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Significant seismic behavior features of two tall buildings inferred from response records

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ABSTRACT

In this paper, recent studies of recorded responses of behavior and performances of two instrumented tall buildings subjected to long-period motions from events that originate at far distances (e.g. 100-800km) are presented. Significant results indicate that (a) computed average drift ratios are substantial (~0.5%), and (b) there is permanent shift of fundamental frequencies for a tall building which was hundreds of km away from the epicenter of a large (M9.0) earthquake. In addition, (c) there are significant local site effects and basin effects, some causing resonance of buildings, (d) beating effect are observed particularly in elongated responses whereby elongated responses can contribute to low-cycle fatigue, and significantly, and (e) identified critical viscous damping percentages are low (<3%). This is consistent with recent recommendations of the Los Angeles Tall Buildings Design Council (LATBDC) [1] and the Tall Buildings Initiative (TBI) of Pacific Earthquake Engineering Center (PEER)[2], and (f) beating effects are observed particularly in elongated responses whereby elongated responses can contribute to low-cycle fatigue.

Analyses of one tall building from Japan affected by the 11 March 2011 M9.0 Tohoku earthquake, and one in Los Angeles, California during the 17 January 1994 M6.7 Northridge earthquake are presented. A variety of methods including spectral analyses, system identification, and time-frequency functions are used to extract dynamic response characteristics (modal frequencies and damping), drift ratios, and effect of site conditions including basin effects.

In general, data-driven analyses show that, the two tall buildings (as well as many others not reported herein) exhibit (a) lower damping than those used in current design process analyses (<3%) and (b) a beating effect and significant basin effect.

These are significant: (1) Additional damping generating elements can be considered during design processes to decrease the prolonged and amplified responses. (2) Basin effects are not considered during design, it is important to at least consider looking into such effects as these can result in resonance and amplified responses as shown in recent studies.

Keywords: tall buildings, earthquake responses, frequencies, damping, drift ratio.

INTRODUCTION

Many cities around the world are expanding their inventories of tall buildings which are and/or may be affected by seismic waves that originate at near and far distant sources. In general, due to the density of tall buildings in most cities, very few seismic ground and structural response arrays are available in close proximity or within the tall buildings (e.g., at distances less than twice the height of the buildings). It is safe to state that, worldwide, a very small percentage (e.g. <1%) of tall buildings are instrumented. In addition, for one reason or another, a significant majority of recorded data sets from the limited number of instrumented buildings are not made public. Hence, there are a limited number of data sets of recorded earthquake responses from tall buildings for in-depth studies. Thus, the limited number of available data sets from instrumented tall buildings in US or elsewhere (e.g. Japan) are even more important for studying and understanding how the behavior and performances of long-period structures (e.g., tall buildings, long-span bridges) are characterized by predominantly long-period responses during medium-to-large events originating at far distances. It is documented that significant effects on the responses of tall buildings due to long-period motions from events that originate at far distances have been observed and/or recorded (e.g. in Japan, United States, Turkey, Dubai and Abu Dhabi at distances of 100-800 km from epicenters) [4,11-14]. This paper is a summary derived from recent studies of available recorded seismic responses of, due to space limitations, only two instrumented tall buildings.

A variety of methods including spectral analyses, system identification, time-frequency functions are used to extract dynamic response characteristics (modal frequencies and damping), drift ratios, effect of site conditions including basin effects.

Many of the tall buildings (i.e. >50 stories) are built on geological basins (e.g., downtown Los Angeles or those in Japan). As such, local site conditions with low shear wave velocities and depths significantly shallower than basins tend to not adversely affect the responses of tall buildings, but, basins (particularly, deep basins) can (e.g., the Los Angeles Basin) [3]. Local site effects and basin effects can and do cause resonance. Generally, basin effects are not considered during design, it is important to at least consider such effects as these can result in resonance and amplified responses as shown in recent studies.

