Variability of Soil-Structure System Frequencies during Strong Earthquake Shaking for a Group of Buildings in Los Angeles Estimated from Strong Motion Records

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Most seismic building codes estimate the design forces in structures based on the seismic coefficient $C(T)$, where T is the "fundamental vibration period of the building." For structures on flexible soil, T is the first period of the soil-structure system, which depends on the structure itself, but also on the foundation system, surrounding soil, and contact conditions between the foundation and the soil. This paper presents results of instantaneous system frequency as function of the level of response for seven buildings in the Los Angeles area that have recorded several earthquakes—1994 Northridge earthquake (M_S= 6.7) and aftershocks, and 1971 San Fernando earthquake (M_S = 6.6). In general, the observed trend is decrease of system frequency during 1994 Northridge and 1971 San Fernando earthquakes, which caused the largest levels of response, and "recovery" during the aftershocks. For one of the buildings, a significant change (30% reduction) that occurred during the San Fernando earthquake appears to have been permanent. For most buildings, the frequency changed up to 20%, and for two buildings, the change was about 30%. Understanding and estimation of the range of these variations during strong earthquake shaking is needed for further refinement of the existing and development of new design code procedures.

INTRODUCTION

The Earthquake Resistant Design Codes have evolved based on principles and procedures derived from the Response Spectrum Method (Biot, 1942). In most codes, the design shear forces are quantified using the seismic coefficient $C(T)$, where T is the "fundamental vibration period of the building," and various scaling factors that depend on the seismic zone, type of structure, soil site conditions, importance of the structure etc. As T

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cannot be measured before the structure is completed, most codes provide simplified empirical formulae to estimate it, based on past experience and recorded response of existing buildings, which is extremely limited (both in quantity and in quality). The problem of estimation of T has been considered by many investigators, based on theory (Biot, 1942), small amplitude ambient and forced vibration tests of full-scale structures (Carder, 1936), and recorded earthquake response in structures (Li and Mau, 1979). Unfortunately, the number of well-documented instrumented buildings that have recorded at least one earthquake is typically less than 100. When the recorded data is grouped by structural systems (moment resistant frame, shear wall etc.) and building materials (reinforced concrete, steal, etc.), the number of records per group becomes too small to control the accuracy of regression analyses, or to separate "good" from "bad" empirical models (Goel and Chopra, 1997; Stewart et al., 1999). This problem is further complicated by the nonlinearity of the foundation soil even for very small strains (Hudson, 1970; Luco et al., 1987). During strong earthquake shaking, the apparent period of the soil-foundation-structure system, $\tilde{T}$, can lengthen significantly (Udwadia and Trifunac, 1974), and it may or may not return to its pre earthquake value. This period lengthening can reach and exceed a factor of two, which adds to the scatter in the empirical regression analyses, and to the ambiguity in choosing a representative T for evaluation of $C(T)$ (Trifunac, 1999; 2000).

For further improvements and developments of the building codes, it is essential to understand the amplitude dependent period lengthening (as function of the level of response of the structure and strain in the soil), and estimate its range, which can be best accomplished by analysis of building periods from multiple earthquake recordings in buildings—of both small and large levels of shaking. The first step towards this goal is to augment the database of multiple earthquake records in buildings, which is very limited, because most buildings records have been recorded on film, and, mostly those with larger amplitudes have been digitized and released. Data of small amplitude response will be generated fast from instrumented buildings with a digital recording system, but it may take many years for these systems to record larger amplitude response. Hence, the use of small amplitude data from newly instrumented buildings is quite limited. Data of smaller amplitude response has been recorded digitally in some buildings complementing larger amplitude response data recorded previously by an analog recording system. In these cases, smaller amplitude analog recordings of past earthquakes are also very valuable—for understanding of the variations of building periods with time, which may be temporary or permanent. In the Los Angeles metropolitan area, there have been many small earthquakes and aftershocks of larger earthquakes that have been recorded in buildings and archived but not digitized and released.

An effort was initiated at the University of Southern California to augment the database of building periods estimated from multiple earthquake recordings, with the immediate objective to trace their variations with time and as a function of the level of response and understand their nature, and with the ultimate objective—to improve the code formulae for estimation of building periods. This paper presents a summary of results of a one year effort, which consisted of digitization and processing of building records from the archives of the U.S. Geological Survey (USGS), gathering of already processed data for the same buildings, and analysis of the building period. Results are shown of the variation of the building apparent frequency (i.e. building-foundation-soil system frequency) as a function of the level of response for seven buildings in the Los Angeles area, which recorded the Northridge earthquake and some of its aftershocks. The records in these seven buildings that have been digitized and processed for this project are those of aftershocks of the 1994 Northridge earthquake as well as those of the main event that have not been digitized previously or have been redigitized for this project. These buildings have been instrumented either by USGS or by the building owner. Detailed results and a catalog of the processed data can be found in Todorovska et al. (2004) and the processed data is available from the USC Strong Motion Research Group web site at www.usc.edu/dept/civil_eng/earthquake_eng/.

STRONG MOTION DATA

Figure 1 shows a map of the Los Angeles metropolitan area and locations of buildings that were instrumented at the time of the 1994 Northridge earthquake, either by the USGS and partner organizations, or by the building owners (as required by the Los Angeles and state building codes), for which the data is archived by USGS. The latter are often referred to as "code" buildings. All of these buildings will be referred to as "USGS instrumented buildings" and identified by their station number.

The sensors in these buildings have been either three-component SMA-1 or multi-channel CR-1 accelerographs, both recording on film. Many of the "code" buildings (about 30 buildings total) have only one instrument, at the roof, due to a change in the original ordinance for Los Angeles, such that only one instrument at the roof was required, which lead to removal or neglect of the instruments at the ground floor and intermediate levels.

This unfortunate fact limits considerably the use of these records, especially for analyses of soil-structure interaction. The roof records can be used to estimate the apparent building period, by approximating the relative roof motion (with respect to the base) by the absolute roof motion.

After the Northridge earthquake, the analog strong motion instrumentation is being gradually replaced by digital, and additional buildings are being instrumented. For some of these buildings, data of smaller local earthquakes and distant larger earthquakes has been recorded and released. The recorded level of response for these events, however, is much smaller than that for the Northridge earthquake. Figure 1 also shows the epicenters of earthquakes that have been recorded in these buildings. The Northridge main event was followed by a large number of aftershocks (9 of these had M > 5, and 55 had M > 4). Many of these larger magnitude aftershocks, as well as smaller magnitude but closer aftershocks, were recorded in the instrumented buildings. The aftershock of March 20, 1994 (M = 5.2; "aftershock 392") was the one recorded by the largest number of (ground motion) stations (Todorovska et al., 1999). The Northridge sequence was recorded on multiple films, archived separately. The largest number of recorded aftershocks known to the authors of this paper is 86—at station USGS #5455, and about 60 at several other stations. Unfortunately, it turned out that the number of aftershock records useable for estimation of the building apparent frequency was small—up to 11.

The usability of an aftershock record for estimation of the first system frequency depends not only on its amplitudes, but also on the shape of its Fourier spectrum, and on the building itself, i.e. on how high is its first system frequency. In principle, a building record is useable if the first system frequency is within the "useable" frequency band of the signal, which is the band where the Fourier spectrum of the signal is above that of the recording and digitization noise, and below the Nyquist frequency. While the high-frequency limit of this band is controlled by the Nyquist frequency, the low-frequency limit is controlled by the noise spectrum, which increases with decreasing frequency and is due to a "wavy" baseline. These limits are determined automatically by standard software for accelerogram data processing (Lee and Trifunac, 1990), which then band-pass filters the digitized accelerogram. In this study, if the first system frequency was too close to, or was suspected to be below the low-frequency cut-off of the data processing software, the record was discarded. A record was also discarded if the system frequency could not be estimated reliably for some other reason. This selection process eliminated many aftershock records. In summary, small aftershock records are more likely to be useable for the shorter buildings, than for the taller ones. Also, for the taller buildings, the records from large but distant earthquakes (like 1992 Landers) are more likely to be useable than those from small nearby events with similar peak acceleration, because the former have more energy in the shorter frequency part of the spectrum and will excite more the first mode, leading to larger signal to noise ratio at low frequencies. Therefore, it is important to digitize and add to the analysis "good" records of the 1992 Landers and 1999 Hector Mine earthquakes.

