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Velocities of seismic waves in structures

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ABSTRACT: Dynamic response of a structure under earthquake loads can be formulated as a wave propagation problem. Seismic waves, which are generated by fault rupture, propagate through the foundation into the building, causing it to vibrate. For multi-story buildings, for example, the parameters required to formulate the problem as a wave propagation problem include the wave travel times between the floors, structural damping values at each story, and the reflection and transmission coefficients at each floor. The wave travel times (or the wave velocities) between the floors are the key parameters in the formulation. The large amount of data that have been collected from the instrumented buildings in recent years provide an opportunity to study wave velocities in multi-story buildings.

The commonly used approaches to calculate wave velocity from vibration records have been to use the phase shift of a characteristic peak in the records, or the delay time for the peak of the cross-correlation function of the records. These two approaches do not give accurate wave velocities, because the damping in the building also alters the phase of the records. In other words, the phase differences in the records are not only due to wave travel times but also the phase shift due to story damping.

This paper presents a methodology to calculate the velocity of seismic waves in multi-story buildings more accurately than the current procedures. The methodology involves utilization of the envelopes of the impulse response functions with respect to roof, and can separate the phase shifts due to damping and the wave travel time. As an example, seismic wave velocities in three instrumented multi-story buildings are calculated by using their earthquake records and the methodology presented.

1 INTRODUCTION

The common approach to study earthquake-induced motions of structures has been to utilize modal analysis techniques, where the vibrations of the structure are expressed as the sum of the responses of one-degree-of-freedom oscillators, each with its unique frequency, damping ratio, and mode shape. In recent years, an alternative approach has been developed based on the propagation characteristics of seismic waves within the structure. In the wave propagation approach, the vibrations of the structure are characterized in terms of wave velocities, attenuation of wave amplitudes, and the wave reflection and transmission coefficients (Safak, 1999). When analysing vibration records from instrumented structures, it has been shown that, for system identification and damage detection, the wave propagation parameters are more reliable and robust than modal parameters, and also more sensitive to damage (Safak, 1998).

This is particularly true for older, historical structures because these structures do not meet the requirements of the classical modal analysis, such as elasticity, linearity, mass and/or stiffness proportional damping (Safak and Cakti, 2009a).

In this paper, first a new methodology is introduced to calculate the wave velocities in multi-story buildings. The methodology provides a more accurate estimation of wave velocities than the commonly used other methods, for it eliminates the phase shifts introduced by damping. Next, the velocities of seismic waves in three instrumented multi-story buildings are calculated by using the vibration records during earthquakes.

2 CALCULATION OF WAVE VELOCITIES

A critical step in using wave travel times for identification and damage detection is the accurate calculation of wave travel times. This first requires a high-quality and high-sampling-rate recording. For multi-story buildings, the sampling interval in the records should be at least $1/10^{th}$ of the shortest travel time between any two successive floors. Wave travel times cannot be calculated accurately from the raw data, because the noise in the signals alters the peak amplitudes and phases. The two processing steps that help to increase the accuracy in wave travel time calculations are band-pass filtering and deconvolution. Band-pass filters should be selected such that the filtered signal has a much higher signal-to-noise ratio than the original signal. This is accomplished by selecting the pass-band to keep only the resonant frequencies of the building. The deconvolution eliminates the components of the excitation (i.e., the ground motion), as well as the effects of soil-structure interaction in the records (Safak, 1995). This results in a much cleaner signal to calculate wave velocities. Typically, the foundation-level records are used to deconvolve the signals, giving the impulse-response functions at instrumented floors to a ground-level impulse. A much better alternative is to calculate the impulse-response functions with respect to roof record (i.e., by deconvolving the signals with the roof record). It can be shown that the deconvolution by the roof record eliminates the upgoing wave components in the signals, resulting in a simple downgoing wave (Snieder and Safak, 2006; Safak and Cakti, 2009b). This is due to the fact that the roof record is simply twice the upgoing wave at the top story (i.e., the free-surface reflection because of the air above). In comparison, the signals deconvolved by the foundation- level records include both upgoing and downgoing waves, resulting in more complex impulse-response functions.

