URBAN SEISMIC GROUND MOTION: A COUPLED EFFECT OF SITE AND URBAN ENVIRONMENT

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ABSTRACT :

During the World Trade Center terrorism attack, several records done by the Lamont network have clearly shown seismic signals from the two aircraft impacts, up to distance 35km far from WTC site. For the first time, the energy of the induced motion produced during the impact of the first tower has been evaluated as equivalent to those produced by an equivalent Ml 0.9 earthquake located at the WTC site while the motion generated by the aircraft impact at the building top was roughly computed as 0.40m. Here we explicitly simulate the WTC tower motion and its induced effect on ground produced by the aircraft shocks. We show that the induced wave has spectral characteristics corresponding to a higher vibration mode of the building and the nearby ground motion might have high amplitude that should not be neglected during a realistic earthquake.

KEYWORDS: WTC, site-city interaction, urban seismology.

1. INTRODUCTION

Recent scientific papers (e.g., Guéguen et al., 2000, 2002; Groby et al., 2005; Guéguen and Bard, 2006; Kham et al., 2006) have shown the effect of the building vibration on the ground motion. In particular, they showed the importance of such a phenomenon in case of dense urban environment. It results from the combination of three processes: (1) the soil-structure interaction process (SSI) that may considerably disturb the seismic building response, especially when the foundation rests on soft soil; (2) the structure-soil interaction (StSI) process that traduces the radiative damping of the structure, i.e. it radiates back into the ground a part of its vibration energy as seismic waves; (3) the seismic site effects process (SSE) that may favor the trapping of the waves induced by the building motion. All these processes define what Guéguen et al. (2002) first called the Site-City effects, a specific part of urban seismology.

Jennings (1970) during an one-scaled experiment performed on the California Institute of Technology campus in California, and more recently Guéguen et al (2000) in Greece at the Volvi European test site during a 1/3-scaled experiment showed the importance of this phenomena and concluded that it is not exclusively a local phenomenon. The induced waves may conserve energy up to sizable distances. Two other observations have been done which convinced us of the non-neglected effect of the StSI. First (Kanamori et al., 1989), when Columbia shuttle was back into the atmosphere, the atmospheric shock wave simultaneously created had excited a group of high-rise buildings located in Los Angeles downtown. These buildings freed a portion of their vibrational energy in the form of compression waves transmitted to the ground via foundations and recorded by the Southern California seismological stations. Second, during the terrorist attack in New York in 2002 which destroyed the World Trade Center twin towers, the aircraft impacts at the top of each tower were recorded by the Lamont seismological network (Kim et al., 2001), thanks to a seismic wave clearly identify as the results of the building vibration effect.

The aim of this work is to model the effect of WTC-1 vibration after the aircraft impact on the ground. After the description of the building and the model used in this study, we compare the modeling and observation of the ground motion induced at Palisades Lamont seismological network station. Then, the close ground motion is computed and compared to the seismic ground motion that could be produced by earthquake.

2. BEHAVIOR OF WTC-1 BUILDING UNDER AIRCRAFT IMPACT LOAD

2.1. Model of building

WTC-1 and WTC-2 were 110-story structural steel office towers with seven basement floors. WTC-1 was 417 m high and 63.5m square in plane. The resistant frame was composed by 4x59 squared-box columns (0.35x0.35) located along the perimeter with steel spandrel beams for resisting to the horizontal design wind load. An additional rectangular core located in the centre of the tower was designed to support about 60% of the gravity load due to the weight of the structure. The total weight of WTC-1 above ground was estimated at $3.63\ 10^3$ MN (Tsuruta, 1970). All the mechanical characteristics of the WTC-1 used in our study are summarized in Tab. 1.

Table 1: Characteristics of the WTC-1 tower used for modeling.