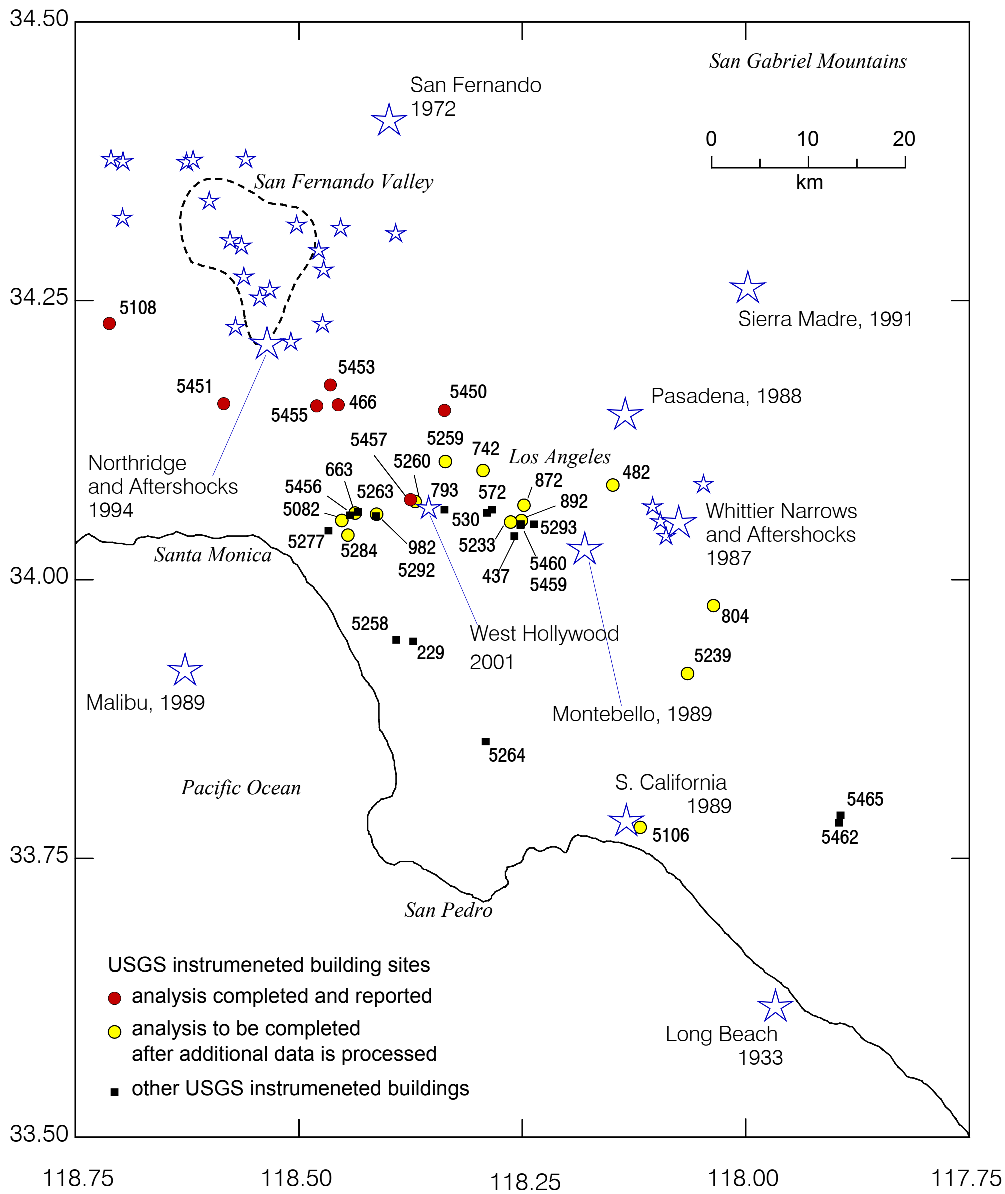


Figure 1. Locations of instrumented buildings in the Los Angeles metropolitan area at the time of the 1994 Northridge earthquake, for which the data is archived by USGS The building sites are identified by their USGS station number.

This paper shows results for 7 buildings for which there were three or more adequate records (of the Northridge sequence or of the 1971 San Fernando earthquake) to estimate the apparent building frequency, and for which there are no other "good" records to add to the analysis, so that the analysis is "complete." These stations are marked by solid dark dots in Fig. 1. For the 15 stations marked by solid light dots, there are some adequate records of the Northridge sequence, as well as other "good" records that have not yet been digitized (e.g. of the Landers and/or of the Whittier-Narrows earthquake). For the other buildings, marked in Fig. 1 by solid rectangles, at this time, only one or maybe two "adequate" records for such analysis are known to exist, and are not included in this analysis.

Table 1 shows a list of earthquakes recorded in "USGS" instrumented buildings. For the Northridge sequence, only the aftershocks are shown for which there is an adequate record that has been used in the analysis presented in this paper. For most of the buildings, the contributing aftershocks have not been identified, but are assigned negative aftershock number, the absolute value of which increases chronologically, and is related to the order of the record on the film (e.g., aftershock –3 means that this was the third aftershock record on the film following the main event, and aftershock –105 means that this was the fifth record on the second role of film, which did not contain the main event). This table also lists the 2001 West Hollywood earthquake (M = 4.2), which occurred close to many of the instrumented buildings (see Fig. 1), and which should have been recorded by these buildings. Table 2 shows a list of buildings included in the analysis in this paper. The processed data (uncorrected acceleration, corrected acceleration, velocity and displacement, and Fourier and response spectra) is available free of charge from the USC Strong Motion Research Group web site at www.usc.edu/dept/civil_eng/earthquake_eng/.

METHODOLOGY

The instantaneous frequency was estimated by two methods: (a) zero-crossing analysis, and (b) from the ridge of the Gabor transform, both applied to the relative roof displacement when there was a record at the base, or to the absolute displacement when only the roof response was recorded, and considered as an approximation of the relative displacement in the neighborhood of the first system frequency. Both methods were applied to the filtered displacement, such that it contained only motion in the neighborhood of the first system frequency, and resembled a chirp signal. The zero-crossing analysis consists of measuring

Table 1. Earthquakes recorded by USGS instrumented buildings (1971 to 2001).