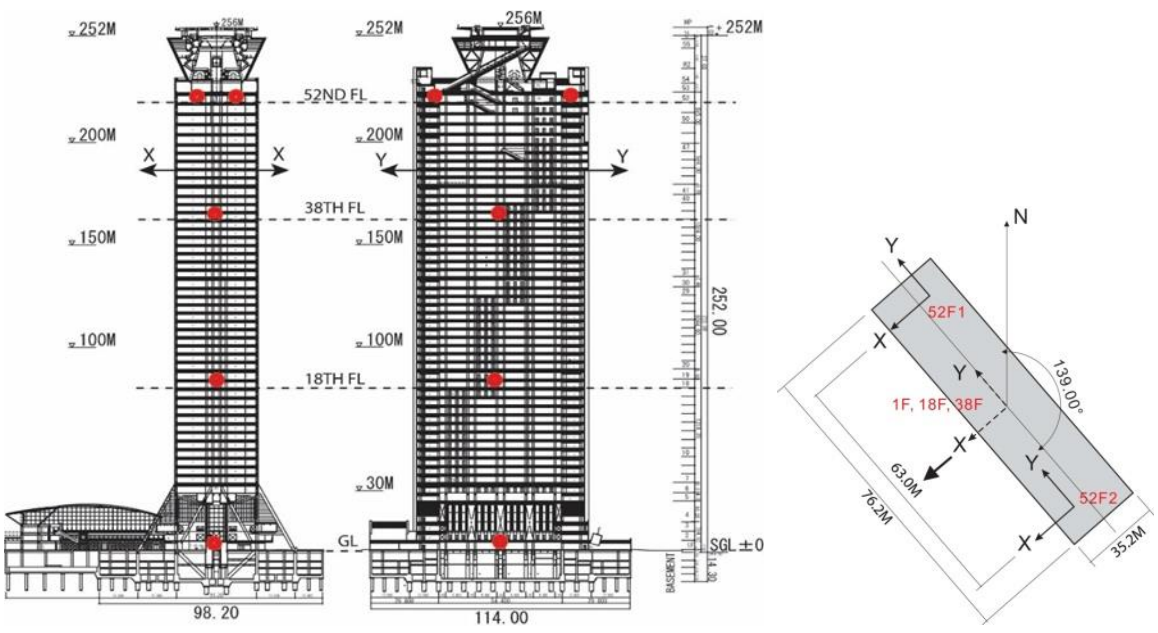
Another significant observation is that in general, identified critical viscous damping percentages are low (<3%) and consistent with recent recommendations of the Los Angeles Tall Buildings Design Council (LATBDC) [1] and the Tall Buildings Initiative (TBI) of Pacific Earthquake Engineering Center (PEER) [2]. Such information can help design processes (e.g. additional damping generating elements can be considered to decrease the prolonged and amplified responses).

In addition, it is possible to estimate with considerable accuracy (a) data-based substantial average drift ratios computed (~0.5%) and permanent shift of fundamental frequencies for a tall building which was hundreds of km away from epicenter of a large earthquake, and (b) beating effect are observed particularly in elongated responses whereby elongated responses can contribute to low-cycle fatigue.

In general, data-driven analyses show that, the two tall buildings (as well as many others) exhibit (a) lower damping than those used in current design process analyses (<3%), beating effect and significant basin effect. The two cases are: one tall building from Japan affected during 11 March 2011 M9.0 Tohoku earthquake, and, one in Los Angeles, California during the (a) the 1992 M7.3 Landers earthquake at an epicentral distance of 169 km and (b) the 1994 M6.7 Northridge earthquake with an epicentral distance of 31 km (www.strongmotioncenter.org, last accessed November 29, 2018) and five other smaller events [3].

CASE 1: 55-STORY BUILDING IN OSAKA, JAPAN

The 55-story steel-framed building in Osaka, Japan was shaken by the far-distant Tohoku earthquake of March 11, 2011 that originated at ~770 km from the building. The earthquake occurred at 05:46:23 UTC (local time 14:46:23) offshore from the east coast of Honshu, Japan (38.322°N, 142.369°E) at 32 km depth; http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/, last accessed July 15, 2011). The earthquake caused a major disaster in Japan, generated one of the most significant tsunamis which left its mark by (a) destroying the four-unit Fukushima nuclear power plant and (b) causing the largest percentage of the 15,776 fatalities associated with this event. Furthermore, it caused widespread destruction and damage of major port and other facilities on a wide portion of north-east coast of main island of Honshu (Japan). Detailed discussion of the building, data and analyses are provided in [4]. Figure 1 shows vertical sections and locations of tri-axial accelerometers as well as plan views, orientation of the building and location of accelerometers at the 52nd floor.



