.

As illustrated in Figure 1, arrival times are delayed by some 50 milliseconds (ms) up the north corner and 100 ms across the top. This time difference is large compared to the period of the 300 Hz excitation pulse, which is \( \sim 1/300 = 3.3 \) ms. Response amplitudes and dominant frequencies decline both upward and across (north to south) the structure. Structure response amplitudes and dominant frequencies decline by factors of 5 at the north corner of building 1, which is closest to the blast. These responses showing large deamplification and significant delays in building response are more reflective of wave transmission than synchronous dynamic response.

**Conclusions**

Measurements of multiple-position, time correlated response of two urban buildings to ultra-high frequency blast vibration excitation allow the following observations to be made. These observations are based upon bidirectional horizontal velocity responses at ten positions during eight blast events which provided over 70 time histories for analysis, only some of which were described in this short article. Time histories of these measurements are archived and made available at [http://iti.northwestern.edu/acm](http://iti.northwestern.edu/acm) by pressing the “High Frequency Excitation” button.

- Measurement of excitation motions with transducers embedded in foundation rock rather than on structures or at street level reveals that close-in blasting produces excitation pulses that are more isolated, and higher in frequency.
- This large urban structure responded predominantly in a wave transmission mode as illustrated by noticeable differences in time, frequency, phase and amplitude of the motions measured at the top corners when compared to those at lower elevations or in the rock.
- Responses of the large urban structure(s) to the high frequency excitation pulses were deamplified at the top for all events, while they have been observed to be amplified at the top of smaller residential structures.

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