Event	Date	Time	M_L	Latitude	Longitude	Depth (km)
San Fernando	02/09/1971	06:00	6.6	34 24 42N	118 24 00W	--
Whittier-Narrows	10/01/1987	14:42	5.9	34 03 10N	118 04 34W	14.5
Whittier-Narrows, 12th Aft.	10/04/1987	10:59	5.3	34 04 01N	118 06 19W	13.0
Whittier-Narrows, 13th Aft.	02/03/1988	15:25	4.7	34 05 13N	118 02 52W	16.7
Pasadena	12/03/1988	11:38	4.9	34 08 56N	118 08 05W	13.3
Malibu	01/19/1989	06:53	5.0	33 55 07N	118 37 38W	11.8
Montebello	06/12/1989	16:57	4.4	34 01 39N	118 10 47W	15.6
Upland	02/28/1990	23:43	5.2	34 08 17N	117 42 10W	5.3
Sierra Madre	06/28/1991	14:43	5.8	34 15 45N	117 59 52W	12.0
Landers	06/28/1992	11:57	7.5	34 12 06N	116 26 06W	5.0
Big Bear	06/28/1992	15:05	6.5	34 12 06N	116 49 36W	5.0
Northridge	01/17/1994	12:30	6.7	34 12 48N	118 32 13W	18.4
Northridge, Aft. #1	01/17/1994	12:31	5.9	34 16 45N	118 28 25W	0.0
Northridge, Aft. #7	01/17/1994	12:39	4.9	34 15 39N	118 32 01W	14.8
Northridge, Aft. #9	01/17/1994	12:40	5.2	34 20 29N	118 36 05W	0.0
Northridge, Aft. #100	01/17/1994	17:56	4.6	34 13 39N	118 34 20W	19.2
Northridge, Aft. #129	01/17/1994	20:46	4.9	34 18 04N	118 33 55W	9.5
Northridge, Aft. #142	01/17/1994	23:33	5.6	34 19 34N	118 41 54W	9.8
Northridge, Aft. #151	01/18/1994	00:43	5.2	34 22 35N	118 41 53W	11.3
Northridge, Aft. #253	01/19/1994	21:09	5.1	34 22 43N	118 42 42W	14.4
Northridge, Aft. #254	01/19/1994	21:11	5.1	34 22 40N	118 37 10W	11.4
Northridge, Aft. #336	01/29/1994	11:20	5.1	34 18 21N	118 34 43W	1.1
Northridge, Aft. #392	03/20/1994	21:20	5.2	34 13 52N	118 28 30W	13.1
Hector Mine	10/16/1999	09:46	7.1	34 36 00N	116 16 12W	3.0
West Hollywood	09/09/2001	23:59	4.2	34 04 30N	118 22 44W	3.7

Table 2. USGS instrumented buildings included in the analysis.

USGS: 0466, SMA-1 185	Los Angeles, 15250 Ventura Blvd., Roof (13th floor)	34.157°N, 117.476°W
USGS: 5108 SMA 1276 and 1277	Canoga Park, Santa Susana, ETEC Bldg 462 (6th and 1st floors)	34.230°N, 118.712°W
USGS: 5450, SMA-1 6146	Burbank, 3601 West Olive Ave., Roof (9th floor)	34.152°N, 118.337°W
USGS: 5451, SMA-1 4048	Los Angeles, 6301 Owensmouth Ave., Roof (12th level)	34.185°N, 118.584°W
USGS: 5453, SMA-1 7073	Los Angeles, 5805 Sepulveda Blvd., Roof (9th floor)	34.175°N, 118.465°W
USGS: 5455, SMA-1 4270	Los Angeles, 16000 Ventura Blvd., Roof (13th floor)	34.156°N, 118.480°W
USGS: 5457, SMA 5491	LOS ANGELES, 8436 WEST 3rd ST., Roof (10th floor)	34.072°N, 118.375°W

the time between consecutive zero crossings of the displacement, and assuming this time interval to be a half of the system period (see Trifunac et al., 2001a, 2001b, 2001c). The Gabor transform is a time-frequency distribution, which is up to a phase shift identical to a moving window analysis with a Gaussian time window. The instantaneous frequency was determined from the ridge of the transform, and the corresponding amplitude was estimated from the skeleton of the transform, which is the value of the transform along the ridge (see Todorovska, 2001). The wavelet transform with the complex Morlet wavelet was initially considered, which is essentially a Gabor transform with a window that varies depending on the frequency, so that it always contains same number of wavelengths. The results by both methods were found to be very similar, and no advantage was seen in using a variable window because the changes of the building frequency are relatively small, much smaller than an order of magnitude. Using constant window was convenient in the estimation of the resolution of the method. The Gabor transform was used with spread $\sigma = 1.5$. Figure 2 shows the Gabor wavelet and its Fourier transform.

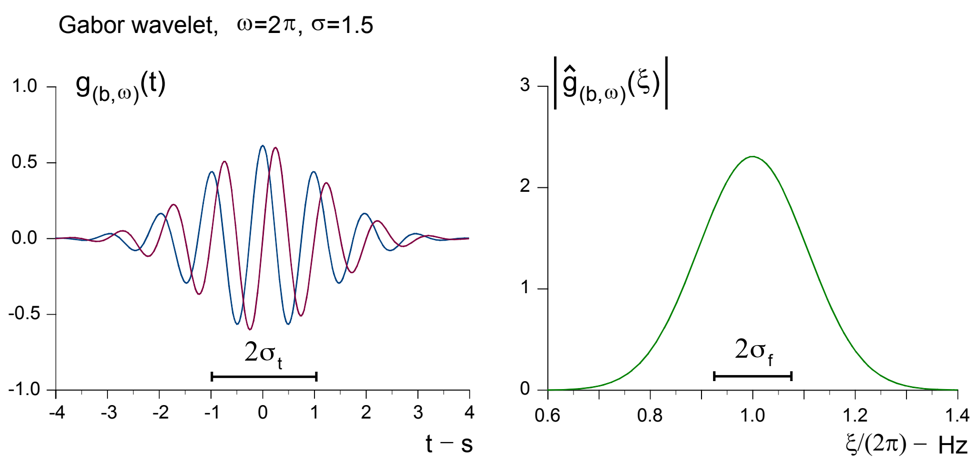


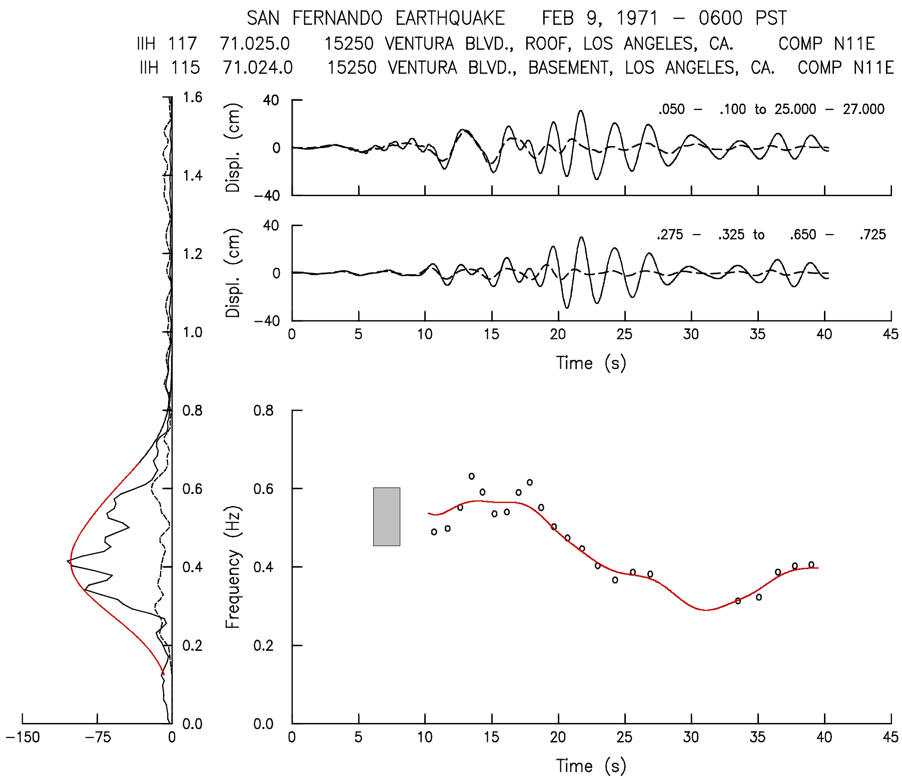
Figure 2 A Gabor wavelet for time shift b = 0 and $\omega = 2\pi$, in the time domain (left) and in the frequency domain (right).