(a) (b)

Figure 1. (a) Vertical sections of the building showing major dimensions and locations of tri-axial accelerometers on the 52n, 38th, 18th and ground level (1st Floor). (b) X and Y denote principal axes of the building and orientations of the accelerometers (from Çelebi et al, 2012[4]).

The building was founded at a site with a computed site frequency (period) of 0.13-0.17 Hz (5.88-7.69 s) [Figure 2] [4]. The parameters used in computing the site transfer functions are the (depth vs. Vs) Profiles A, B, and C shown in Figure 2a. Profile

A is an approximation based on the geotechnical data for free-field KIK-NET[1] station OSKH02 that is near (~2.5km) the building. In this profile, the upper and softer layers have been ignored. By way of comparison with the transfer functions computed for Profiles B and C, it is concluded that the upper layers do not significantly alter the computed fundamental frequency of the site of this building. Q values used in calculating the transfer functions range between 25-60 for shear wave velocities between 200-600 m/s – having been approximately interpolated to vary linearly within these bounds. Figure 2b shows the transfer functions that depict the site fundamental frequency in the range of 0.13-0.17 Hz due to the dominant characteristics of layers 3 and 4 (typically of the area of the site of the building and KIKNET OSKH02 strong-motion station as described in Figure 2a and b). Site transfer functions are computed using software developed by C. Mueller (pers. comm., 1997), which is based on Haskell's shear wave propagation method [5.6]. In this method, the transfer function is computed using linear propagation of vertically incident SH waves, and has, as input, data related to the layered media (number of layers, depth of each layer, corresponding Vs, damping, and density), desired depth of computation of transfer function, computation frequency (df), half space substratum shear wave velocity and density. Damping (ξ) in the software is introduced via the quality factor (Q), a term used by geophysicists that is related to damping by $\xi = 1/(2Q)$.

The building was subjected to an input motion at ground level with peak accelerations of ~3% g during the Tohoku earthquake. The building exhibited fundamental frequencies (periods) of 0.152Hz (6.58 s) in the X-direction and 0.145 Hz (6.90) in the Y-direction as seen in the ratios of amplitude spectra of accelerations at the 52nd, 38th and 18th floors with respect to that at the 1st floor (Figure 2c) . Second and third modal frequencies are also clear seen in the spectral ratio plots. Such close frequencies of site and building are clear confirmation of resonance that led to prolonged responses (~1000s recorded) and long duration high amplitude shaking as exhibited in Figure 3 that shows system identification (SID) analysis results applied to the mainshock records. In SID analysis, a model is estimated using appropriate pairs of recorded acceleration responses as single-input, single-output (SISO). The auto-regressive extra input (ARX) model based on least squares method is used in this analysis. The reader is referred to Ljung (1987) [7] and MATLAB Users Guide 1988 and newer versions [8] for detailed formulations of the ARX and other SID methods. Some of the key frequencies for two modes in the X-direction and three modes in the Y-direction, as well as associated modal damping percentages (x), are identified by the SISO SID method. First-floor accelerations are used as input and 52nd-floor accelerations as output. The recorded and computed accelerations at the 52nd floor and their corresponding amplitude spectra match well. The damping percentages extracted from SID analyses are quite low (1.2–1.6% for the fundamental modes).