Static properties			*Dynamic properties*		
Dimensions	HxLxB	417x63.5x63.5 m	Steel Young modulus	E	$2.1\ e^{11}$Pa
Number of floors	N	110			
Story height	h	3.79m	Damping	ζ	3%
Total mass	M	$3.63\ 10^8$ kg	1st-Period	T_1	12.9 s
Mass/floor	m	$3.3\ 10^6$ kg	2nd-Period	T_2	4.3 s
Column dimension	b_ext	0.35x0.35 m	3rd-Period	T_3	2.6 s
	b_int	0.32x0.32 m			
Inertia momentum	i	$3.76\ 10^{-4}\ m^4$			
Number of columns	Nc	4x59			
Inertia of tower	I	$0.08\ m^4$			

Even if some elevation irregularities of design exist, the WTC-1 tower was assumed to behave as a uniform shear beam (Fig. 1). The building mode shapes and frequencies are given by:

$$\phi_n = \sin\frac{2n-1}{2}\left(\frac{\pi x}{H}\right) \qquad (1)$$

$$\omega_n = \frac{2n-1}{2}\pi\left(\frac{12\sum EI}{m.h.H^2}\right)^{1/2} \qquad (2)$$

Periods found by this formula, and considering the characteristics given in Tab. 1, are 12.9, 4.3 and 2.6 seconds for the first, second and third modes, respectively (Fig. 1), close to the values given by Omika et al (2005). Structural damping of 3% was measured by Mahmoodi et al. (1987) for the fundamental and secondary vibration modes, based on wind response analysis.

The time history of the damped free-vibration response is given by:

$$Y_n(t) = \left[Y_n(0)\cos\omega_{Dn}(t) + \frac{\dot{Y}_n(0)+Y_n(0)\zeta_n\omega_n}{\omega_{Dn}}\sin\omega_{Dn}(t)\right]e^{-\zeta_n\omega_n t} \qquad (3)$$

in which $\omega_{Dn} = \omega_n\sqrt{1-\zeta_n^2}$, $Y_n(0) = \frac{\phi_n^T m v(0)}{\phi_n^T m \phi_n}$ and $\dot{Y}_n(0) = \frac{\phi_n^T m \dot{v}(0)}{\phi_n^T m \phi_n}$.

The initial conditions $Y_n(0)$ and $\dot{Y}_n(0)$ are then determined from the initial displacement $v(0)$ and velocity $\dot{v}(0)$ vectors. Time histories of the total displacement can be obtained using the modal superposition as follow:

$$\mathbf{v}(t) = \Phi_1 Y_1(t)+\Phi_2 Y_2(t)+ \ldots+\Phi_N Y_N(t) \qquad (4)$$

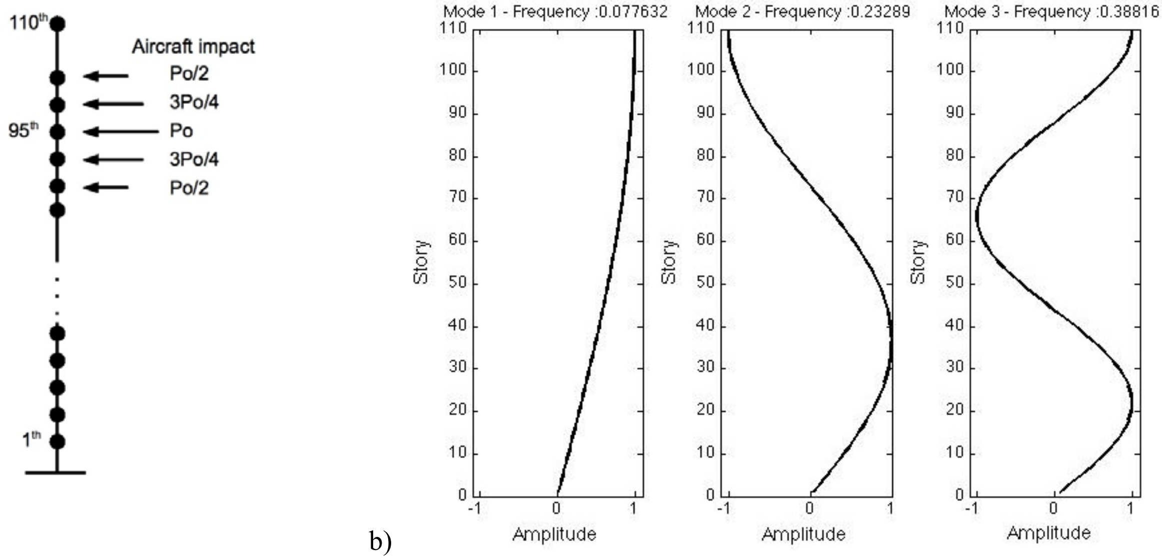
a)  b)

Figure 1. a) Lumped mass model used for WTC-1 tower modeling with the position of the loading due to the aircraft impact; b) Mode shapes and frequencies of the 1st, 2nd and 3rd modes.