The methodology for estimation of the instantaneous frequency of building-soil systems is illustrated in Fig. 3, parts a and b, respectively for two records—component N11E of the record of the 1971 San Fernando earthquake at station USGS 466 (Los Angeles, 15250 Ventura Blvd.), and component N00E of the record of the 1994 Northridge earthquake at station USGS 5453 (Los Angeles, 5805 Sepulveda Blvd.). For each record, the plot on the left hand side shows the Fourier spectrum of the relative roof displacement (solid line), or its approximation by the absolute displacement when only a roof record was available, the

Fourier spectrum of acceleration at the ground floor (dashed line)—if available, and a smooth approximation of the relative (or absolute) roof displacement spectrum by the marginal Gabor transform distribution (the smooth line). There are three plots in the right hand side, as follows. The plot on the top shows the time history of the roof relative (or absolute) displacement (solid line), and of the ground floor displacement (dashed line) if available, for the "broad-band" data, which is the output of the standard data processing. The plot in the middle shows the same time histories but for the "narrow-band" data, which is the broad-band data filtered so that it contains only the frequencies in the neighborhood of the first building-soil system frequency. The cut-off and role-off frequencies, in Hz, of the Ormsby filters used are shown in the upper right corner of these plots. The plot in the bottom shows the instantaneous frequency versus time estimated by the zero-crossing analysis (open circles), and Gabor analysis (with $\sigma = 1.5$ for all the records). The shaded rectangle in this plot has width $2\sigma_t$ and height $2\sigma_\omega$ and is a measure of the resolution of the Gabor analysis. The Gabor transform at a point $\left(t, f\right)$ in the time frequency plane is the weighed average of the components of the function (effectively) within such a rectangle centered at that point. The method cannot resolve frequencies that are closer than σ_ω, and estimates in time that are closer than σ_t. The resolution in frequency can be increased only if the resolution in time is decreased (by increasing the time window of the Gabor wavelet, and consequently—σ_t), and vice versa.

The results in Fig. 3 show that the estimates by the zero-crossing and Gabor analyses are consistent. The estimates by the latter method are smoother, as the Gabor transform is a smoothing operator. The zero-crossing analysis is not accurate when the oscillations of the signal depart too much from a "pure" harmonic, and these estimates are not shown. Both methods are most accurate when the amplitude of the signal is large and does not vary significantly during one cycle of oscillation, least accurate—when the amplitude is small and varies significantly during one cycle, and are arbitrary when the amplitude is practically zero. A significant change (decrease) in the system frequency of about 30% during a single earthquake is seen for both buildings.

a)



b)

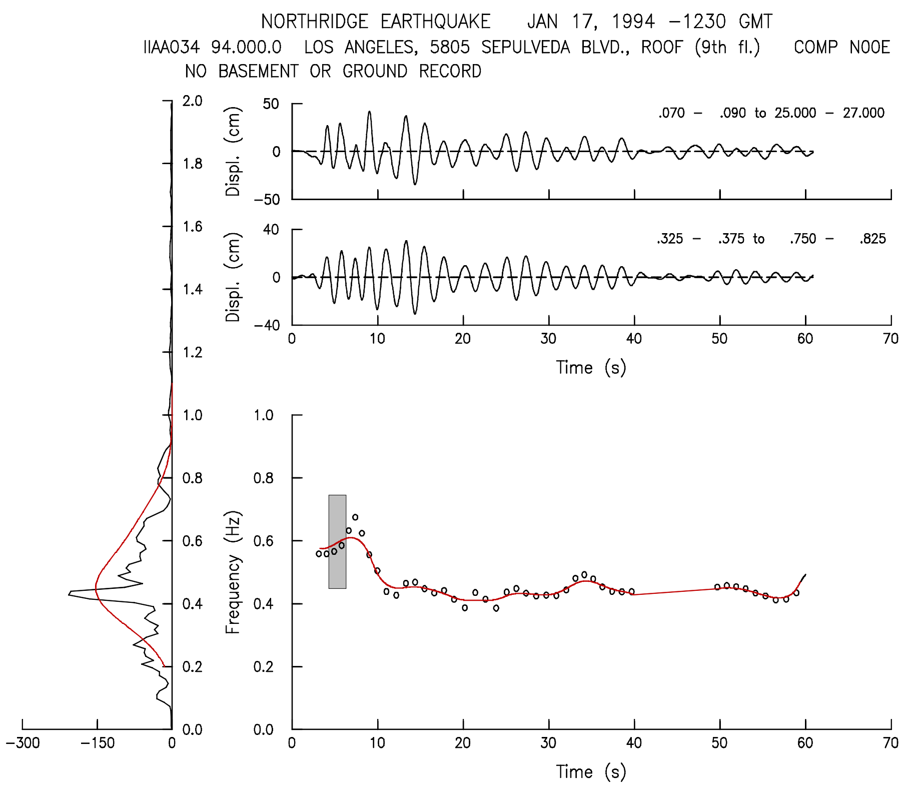


Figure 3. Estimation of the instantaneous frequency for a) component N00E of the record of the 1994 Northridge earthquake at station USGS 5453 (Los Angeles, 5805 Sepulveda Blvd.), and b) component N11E of the record of the 1971 San Fernando earthquake at station USGS 466 (Los Angeles, 15250 Ventura Blvd.).

RESULTS

Figures 4 through 10 show, in a compact form, results for the variation of the building-soil system frequency in time as function of the amplitude of response for the seven buildings. Detailed results, like those in Fig. 3, for every earthquake and component of motion, can be found in Todorovska et al. (2004). Each of these figures shows four plots, as follows. Those on the top correspond to one of the two horizontal component of motion, and those on the bottom—to the other horizontal component of motion, while those on the left correspond to estimates by zero-crossing analysis, and those on the right—by Gabor analysis. In each plot, the horizontal axis corresponds to the instantaneous frequency, the vertical axis corresponds to the amplitude of response (of the filtered signal) expressed as a rocking angle in radians, and each point corresponds to a particular instant in time. The rocking angle was computed by dividing by the distance between the top and bottom instruments, estimated using average floor height of 12.5 feet (1 foot=30.48 cm) the amplitude of the relative (roof minus base) response, if motion at the base was recorded, or otherwise—the absolute horizontal response of the roof or top floor. It is noted here that this rocking angle includes the *rigid body* rocking, which could not be separated because of insufficient number of instruments at the base, in addition to motion resulting from *deflection* of the structure.

In Figs 4 through 10, the points corresponding to consecutive instants of time are connected by a line, each line corresponding to a particular earthquake. In the plots showing results from the zero-crossing analysis, the first and last point shown for a particular earthquake are marked respectively by an open and a closed circle. The backbone curve, drawn by hand, indicates roughly the trend of the variation of the system frequency as function of the amplitude of response. It can be seen that for the largest motions (during the 1971 San Fernando and 1994 Northridge earthquakes), the system frequency generally decreased during the shaking. For all but one building, this change seems to have been temporary, as the system frequency increased during the shaking by the aftershocks. For one building, permanent change appears to have occurred during the 1971 San Fernando earthquake (USGS 466). Detailed interpretation of the causes of these changes is beyond the scope of this project. The maximum and minimum frequencies determined from the backbone curves in Figs 4 through 10, and the corresponding maximum and minimum levels of response, are summarized in Table 3 and the percentage change for all the seven buildings