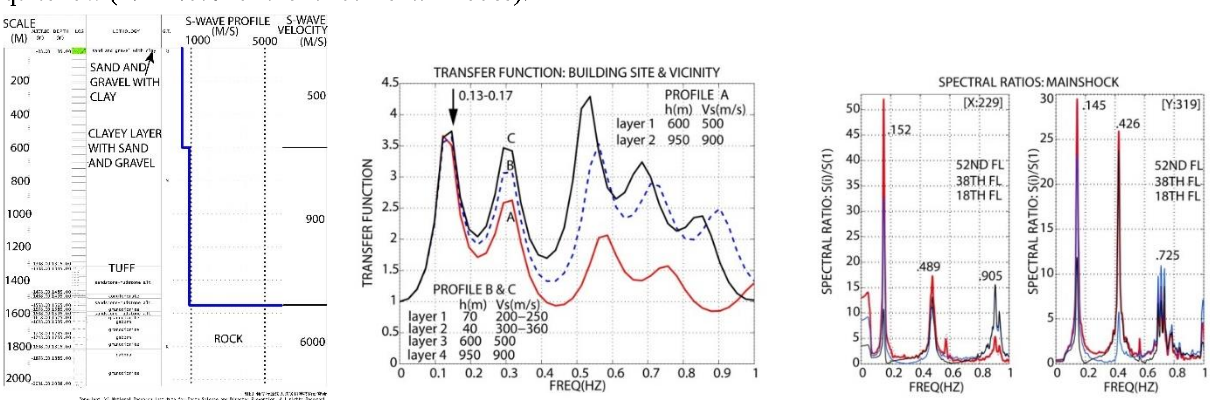


Figure 2. (a) Profile near the OSKH02 strong-motion station near the building (www.kik.bosai.go.jp/, last accessed 09/16/2011), (b) Transfer functions computed for Profile A and Profiles B and C below the building. The depth of the softer upper two layers (to about 1500 m depth) below the building do not significantly change the position of the peaks in the transfer function, particularly for the fundamental mode of the site. (c) Spectral Ratios of amplitude spectra of accelerations at 52nd floor, 38th floor and 18th floor with respect to that at first floor. Note that 3rd mode in X-direction is identified from the ratios. Different colors (red, black and blue) are used only to distinguish lines corresponding to different floors in descending order.

[1] KNET and KIKNET are free-field networks (www.k-net.bosai.go.jp and www.kik.bosai.go.jp/)

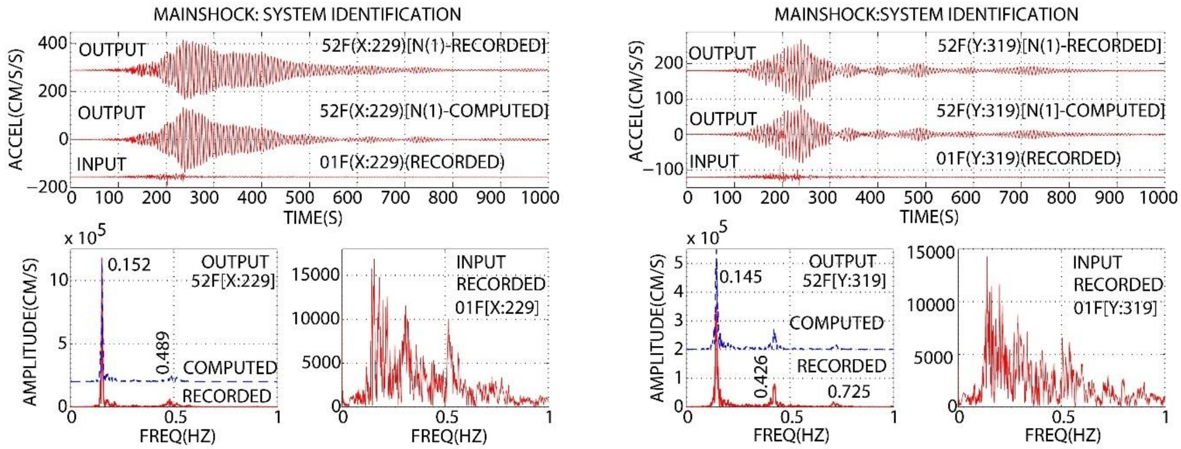


Figure 3. System identification applied to mainshock records. First-floor accelerations are used asinput and 52nd-floor accelerations as output. The computed 52nd-floor accelerations match well those that were recorded.

The average drift ratios (Figure 4) computed from relative displacements between many floors indicate that maximum average drift ratios experienced during the mainshock were between 0.5-1.0 % for the X-direction and 0.2-0.4% for the Y-direction. These average drift ratios are less than the maximum 1% limit usually used in Japan for collapse protection level motions (level 2 used for buildings 60 m or taller (The Building Center of Japan, 2001a and 2001b) [9,10]. However, average drift ratios are much larger than expected for an input motion with a small peak acceleration in the order of only 3% g. In the United States, the comparative maximum drift ratio for tall buildings for Risk Category 1 or 2 is 2% (Table 12.12, ASCE7-10, 2007).