An example of this is given below by using data from the Factor Building at the University of California campus in Los Angeles (UCLA). With four channels at every floor, the 17-story, steel-frame Factor Building is one of the most densely instrumented buildings anywhere, providing continuous data from 72 channels at 500 Hz (Kohler et al., 2007). The building, and the recorded EW accelerations during the M=4.7 Yorba Linda earthquake of 3 September 2002, are shown in Figure 1. For a one-second long segment of the records, as depicted with a pink band in Figure 1, the calculated impulse response functions with respect to the foundation level and the roof level are given in Figures. 2a and 2b, respectively. As the figures show, the roof level impulse results in a purely downgoing wave, making it easier to calculate wave travel times.

The standard approach to calculate the wave travel times between two recording points have been either to use the time difference for a characteristic peak in the signal, or to determine the time lag where the cross-correlation of the signals has a maximum. These methods are acceptable for non-dispersive, non-attenuating media, where the waveforms do not change their shape as they travel. In structures, the waves attenuate due to damping. The attenuation changes the shape (i.e., the phase) of the waves. In other words, the phase shifts in two records are caused by the combined effects of wave travel times, plus the phase distortions due to damping (Safak and Cakti, 2009a). A rigorous theoretical analysis of wave dispersion in an attenuating medium can be found in Aki and Richards (1980).

It is possible to eliminate the phase shifts introduced by damping on the calculated wave travel times. This can be accomplished by calculating the time shifts from the envelopes of the signals, rather than the original signals. The envelope functions are calculated by taking the Hilbert transforms of the signals, and calculating the corresponding analytic functions. It can be shown that for narrow-band signals that are propagating in a frequency-dispersive medium, the envelope functions are not affected by the dispersive properties of the medium (Safak and Cakti, 2009a).

3 EXAMPLES

Using the methodology presented above, seismic wave velocities in three buildings are calculated from their earthquake-induced vibration records. The first building is the UCLA's Factor Building, described above. The Fourier amplitude spectra of the EW and NS accelerations from the M=4.7 Yorba Linda earthquake of 3 September 2002 are shown in Figure 3. From the figure, it is clear that the building has three dominant frequencies, and the corresponding mode shapes are three-directional (i.e., modes include two translations and a rotation, since the resonant peaks are the same in both directions). This observation is fairly common in tall buildings, because even the building is perfectly symmetric, the distribution of mass is not. In order to determine the dominant directions of the modes, we band-pass filtered the roof records around the resonant frequencies and plotted the corresponding particle displacements of the roof. Next, we calculated the envelopes of roof impulse-response functions and the wave velocities for each direction. The identified wave velocities are summarized in Table 1 below.

Table 1. Seismic wave velocities at Factor Building

Dominant Direction	**Frequency (Hz)**	**Travel time (s) for h=74.77 m**	**Velocity (m/s)**
East-West	0.40	0.52	145
North-South	0.50	0.42	180
Torsion	1.70	0.23	330

The second building is the 10-story, reinforced-concrete Millikan Library at the Caltech's campus in Pasadena, California, as shown in Figure 4a (Snieder and Safak, 2006; Clinton et al,. 2006). The building has three accelerometers at every floor and continuous recording. For the same Yorba Linda earthquake, the Fourier amplitude spectra of the recorded EW and NS accelerations are plotted in Figure 4b. The dominant frequencies can be seen clearly in both directions. The roof particle displacements, calculated by band-pass filtering the records around the resonant frequencies, show that the modes are mainly uni-directional with not much torsional component. Thus, from the envelopes of roof impulse-response functions for each direction, the wave velocities are calculated as shown in Table 2 below.