2.2. Impact load on the WTC-1 tower

Each tower was hit by a Boeing 767, the WTC-1 tower at 12:46 TU. The aircraft chocked the North face of WTC-1 close to the 95th floor, perpendicular to the face. The impact was close to the center of the WTC-1 side. A lot of hypothesis must be done for evaluating the impact force loading that can be approximately calculated according to Boeing data on this type of aircraft and reports published after the event. The mass of the aircraft is about 150 10^3kg and its velocity at the impact is around 500 km/h. Because of the plane did not totally cross the tower, we assume a reasonable decrease of aircraft speed over the horizontal dimension of the building, i.e. 63.5m. The aircraft was then arrested by the tower in t_l=0.45 second. The equivalent impact force can be calculated considering the momentum of the aircraft (i.e., mass x speed) divided by the effective time of impact, that led us to consider an impact force equal to 46 MN. This value is close to the impact force considering by Omika et al. (2005) for modeling the building response. Moreover, this force is less than the design wind force on one face of the building, conform to the fact that total building collapses were not due to impacts.

We assumed in this study the impact occurred from the 92th to the 98th floors, with linear reduction of impact loading (Fig. 1). As reported by several authors (e.g. Sugano et al, 1993), the time history of the impact loading is a rectangular impulse load. Then, the response of the structure may be divided into the loading phase (t_l=0.45 second) and the subsequent free-vibration phase. Because of the short time duration of the impact, the response of the structure is calculated for an undamped Multi-Degree-Of-Freedom system, before the damping forces can absorb energy. During the loading phase, the modal response of the structure is given by:

$$Y_n(t) = D_n \frac{P_{on}}{K_n}\left(1-\cos\omega_n t\right) \tag{5}$$

in which $K_n = M_n \omega_n$ and $P_{on} = \phi_n^T P_o$

where D_n is the modal magnification factor for rectangular impulse force, M_n is the mass modal matrix and P_o is the vector of force applied along the North face of WTC-1 tower. Using superposition, displacements and velocities of the building at the end of the impact loading phase are considered as initial condition ($v(0)$ and $\dot{v}(0)$) for the free-vibration phase (Eq. 3).

The shear force and the resultant overturning moment at the base of the building, that will be considered as acting on the ground, are given by the sum of all story forces, that is,

$$V(t)=\sum_{i=1}^{N} f_{si}(t) \quad \text{and} \quad f_{si}(t)=m\Phi\left\{\omega_n^2 Y_n(t)\right\}$$
$$M(t)=\sum_{i=1}^{N} x_i f_{si}(t) \tag{6}$$

where x_i is the height of story *i* over the base.

Figure 2 displays the time histories of building top displacement and resulting forces acting on the ground. The maximum displacement was approximately 45 cm on the 110th floor. The resultant shear base force and overturning moment are around 200MN and 20 10^3 MNm. We can show on the Fourier spectra that several modes are exited by the impact loading. Due to its time duration (t_l=0.45s) and position, higher mode are significantly exited in comparison to the fundamental one.