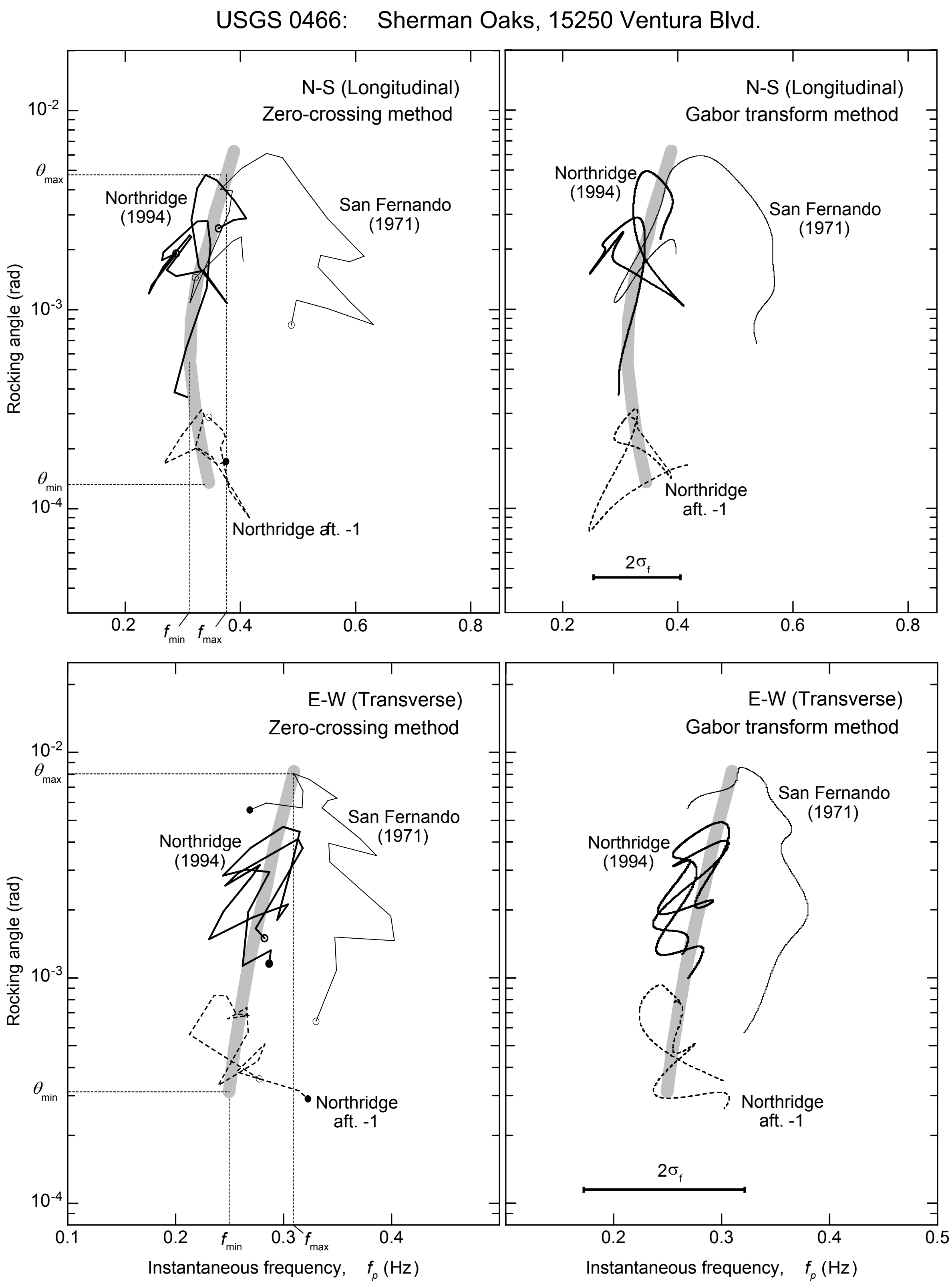


Figure 4. Instantaneous frequency versus amplitude of motion for station USGS 466.

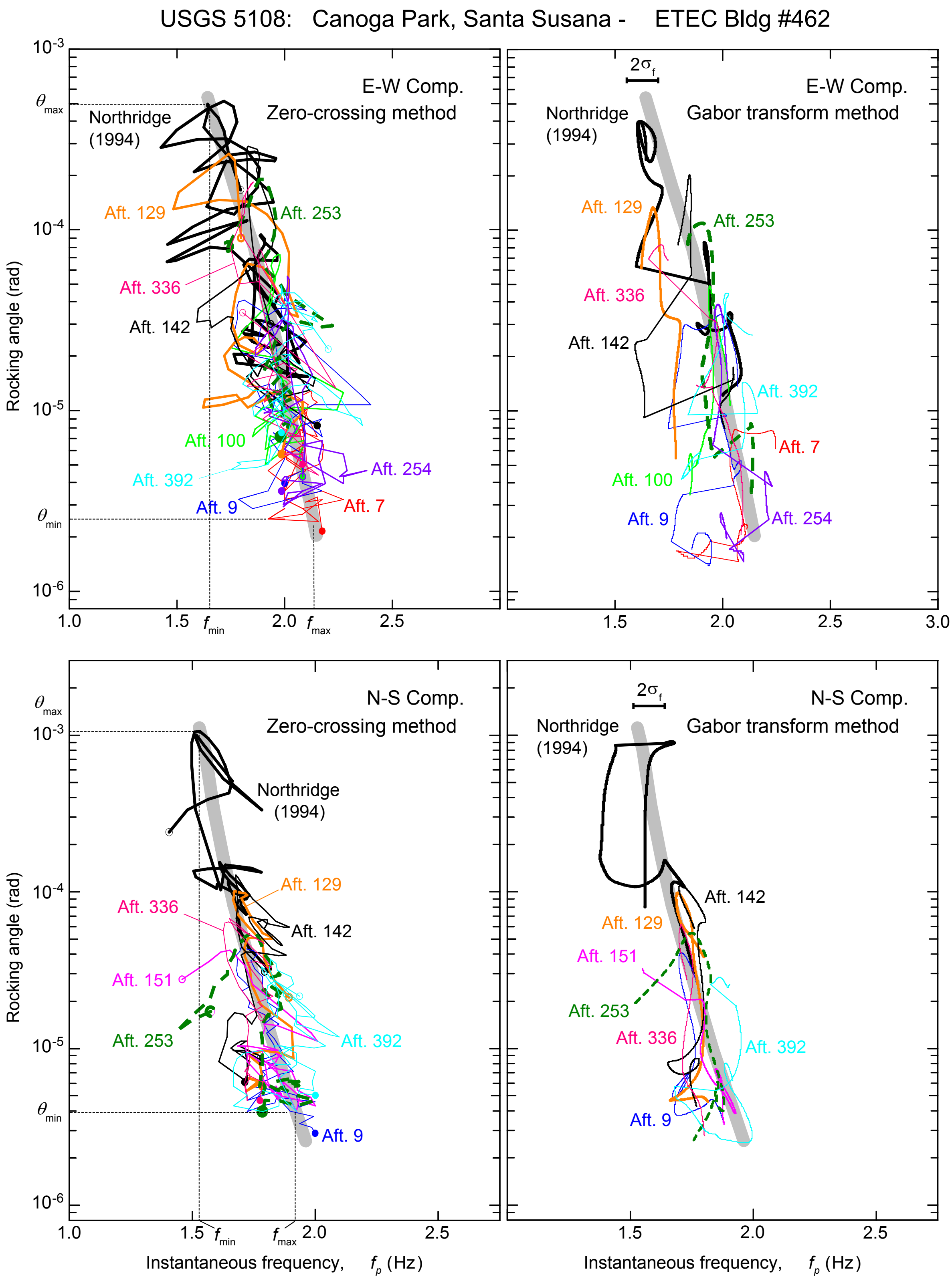


Figure 5. Instantaneous frequency versus amplitude of motion for station USGS 5108.