Table 2. Seismic wave velocities at Millikan Library

Dominant Direction	**Frequency (Hz)**	**Travel time (s) for h=39 m**	**Velocity (m/s)**
East-West	1.00	0.25	156
North-South	1.70	0.16	243

The third building is the 62-story, reinforced-concrete Sapphire Building in Istanbul (Figure 5a). With a height of 261 meters, it is currently the tallest building in the city. The building is being monitored continuously with 30 accelerometers, placed as shown in Figure 5a. The wave travel times are calculated by using the data from the M=6.2, Aegean Sea earthquake of 8 January 2013. The Fourier amplitude spectra of the records in Figure 5b shows the dominant modes of the building. In order to determine the directions of the modes, we again band-pass filtered the roof records around the resonant frequencies and plotted the corresponding particle displacements of the roof. The particle motions have shown that the building's motions are dominated by torsion. This is probably due to the fact that the building is much wider in the NS direction. For each horizontal direction and rotation, we calculated the wave velocities from the envelopes of roof impulse-response functions. The results are summarized in Table 3 below.

Table 3. Seismic wave velocities at Sapphire Building

Dominant Direction	**Frequency (Hz)**	**Travel time (s) for h=187 m**	**Velocity (m/s)**
East-West	1.90	0.52	145
North-South	0.40	0.42	197
Torsion	0.80	0.23	1247

4 CONCLUSIONS

The wave travel times in multi-story buildings give a critical insight into the behaviour of multi-story buildings, as well as superior tools for system identification and damage detection. Impulse-response functions provide much clearer signals than the original records for the calculation of wave travel times. The roof impulse-response functions are better than the commonly used foundation impulse-response functions, because the former one leads to a simple downgoing wave in multi-story buildings. The story damping alters the phase characteristics of the waves as they propagate up and down the building. This may create an error in the calculation of wave travel times. To eliminate the phase shifts due to damping, the wave travel times should be calculated from the envelope functions of the impulse response functions.

The calculated wave velocities from the earthquake records of three buildings indicate that the wave velocities are around 150 to 250 m/sec. for translational motions, and higher for torsional motions.

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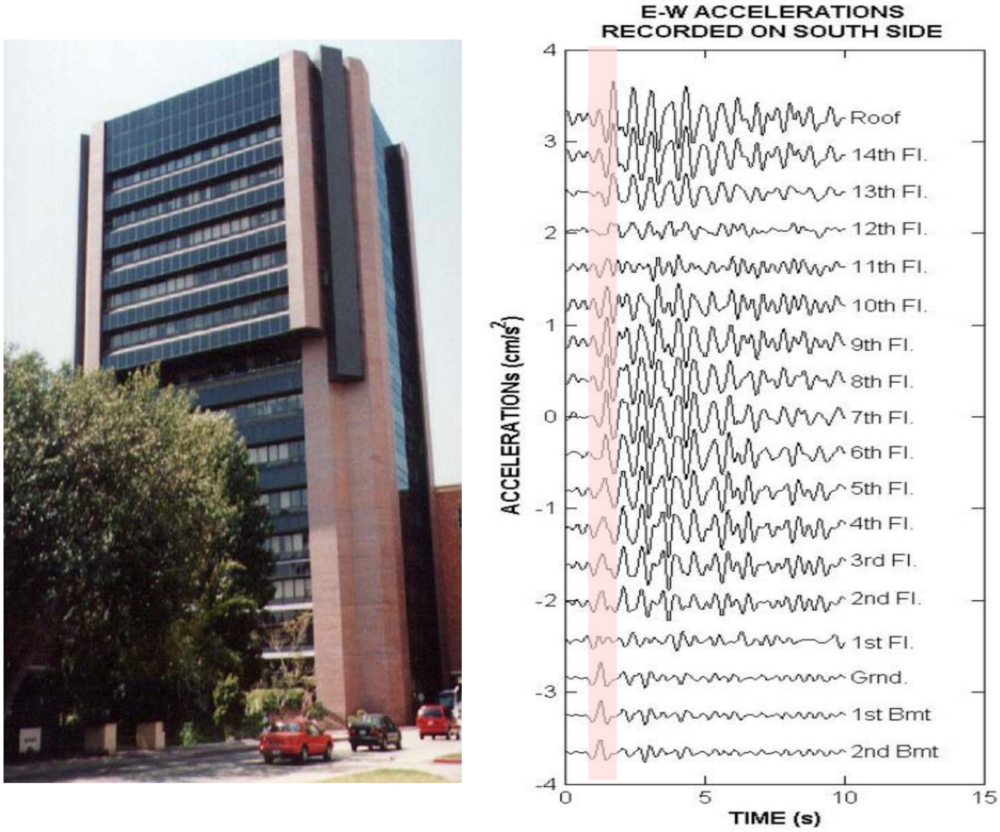

Figure 1. Factor Building and recorded acceleration from the M=4.7 Yorba Linda earthquake.