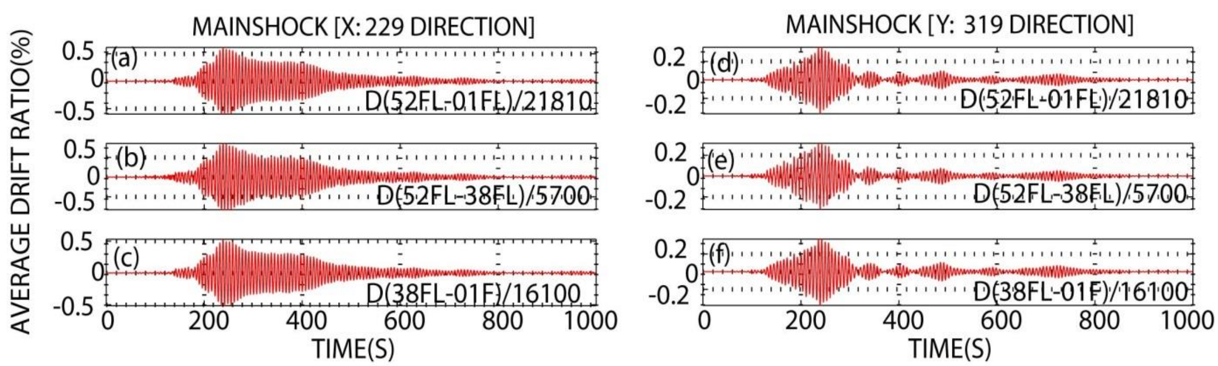


Figure 4. Average drift ratios computed from displacements between 52nd, 38th and 1st floors. In each frame, the numbers in denominators are distances (in cm) between the designated floors.

In summary, during the Tohoku event, the building was subjected to ground level input acceleration of 3% of g. But the deformations were large enough (to realize sizeable average drift ratios) that the building lost its functionality for several weeks. Elevator cables were entangled. This case, along with others, deserves further studies as to how tall buildings would respond if the ground input accelerations were 20-30% of g with similar low frequency content that could be caused by a closer earthquake (e.g. ~100 km or less) [e.g. similar to 1923 Kanto and 1995 Kobe earthquakes]. It is important to note that same elevator cable tangling problems also occurred in several tall buildings in the Shinjuku area of Tokyo, Japan [11,12].

Furthermore, the actual drift ratios computed from relative displacements divided by story heights between some of the pairs of two consecutive floors are certainly to be larger than the average drift ratios computed from differential displacements between several floors, due to sparse deployments of instruments, as in this case. The average is therefore the lower bound of the maxima. These results are summarized in Table 1 and compared to results of other cases that follow.

CASE 2: 52-STORY BUILDING IN LOS ANGELES, CA

The 218m tall, 52-story above and 5-story below ground level building known as CSMIP station 24602 located in downtown Los Angeles, CA within Los Angeles basin was instrumented by California Geological Survey (CGS) with 20 accelerometers distributed throughout the building to acquire mainly translational and torsional responses as shown in Figure 5. The base dimensions of the steel-framed building are 83.5m x 80.2m and sits on concrete spread footings that are 2.7-3.3 m thick. All floors of the tower structure as well as those at the imprint of the tower at the basement (Level E) are symmetrical in both directions (e.g., from 1st floor to 45th floor, the in-plan overall dimensions are 47.5m x 47.5m; then reducing at the roof to basically the core area. The tower structure comprises concentrically braced steel frame at the core with outrigger moment frames in both directions. The core area of the building is 21.3m x 17.4m and extends from the 1st sub-basement (Figure 5) all the way to the roof [3]. The vertical load carrying system comprise 7.6–17.8 cm concrete slabs on steel deck supported by steel frames (from http://www.stronmotioncenter.org/, last accessed December 18, 2018).

The building array recorded at least 7 earthquakes. Two of the largest responses of the building were recorded during (a) the 1992 M7.3 Landers earthquake at an epicentral distance of 169 km and (b) the 1994 M6.7 Northridge earthquake with an epicentral distance of 31 km (www.strongmotioncenter.org, last accessed November 29, 2018). Largest horizontal peak accelerations at ground level were 0.05g and 0.15g, respectively, and at top floor, 0.17g and 0.40g, respectively. Similarly, largest horizontal peak displacements at ground level were 9.81 cm and 3.10cm, respectively, and at top floor, 40.8 cm and 21.9 cm, respectively.