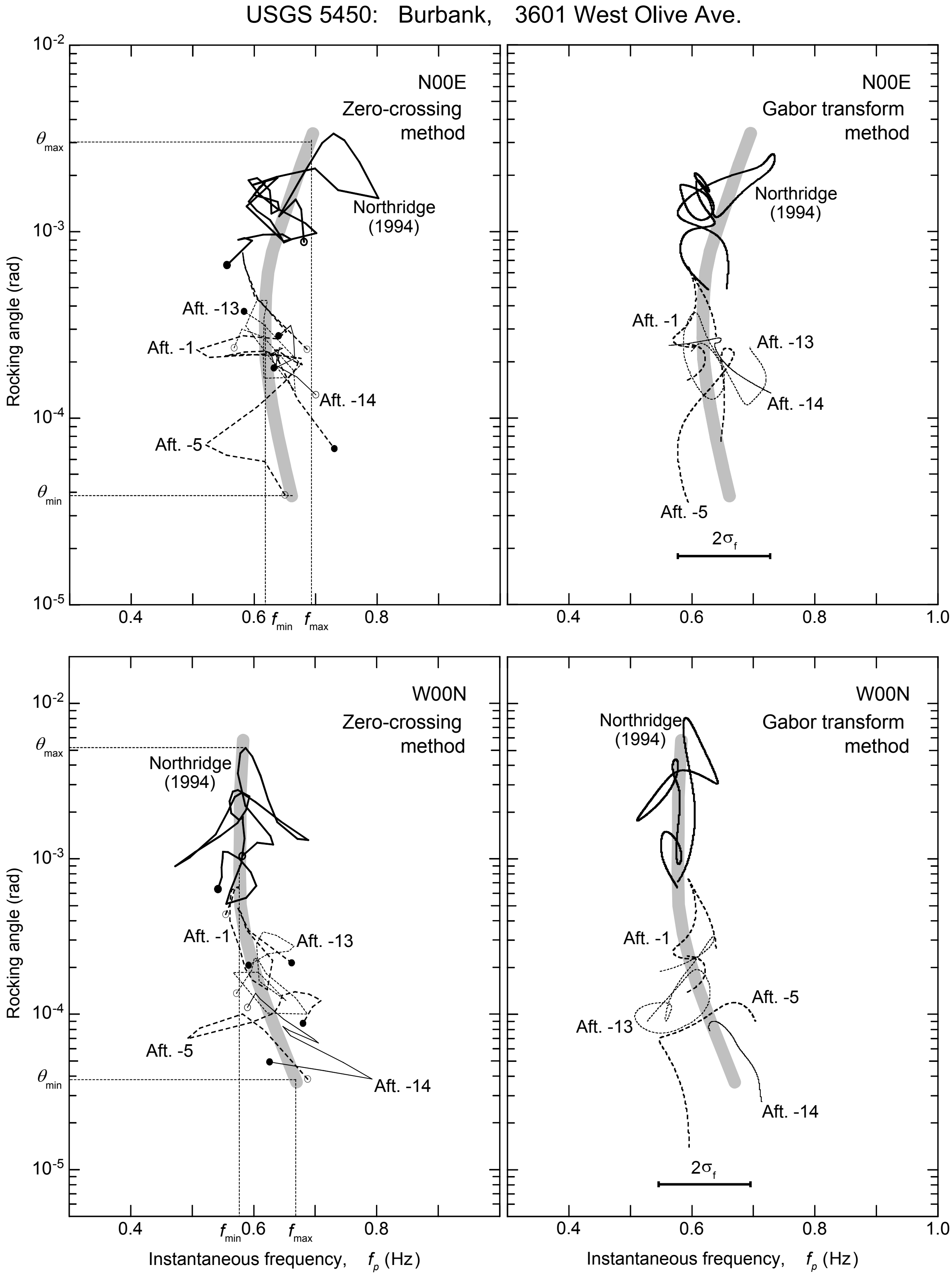


Figure 6. Instantaneous frequency versus amplitude of motion for station USGS 5450.

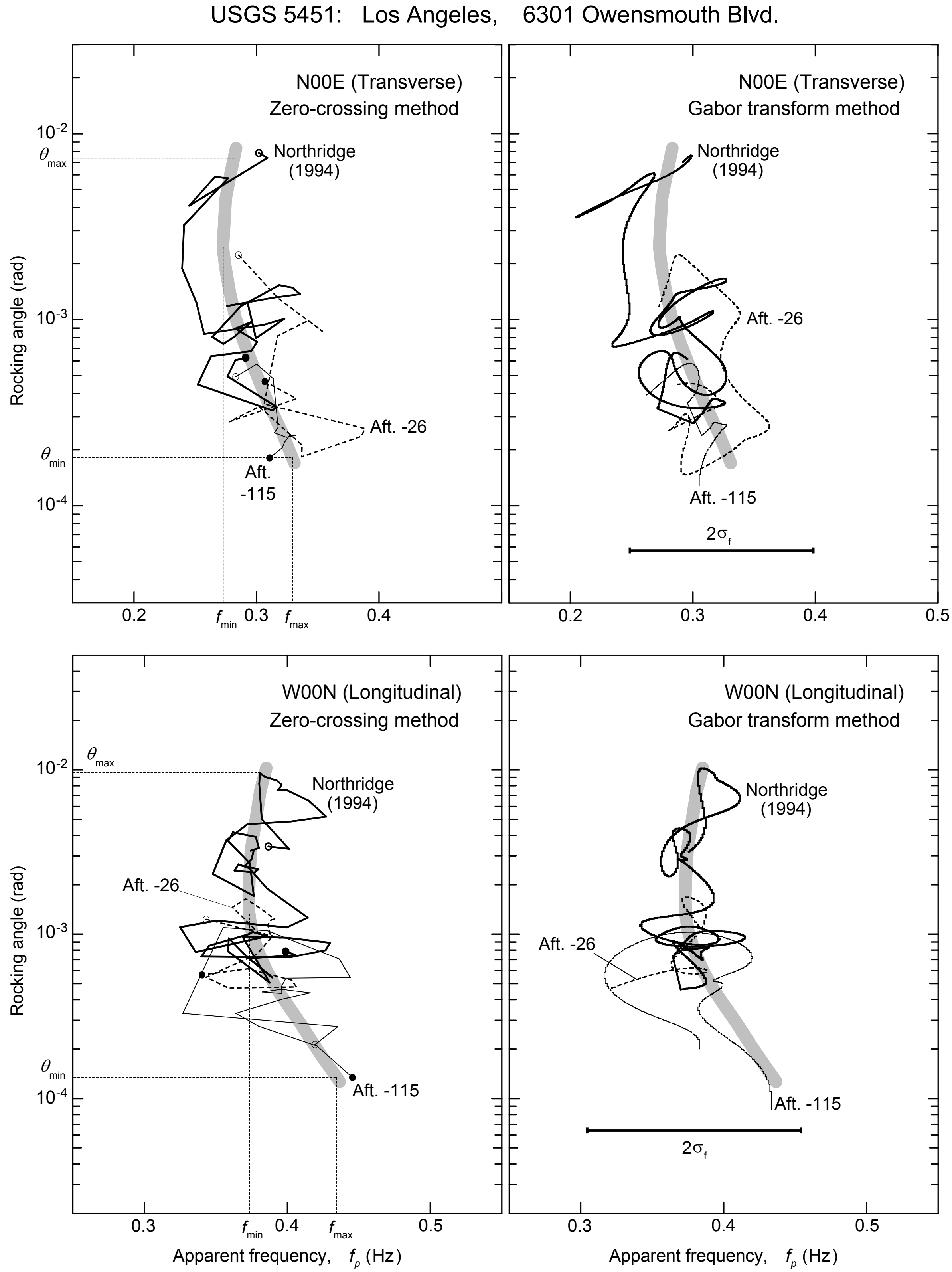


Figure 7. Instantaneous frequency versus amplitude of motion for station USGS 5451.

