COIMPARISON OF THE DYNAMIC PARAMETERS EXTRACTED FROM WEAK, MODERATE AND STRONG MOTION RECORDED IN BUILDINGS.

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SUMMARY

Ambient vibration analysis is proposed as an alternative way to inspect buildings before or after an earthquake. This fast and low-cost method is well-adapted to large-scale studies for which a large amount of buildings has to be checked. One of the most common critics usually done on the use of ambient vibrations in structures is the very low level of vibrations. Because of the low amplitude range of the ambient vibration (PGA<10^-5g), dynamic characteristics obtained from weak-motion are generally expected to be significantly different from those obtained using strong-motion (PGA>0.1g). The objective of this paper is to present a comparison of the structural dynamic characteristics deduced from strong, moderate and weak motion recordings for a set of twelve Californian buildings and four European buildings. The present study differs from numerous previous investigations in two aspects: (a) the number of compared building is larger; and (b) for two buildings, more than 10 earthquakes records are available, which allows to investigate the dependence of dynamic characteristics with shaking intensity.

Keywords: building response; ambient vibration; strong motion; existing buildings.

1. INTRODUCTION

In areas of low or moderate seismic activity, the effects of possible large earthquakes are usually explored through earthquake scenarios. One of the main parameters controlling the possible consequences of strong events is the ability of the building stock to resist to the ground motion. Different techniques are usually employed to assess the vulnerability of existing buildings which are usually considered as the most vulnerable. These methods were developed for wide-area data collection. Many of them are based on the inventory of parameters of the structural design collected by visual inspections and related to observational data of damage during past earthquakes (e.g., EMS98, HAZUS, GNDT). Nevertheless, these methods are not well-adapted in countries with moderate seismicity where no significant damages due to recent earthquakes have already been observed. These observations are generally used for the calibration of the vulnerability curves, accounting for the specificities of the structural design of each region.

Ambient vibration analysis is proposed as an alternative way to inspect buildings before or after an earthquake. This fast and low-cost method is well-adapted to large-scale studies for which a large amount of buildings has to be checked. One of the most common critics usually done on the use of ambient vibrations in structural engineering is the very low level of vibrations. Because of the low amplitude range of the ambient vibration (PGA<10^-5g), dynamic characteristics obtained from weak-motion are generally expected to be significantly different from those obtained using strong-motion (PGA>0.1g). This difference has been already observed
essentially on frequency and on damping values, in case of forcing vibrations and seismic strong ground motion. These variations are generally attributed (1) to the non-linear behaviour in the structure material; (2) to the slip of the connections; (3) to the interaction between structural and non-structural elements; and (4) to a possible non-linear soil-structure interaction effect.

The objective of this paper is to present a comparison of the structural dynamic characteristics deduced from strong motion (earthquakes) and weak motion (ambient vibration) recordings for a set of twelve Californian buildings. The present study differs from numerous previous investigations in two aspects: (a) the number of compared building is larger; and (b) for two buildings, more than 10 earthquakes records are available, which allows to investigate the dependence of dynamic characteristics with shaking intensity.

2. BUILDING SET

The twelve buildings are located in California (US) at Los Angeles or in the San Francisco Bay area. Half of them have a structural system made of reinforced concrete (RC) and the other half is made of steel. The structural system can be moment-resisting frames or shearing walls in case of RC. Steel buildings are moment-resisting frames in all the cases. The number of stories is varying from 4 to 13 and from 5 to 48 for RC and steel buildings, respectively. A detailed description of each building can be found in Dunand et al. (2004). Among the set of buildings, two were particularly analysed (Fig. 1):

Alhambra LA County Services building (Station 0482)
The 12-story Los Angeles County Public Works Headquarter was constructed in 1970. The structural system consists on large reinforced concrete piers and shear walls up to the second floor, with a steel moment frame with pre-Northridge connections above the second floor. Its dimensions in plan are 50x50 m and its height is 60 m.

Pasadena Millikan library (Station 5407)
Caltech's 9-story Millikan Library is one of the most extensively-studied buildings in the world (Clinton, 2004). The building was constructed in 1966-67 and it has undergone a large number of earthquakes. Moreover, an eccentric mass shaker is permanently placed at the building roof and numerous forced-vibration experiments have been conducted. The building has concrete moment resisting frames in both longitudinal and transversal directions. In addition, there are transversal shear walls on each sides of the building. Shear walls in the central core provide added stiffness in both directions. The general plan dimensions of this building are 21x23 m and its height is 44 m.

![Figure 1: The Alhambra LA County Services building (left) and the Pasadena Millikan library (right)](image)

3. EXPERIMENTAL RESULTS

In order to compare the structural dynamic characteristics from strong to weak motion, strong motions (SM) recordings in the 12 buildings have been analyzed with various system identification techniques to obtain frequency and damping ratio of the first vibration mode. The strong motion recordings were provided from the USGS permanent strong motion network. One to sixteen seismic records have been processed for each building.
located at Los Angeles or in the San Francisco Bay area. Ambient vibration recordings were collected using portable velocimeters or using the permanent strong-motion network accelerometers.