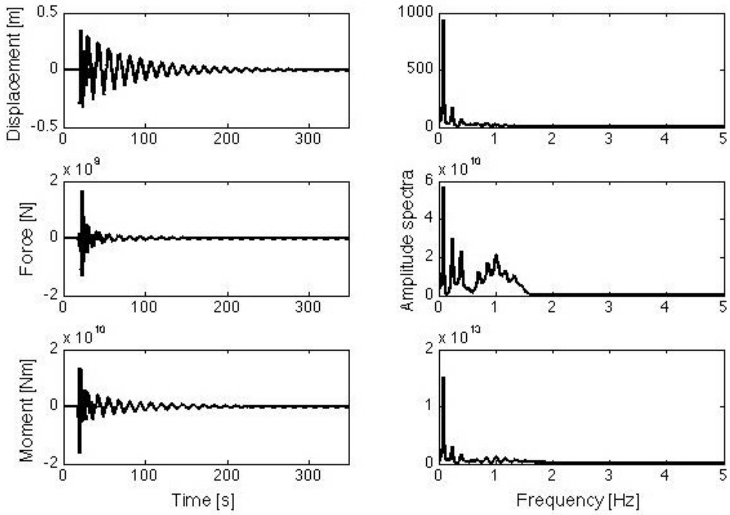


Figure 2. Time histories (left) and Fourier spectra (right) of the building top displacement (upper row), shear base force (mid row) and overturning resisting force (lower row) resulting of the WTC-1 modeling subjected to the aircraft impact.

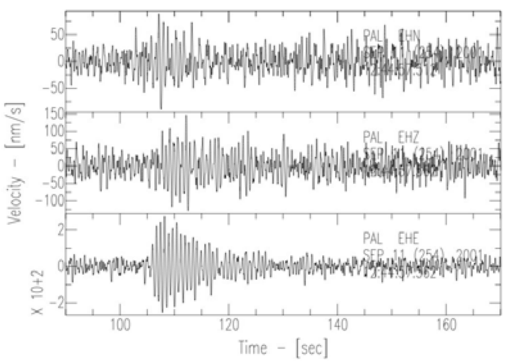
3. GROUND MOTION INDUCED BY THE BUILDING MOTION

Shear base force and overturning moment were then assimilated to point-specific seismic sources applied at the surface of the ground. The induced wavefield was then computed at any point in the space by using the Hisada's code (1994, 1995). With this code, the analytic Green's functions are computed for any soil stratified model and for any source-receivers configuration. One advantage of this code is it allows having sources and receivers at the same depth that is the case in our study. In order to reproduce the extended shape of the foundation, these forces are substituted by a couple of two forces spread along the soil-footing contact, given the equivalent amplitude of force in the horizontal direction and the same amplitude of moment in vertical direction. As mentioned in Guéguen (2000), the effect of the number of discrete forces used to simulate the extended shape of the foundation is insignificant enough to consider only two forces. In our study, we computed wavefield up to 5 Hz, equivalent to the low-pass filter applied to the data recorded by the Lamont observatory seismological network.

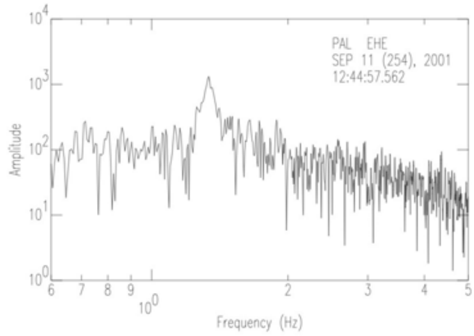
The soil profile is adapted from the analysis done by Kim et al. (2001) on the wavefield induced by the collapse of WTC towers, recorded by Lamont-Doherty seismological network. It consists on a 400 m thick layer (shear wave velocity β_1= 1500 m/s; compressive wave velocity α_1=3000m/s; density ρ_1 = 2000 kg/m^3; S wave quality factor Q_{S1} = 50; P wave quality factor Q_{P1}=100), over a stiff half-space (β_2 = 2500 m/s; α_2=5000m/s; ρ_2 = 2200 kg/m^3; Q_{P2} = 200; Q_{S2} =100).

During the impact, the Palisades (PAL) seismological station (distance 34km toward the North-West) recorded the induced wavefield (Fig. 3a). For that, we computed first the induced wavefield at the position of the PAL station (Fig. 3b).

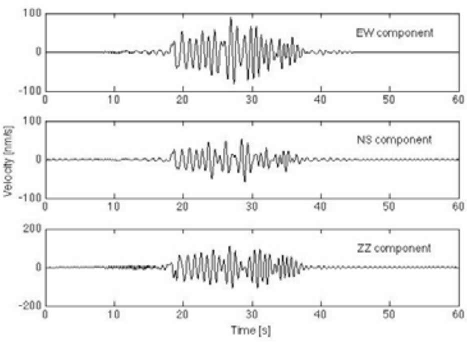
a) EHN, EHE and EHZ components – Filter:0.6-5Hz – PAL station