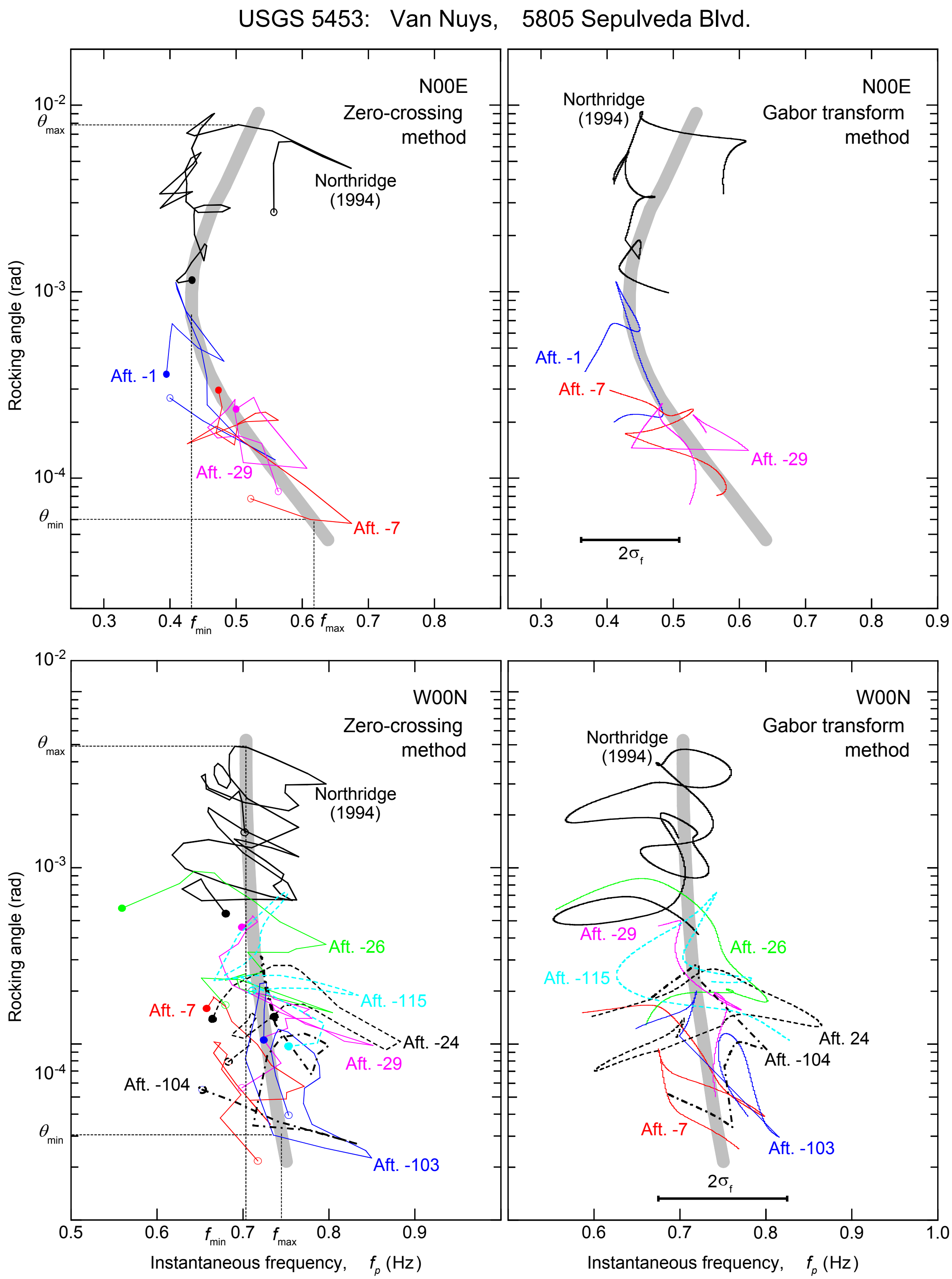


Figure 8. Instantaneous frequency versus amplitude of motion for station USGS 5453.

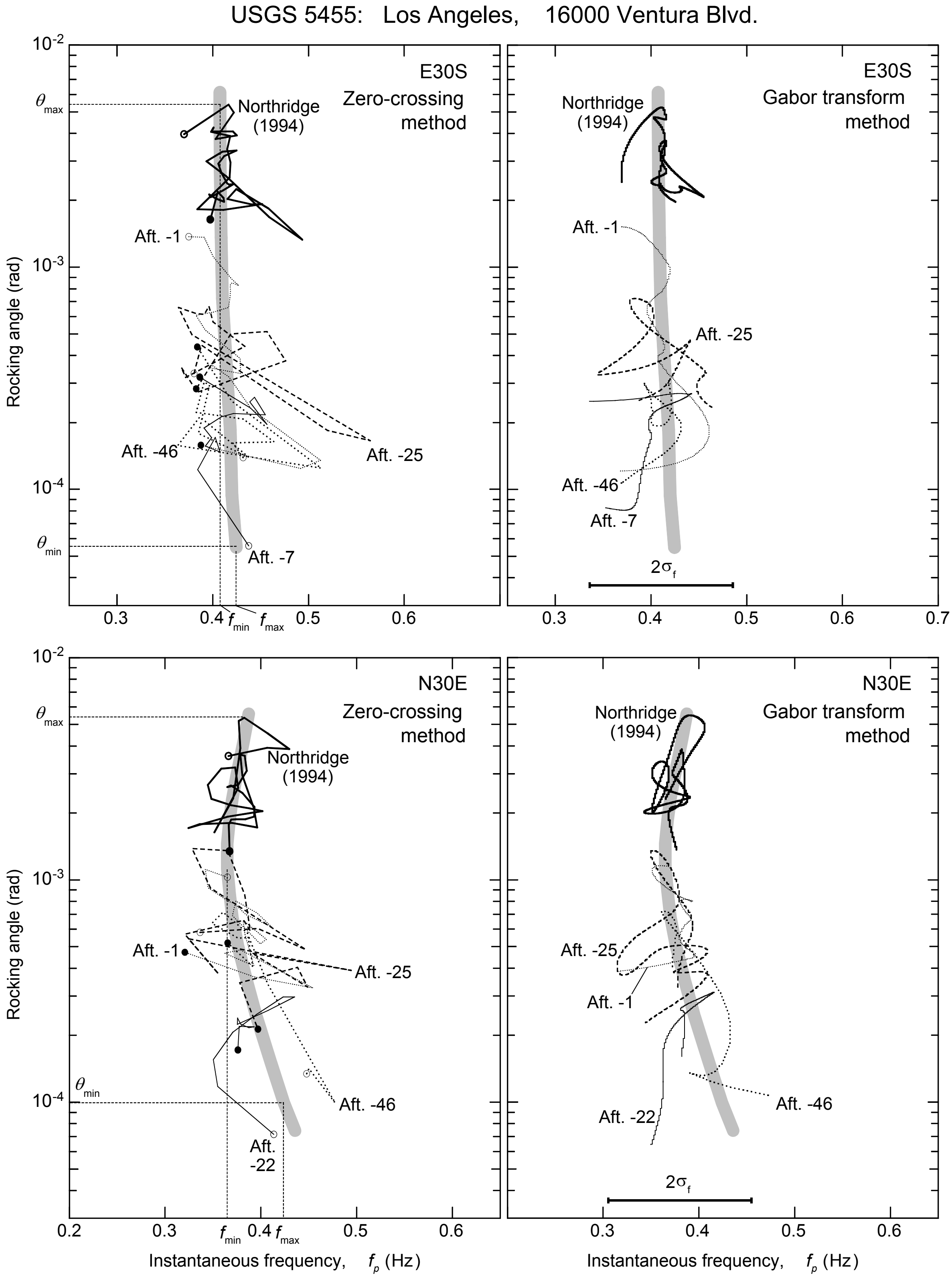


Figure 9. Instantaneous frequency versus amplitude of motion for station USGS 5455.