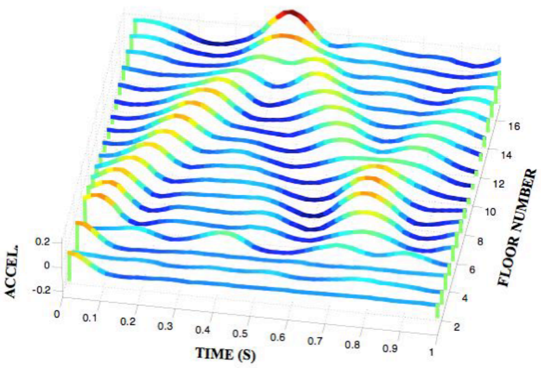

Figure 2a. Propagation of seismic waves, after deconvolution by the basement record, during a one-second interval in Factor Building.

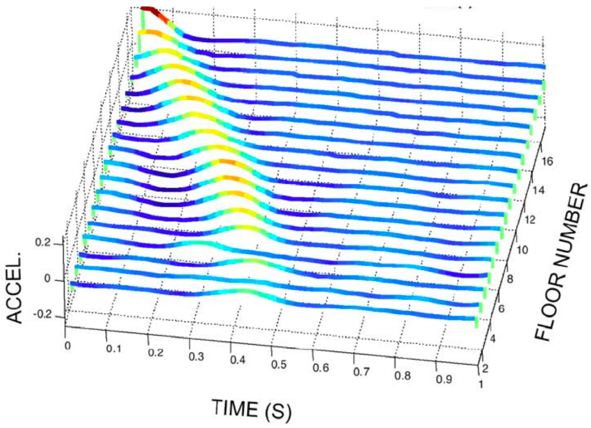

Figure 2b. Propagation of seismic waves, after deconvolution by the roof record, during a one-second interval in Factor Building.

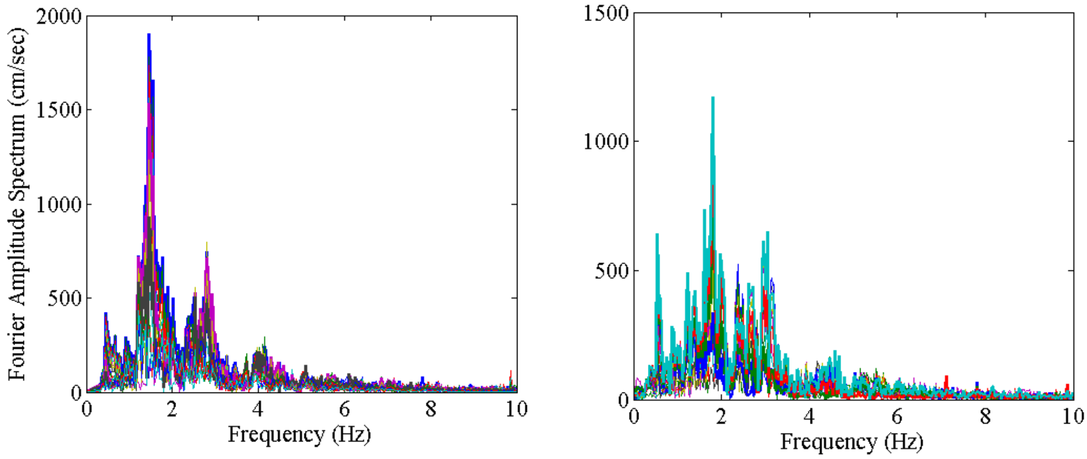

Figure 3. Fourier amplitude spectra of EW and NS accelerations at the Factor Building.