Fourier amplitude spectra - EHE component



b) EW, NS and ZZ components – Filter : Low-pass 5Hz – PAL site



Fourier amplitude spectra – EW, NS and ZZ components

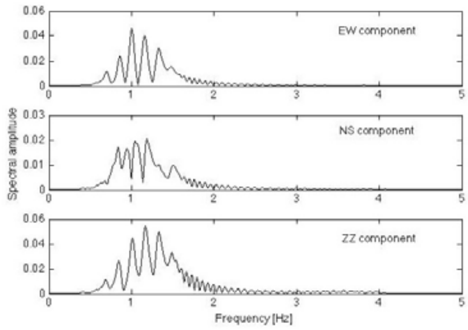


Figure 3. Time history (left) and amplitude spectra (right) of the induced wavefield observed (a) and calculated (b) at the PAL station, 34 km toward the North-West from WTC-1 tower.

We observe similar time duration of the ground motion computed and observed at PAL station on the EW component (around 20 s). On the other hand, the amplitude of the observed (273 nm/s) wavefield is higher than computed one (around 100 m/s) but the same order of magnitude is considered. Differences may be due to the hypothesis done on the building modeling and impact loading, as well as on the unknown parameters of the soil profile. It is important to note that seismic signal from impact was characterized by relatively periodic motion and its spectra was above noise only for frequencies from about 1.3 and 1.6Hz (Kim et al, 2001). We observe also the same frequency content in our modeling, frequency that is 10 times the fundamental frequency computed for WTC-1.

With the same model, we calculated the induced wavefield at the close vicinity of WTC-1 building. Figure 4 displays the EW and ZZ ground motion at 100, 200, 500, 1000 and 5000m from the WTC-1, at receivers spread along the EW direction. We observed a strong ground motion with amplitude of 50 µm/s at very short distance on the vertical and East-West components. At 1km the amplitude still remain quite strong (around 1 µm/s). In comparison, an M_L=2.4 earthquake (2001/01/17) in Manhattan (New-York) produced at PAL a seismic ground motion of 10 µm/s (Kim et al., 2001) that confirms the strong effect of the building vibration on the ground motion.

4. CONCLUSIONS

In most instances, buildings are studied as though they were isolated and ground motion is assumed to stem solely from seismic activity. The notion of a potential man-induced modification to seismic risk within an urban zone seemed completely incongruous. On the basis of simple analytical models, this study shown here reveals that an isolated building submitted to shaking is capable of generating a wavefield detectable up to distances on the order of 30 kilometer. The energy released within the soil suggested potential interaction at a much larger scale, representative of an entire city. In fact, in the very close vicinity, induced ground motion may be as strong as those produced by earthquake and it is not totally absurd to consider an additional seismic wavefield coming from urban environment, in complement to the so-called seismic free-field motion.

The topic is far from being exhausted. A number of analytical perspectives remain to be examined in depth, whether this pertains to improving knowledge of these phenomena, developing more efficient estimation tools or simply furthering the experimental work to back up theoretical findings.

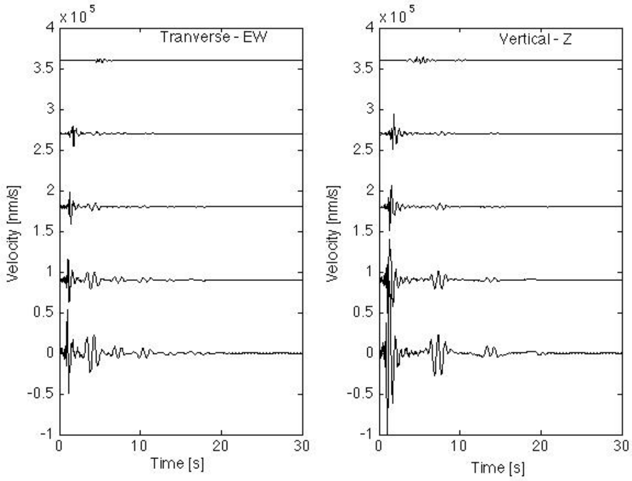


Figure 5. Time history of the wavefield induced by the WTC-1 building at 100, 200, 500, 1000 and 5000 m in the Est direction

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