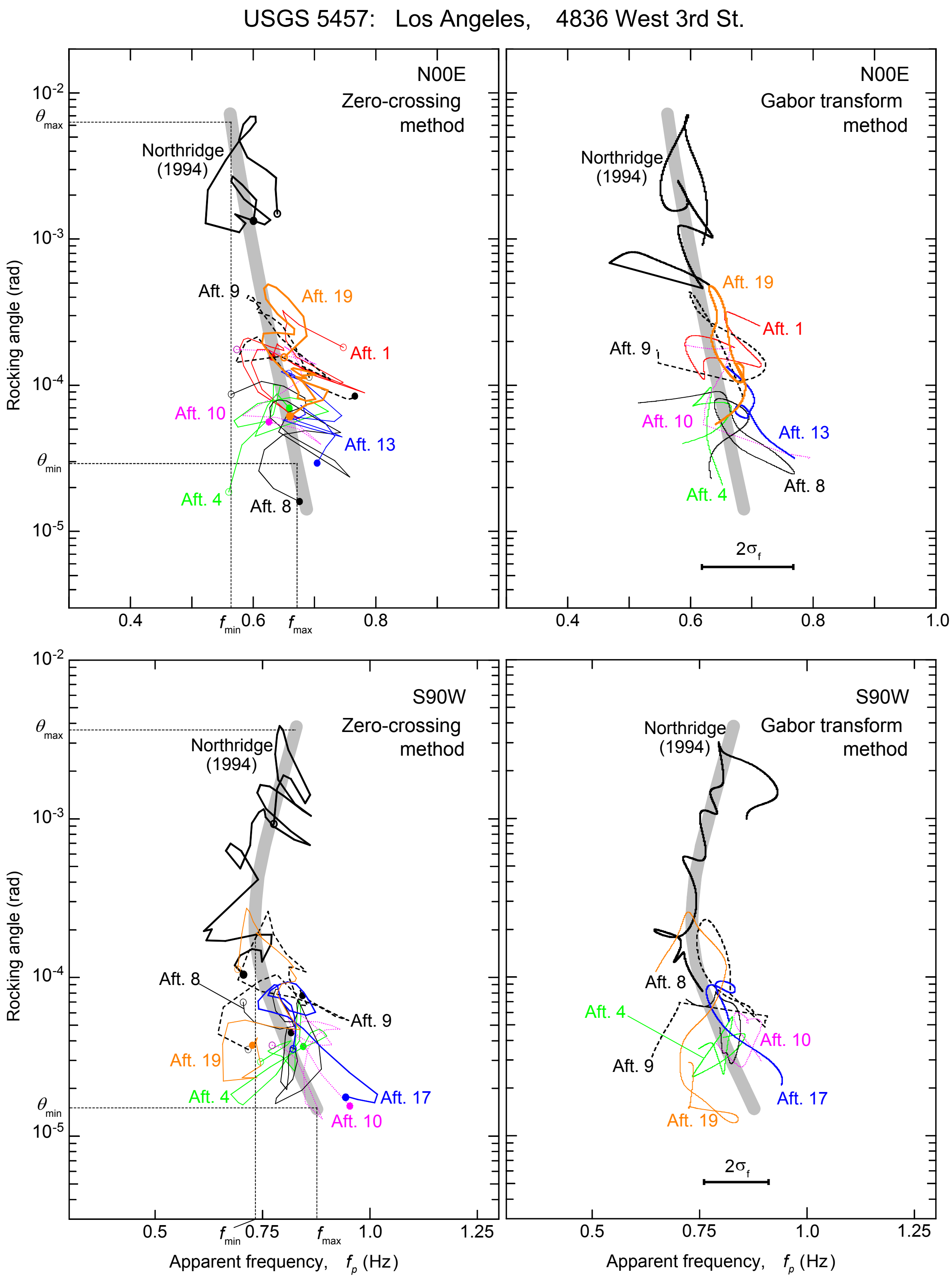


Figure 10. Instantaneous frequency versus amplitude of motion for station USGS 5457.

Table 3. Maximum and minimum system frequencies and maximum and minimum rocking angles for seven instrumented buildings.

Station no.	Comp.	f_{max}, f_{min} (Hz)	$\Delta f / f_{max}$ (%)	θ_{max}, θ_{min} ($\times 10^{-3}$ rad)	Comp.	f_{max}, f_{min} (Hz)	$\Delta f / f_{max}$ (%)	θ_{max}, θ_{min} ($\times 10^{-3}$ rad)
5108	E00S	2.130, 1.648	22.64	0.49607, 0.00251	N00E	1.899, 1.525	19.68	1.05640, 0.00395
0466	N00E	0.377, 0.312	17.23	4.74628, 0.12339	W00N	0.295, 0.215	27.23	4.66436, 0.31591
5450	N00E	0.691, 0.614	11.16	3.08807, 0.03879	W00N	0.666, 0.576	13.52	5.16651, 0.03820
5451	N00E	0.329, 0.273	17.16	7.38386, 0.18001	W00N	0.434, 0.373	14.14	9.57349, 0.13386
5453	N00E	0.613, 0.434	29.20	7.87023, 0.06008	W00N	0.744, 0.712	5.69	4.88160, 0.02566
5455	E30S	0.434, 0.408	3.86	5.39350, 0.05552	N30E	0.425, 0.363	14.59	5.36059, 0.09933
5457	N00E	0.675, 0.569	15.76	6.34016, 0.02940	S00W	0.866, 0.704	18.62	3.62546, 0.01286

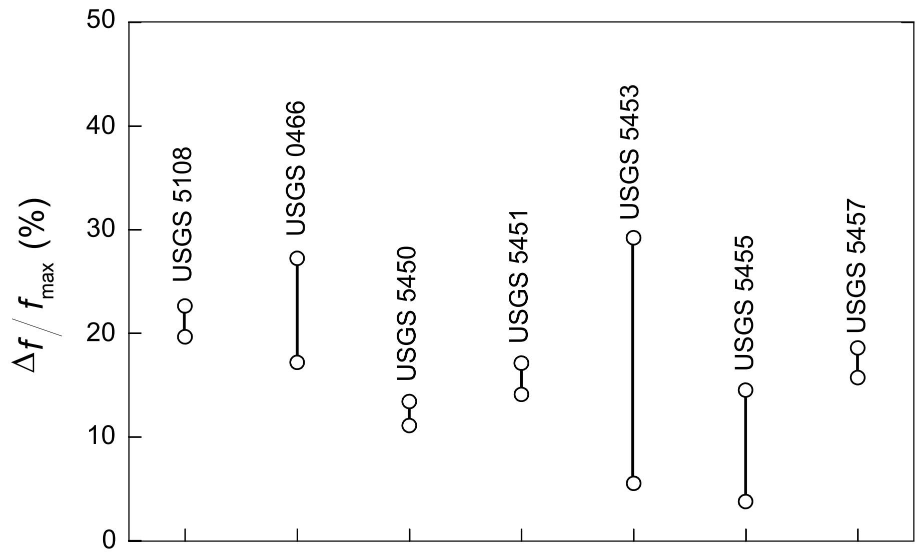


Figure 11. A summary of the changes of the building-soil system frequencies of the seven buildings analyzed in this paper, determined from the observed trends during multiple earthquake excitations (see Figures 4.1 through 4.24). For each building, two values are shown, corresponding to the two horizontal components of motion. The change is expressed as a percentage of the maximum frequency.

is shown in Fig. 11. It is seen that, for these levels of response, the change for most of the buildings is not more than 20%, but it reaches 30% for two of the buildings.

SUMMARY AND CONCLUSIONS

This paper presents results for apparent building frequency for seven buildings in the Los Angeles area that have recorded the 1994 Northridge earthquake and some of its aftershocks. Although the number of recorded aftershocks in these buildings was large (up to about 80), only a small number of records were found to be useable for this analysis, because of the small signal to noise ratio at long periods which lead to high lower cut-off frequency, higher or too close to the system frequency.

The system frequency was estimated by two methods—zero crossing and Gabor analyses. The results by both methods are consistent. The general observed trend of the variation of the system frequency is decrease during the 1994 Northridge main event, and the 1971 San Fernando earthquake, which caused the largest amplitude response. For all but one building, the frequency was again larger during the aftershocks, indicating system recovery. For most buildings, the frequency changed up to 20%, and for two buildings, the change was about 30%. A permanent reduction of the frequency is consistent with permanent loss of stiffness, while a "recovery" to the initial higher value is consistent with the interpretation that the change was mainly due to changes in the soil (rather than in the structure itself), or changes in the bond between the soil and the foundation. Other possible causes of the temporary changes are: contribution of the nonstructural elements to the total stiffness in resisting the seismic forces, and opening of existing cracks in the concrete structures during larger amplitude response. The degree to which each of these causes contributed to the temporary changes cannot be determined from the current instrumentation and is beyond the scope of this analysis. What matters for the design codes, however, is the overall effect, which can be estimated even from the minimum (roof only) building instrumentation.

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