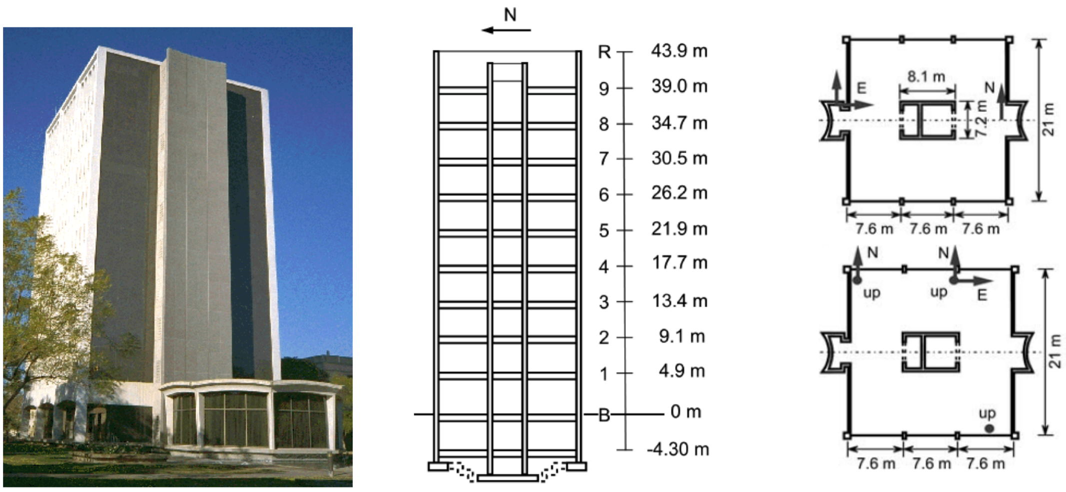

Figure 4a. Millikan Library, vertical cross-section, and typical floor and basement sensor locations.

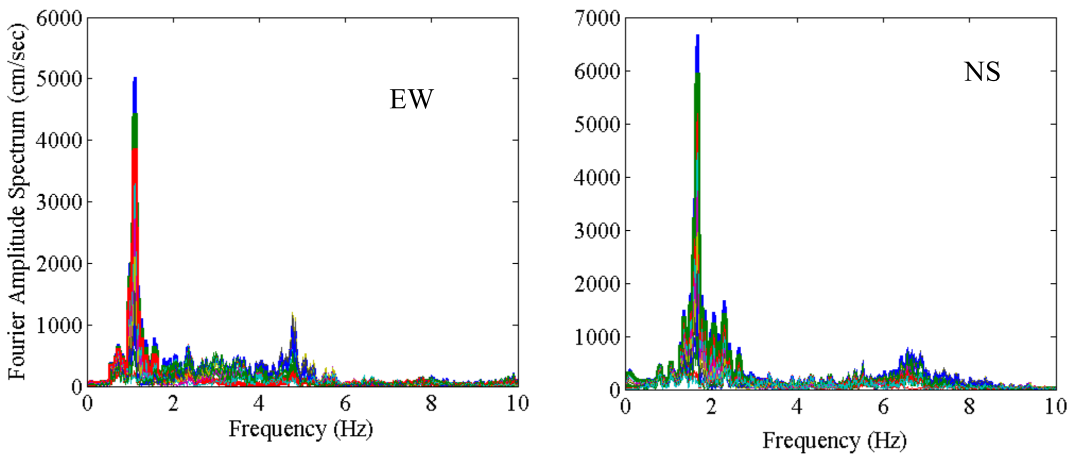

Figure 4b. Fourier amplitude spectra of EW and NS accelerations at Millikan Library.