The site geology of the building is defined as alluvium over sedimentary rock (www.strongmotioncenter.org). Detailed borehole data at the top 100-200m is not available. Nonetheless, in order to compute site transfer functions for low frequency bandwidth (<1Hz), we used the Southern California Earthquake Center (SCEC) seismic velocity model (SCEC CVM-H version 5.3) for Los Angeles basin derived from sonic logs and industry reflection data [13]. Figure 6a shows the depth - shear wave velocity (Vs) profile representative at the CSMIP stations 24602. Computed transfer function using the approximated Vs-depth step-profile C is shown in Figure 6b and demonstrates and infers significant amplification of motions at particularly low frequencies <0.5 Hz. Minor changes in approximated step-profile do not affect the inference that the fundamental site frequency is low (~0.12-0.13 Hz). Process to compute the transfer function is same as in Case 1

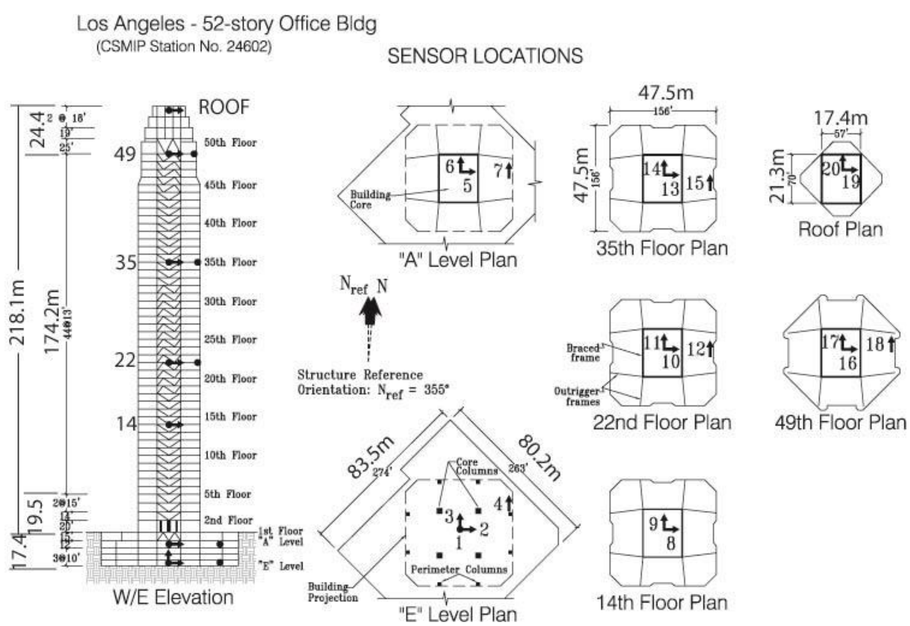


Figure 5. Schematic of vertical section and plan views as well as accelerometer deployment locations (from http://www.stronmotioncenter.org/, last accessed November 29, 2018)

Average drift ratios can be computed using displacements computed from double-integrated accelerations from any two instrumented floors. Seven instrumented floors have two parallel accelerometers that allow computation of torsional behavior of the building. There is only a single vertical accelerometer at the center of the core area (Figure 5). This prohibits direct computation of rocking motions of the foundation and the superstructure.

Equiscaled plots of basement and top floor accelerations (Figure 7) and displacements (Figure 8) in the NS and EW directions are provided for 7 events. The largest accelerations are recorded during the Northridge earthquake, but largest displacements were recorded during the Landers events.

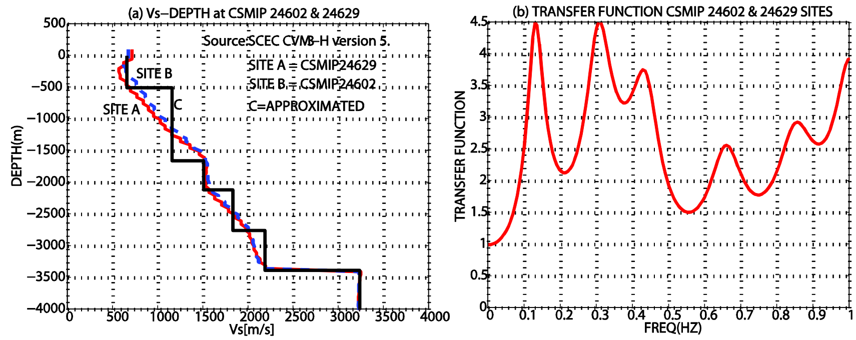


Figure 6. (a) Vs-depth profile [from SCEC CVM-H version 5.3] for downtown Los Angeles [Site A (red line) and Site B (dashed black line)] represent sites of tall buildings with CSMIP station numbers 24602. The profile C (step-line) represents approximated profile for both building sites. Alternate variations of approximations of step-profile should not alter the results significantly. (b) Transfer function is computed using approximated step profile C.