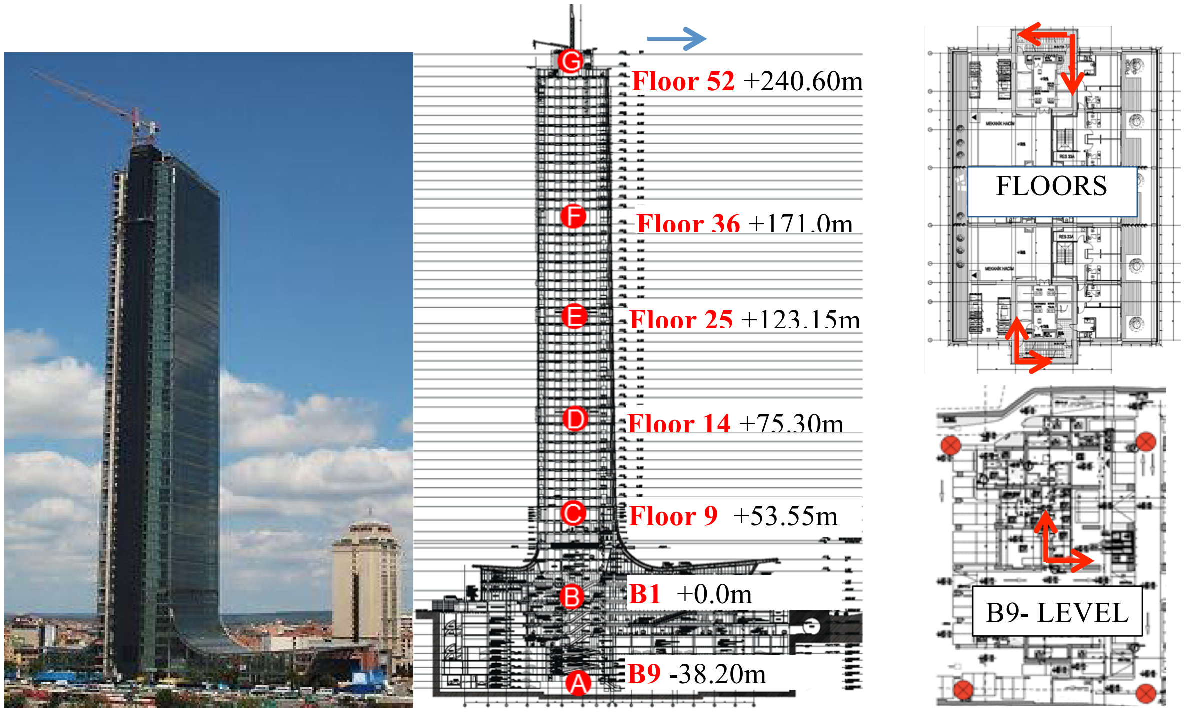

Figure 5a. Sapphire Building, vertical cross section, and typical floor and basement sensor locations.

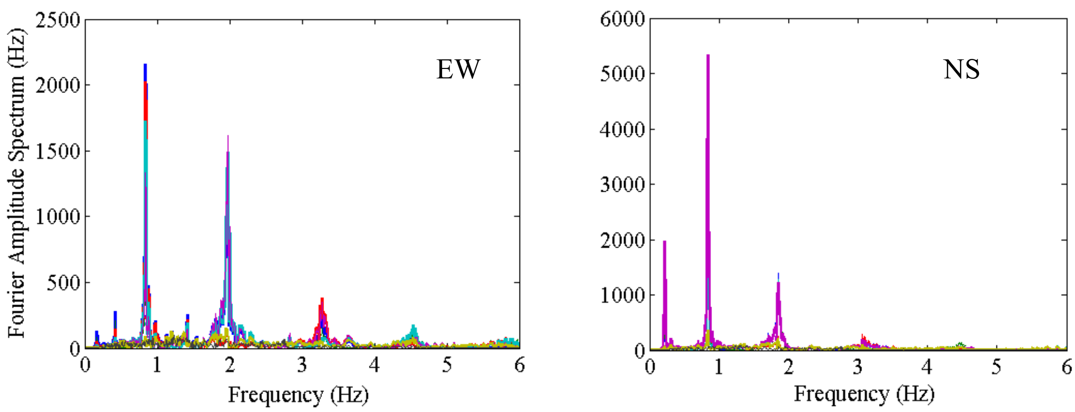

Figure 5b. Fourier amplitude spectra of EW and NS accelerations at Sapphire Building.