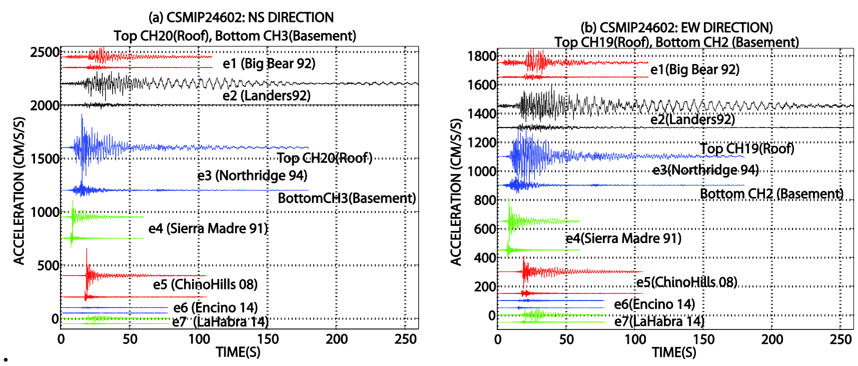


Figure 7. Equiscaled accelerations at basement and roof of the building for seven events: (a) NS, (b) EW direction.

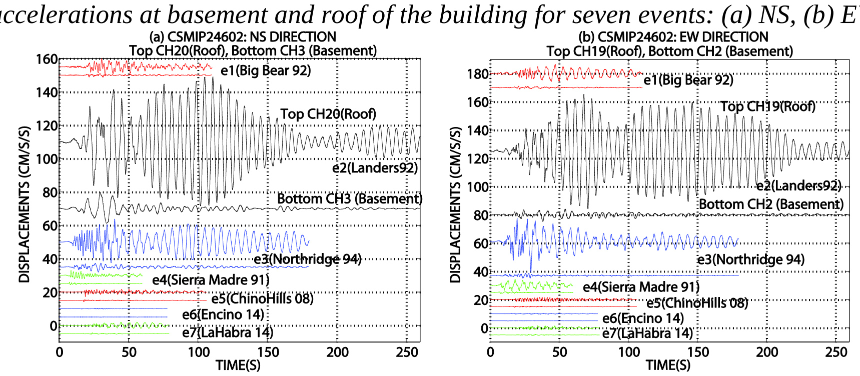


Figure 8. Equiscaled displacements at basement and roof of the building for seven events: (a) NS, (b) EW direction.

Figure 9 shows the transfer functions for all seven events and depicts repeatability of the significant frequencies regardless of amplitude of input motions. In other words, there is no amplitude dependency.

Figure 10 shows for the first three modes in the NS, EW and torsional directions. In each frame, extracted modal frequencies and damping percentages extracted with N4Sid system identification method within Matlab [8] are inserted. These results are also shown in Table 1.

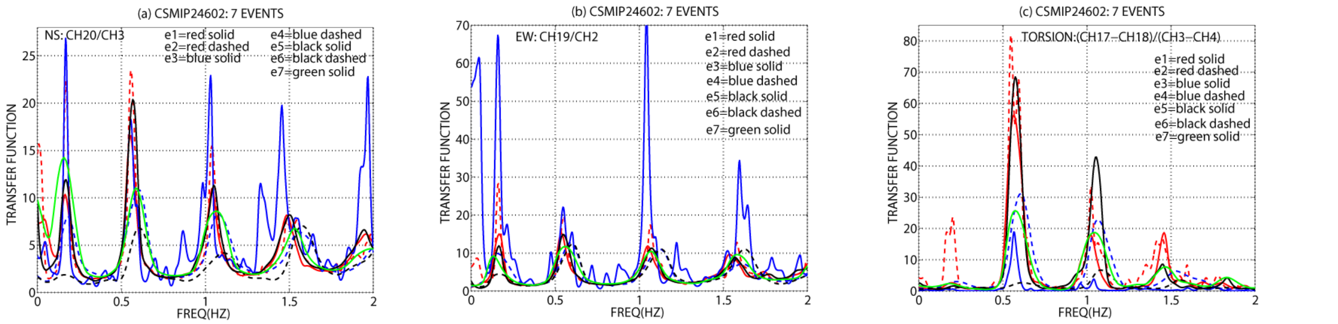


Figure 9. Transfer functions computed from amplitude spectra of accelerations at the roof and basement for 0-2 Hz bandwidth respectively in (a) and (b) NS direction (CH20/CH3), (c) and (d) EW direction (CH19/CH2, respectively and (c)torsion ((CH17-Ch18)/(CH3-CH4)).

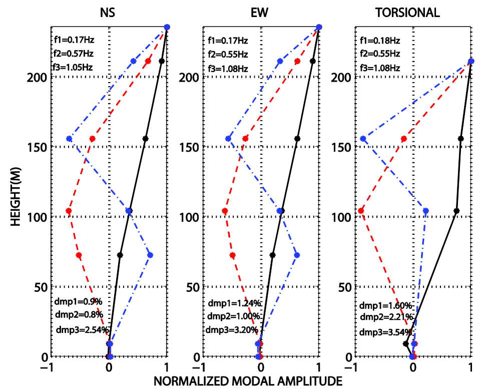


Figure 10. Three for each of NS, EW and torsional modes using Landers earthquake accelerations. Identified frequencies and critical damping percentages (abbreviated as dmp) are also shown.

SUMMARY OF RESULTS AND CONCLUSIONS

The results of analyses of two tall (>50 stories) buildings subjected to far-distant earthquakes are studied. Ground level and top instrumented level (e.g. roof) maximum peak accelerations, identified site periods/frequencies, fundamental periods (frequencies) and critical damping percentages of the buildings, computed maximunm drift ratios are summarized.

Table 1. For the two building cases and the events considered, maximum ground level and top level peak accelerations, site periods (Ts),frequencies (fs), building periods(Tb), frequencies (fb), building critical damping percentages and drift ratios.

	Max. Peak Acc (g)		Ts(s)/fs (Hz)	Tb(s)/fb(Hz)	Damping ξ (%)	Comments
	Gr. Level	Building Top				
Case 1 Osaka(Japan) 55-story (steel) 2011 M9 Tohoku Eq. (D:epicentral distance 770km)	0.03	0.13	5.9-7.7s 0.13–.17Hz	Translation: 5.6-5.9s 0.17-0.18 Hz. Torsion:3.7s 0.27 Hz	~2.0	Long record (~1000s) (continuous recording) Beating occurs. Max drift ratio: 0.5% Instrumented by Building Research Institute (Japan)
Case 2 (a)1992 M7.3 Landers EQ D:169km. (b)1994 M6.7 Northridge EQ D: 31 km. 55-story (steel) with concrete core	.05 .15	.17 .41	7.7-8.3 0.12-0.13	5.88/.17 5.88/.17	~1.7 ~1.7	(a)260s record (triggered) (b)170 s record. Instrumented by CSMIP of CGS Max drift ratio: 0.2%

As noted in Table 1, for Case 1, fundamental frequencies of the site and the building are close enough to cause very long response (~1000s). In addition, low damping percentages cause a beating effect as observed in Figures 3 and 4. For each case building, it is shown in Figures 2 (Case 1) and 6 (Case 2) that deep basin velocity structure in close proximity to the building yields computed site frequency that is close to the building considered. This and other studies show that in urban environment that are founded on basins, such effects on tall building responsees should be considered. Critical damping percentages are low (<2%) as also indicated in recent recommendations [1,2] and should be considered in future designs. Low damping percentages (<2%) has implications. A building usually designed for 5% damped design response spectra means it is actually prone to higher level of shaking. For new designs, 2% damped design response spectrum means higher demand in the new design Building in Case 1 has a computed drift ratio of ~0.5 % which is the starting threshold drift ratio of damage according to the Japanese code [9,10]. Beating effects are not considered during desig/analysis processes> However, it is recommended that expectedbehavioral parameters extracted during design/analysis processes could be used to look into it, essentially find ways to avert it.

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