Under ambient noise

For each studied building, at least one ambient vibration recording has been used. The sensor was located as close as possible to a permanent accelerometer at the top of the building. The records were 30 minutes long at a sample frequency of 200Hz. The ambient vibration tests carried out on each building were performed with a vibration measurement equipment composed by two CityShark™ (Chatelain et al., 2006) acquisition systems each one connected to a Lennartz LE-3D 1Hz velocimeter with three components. However, due to experimental constrain, the ambient vibration recordings for some buildings were obtained from accelerometers of the permanent strong motion network of USGS. The extraction of modal frequency from ambient vibration data was performed with two techniques. The first one is based on the classical spectral analysis. Amplitude spectra are estimated by averaging amplitude spectra of selected windows of the signal. Data were processed using the following way:

- The selection of windows (30 seconds long) is done using an anti-trigger algorithm, which allows to reject all parts of the signal that, under the white noise assumption, are not ambient vibrations, such as the effect of local perturbations;
- The amplitude spectra are derived from these selected windows with a FFT;
- The amplitude spectra are smoothed using the Konno and Omachi (1998) method with a $b$-value of 40;
- The smoothed spectra are then averaged.

The second technique is used to obtain the damping of each mode. This method, called the Randomdec method (Dunand, 2004) is based on the extraction of the impulse response characteristic of an oscillator forced into vibration by ambient vibration (Fig. 2). This vibration is considered as a random solicitation. The damping is obtained by stacking a large number of signal windows, which all have the same initial conditions (e.g. null displacement and positive velocity). The window stacking lessens the importance of the random component of the signal, which at the end of the process has a zero average. Then, the staking allows defining the oscillator impulse response which is deterministic. Once the impulse response obtained, damping ratio and frequency are derived by using the logarithmic decrement method.

Under earthquakes

Each of the buildings has its own permanent strong motion array maintained by the USGS. The number of strong motion sensors in each building can vary from a minimum of three sensors at the bottom and three sensors at the top, to more than twenty with sensors at intermediate stories. Seismic events were downloaded from the USGS National Strong Motion Program (NSMP) website (http://nsmp.wr.usgs.gov/): the list of available recordings and details about earthquakes can be found in Dunand et al. (2004).

Frequency and damping are derived from these records with an identification technique by finding a transfer function which applied to the bottom record can explain the top record. The transfer function has the form of ARMA models (Fig. 3). The frequencies and damping ratios are derived from the ARMA model characteristics by comparing the Z-transform of the theoretical impulse response of oscillator to the ARMA model characteristics.

![Figure 2: Example of the Randomdec method applied to the Milikan Library building](image-url)
Figure 3: Example of the ARMA model found for the Milikan Library building

4. RESULTS AND ANALYSIS

Alhambra LA County Services building (Station 0482)
For this building 16 earthquake records are available from 1971 to 2003. Maximum top accelerations (MTA) are ranging from 3 to 261 cm/s², PGA are ranging from 2 to 281 cm/s² and maximum drifts are ranging from 0.002 to 1.4 cm/story. Identification of frequencies and damping could be done on all events. Identified frequencies from events are varying within a small range: 0.46 to 0.54 Hz (max of 18% variation) for the first mode (f₁) and 1.30 to 1.62 Hz (max of 20% variation) for the second mode (f₂). The structural damping ratio is varying from 1.7 to 6.6% for the first mode and from 3.0 to 11.2% for the second mode. As shown on Fig. 4, the frequencies are not depending on the chronological order (a difference of 4% between the first mode frequency of the first event and of the latest event). That suggests that no significant loss of rigidity occurred whatever the earthquake, and the building can be considered as in the same state of degradation for all the events.

By plotting frequency versus log of the MTA indicator (Fig. 5), it can be observed that seismic frequency (f₀) is lower than ambient vibration frequency (F₀) and is decreasing linearly with the log of the MTA indicator.

Figure 4: Frequency evolution of the longitudinal (circle) and transverse mode (square) as function of the seismic sequence – Alhambra building
Figure 5: First (circle) and second (square) modes frequencies from earthquakes recordings and from ambient vibration as function of the Maximum Top Acceleration – Alhambra building

Pasadena Millikan library (Station 5407)
Since 1970, the Milikan library building has suffered nine seismic events recorded in this 13-story RC building with a maximum top acceleration ranging from 7 to 525 cm/s², out of which only six are available on the NSMP server. The other events have been studied by different authors and Clinton (2004) performed a synthesis of these results. Since 1967, numerous dynamic analyses have also been carried out, forcing the building into vibration with the eccentric shaker, most of them performed after all strong events (Clinton, 2004). It can be noted (Fig. 6) that frequencies obtained from these forced vibration drop of 21% and 12% for the longitudinal and transversal directions between the first test (1971) and the last test (2002). The frequency drop appears to be due to a permanent loss of structural stiffness which occurred during earthquakes, the most noticeably being the "1971 San Fernando" event. Indeed, it can be observed a frequency drop of 16.6% and 6.8% in both longitudinal and transversal directions after the "1971 San Fernando" earthquake. In order to study the building in the same state of degradation, the frequency comparison was done on recordings which occur after the "1971 San Fernando" event.

Identification using earthquakes and results from Clinton (2004) after the "1971 San Fernando" event show variations of the first longitudinal mode frequency between 0.92 Hz and 1.16 Hz and variations of the first transversal mode frequency between 1.29 Hz and 1.70 Hz. Frequency derived from velocity ambient vibrations or acceleration ambient vibrations are identical: 1.22 Hz and 1.72 Hz for the first longitudinal and transversal modes, respectively. Damping ratios exhibit no large variations (less than 18%) between the two estimations which can be considered as not significant according to the precedent comment on damping estimation.

Our seismic frequencies estimate compared to the frequencies listed by Clinton (2004) show a difference lower than 8% for the "1970 Little Creek" event, lower than 2% for the "1971 San Fernando" events and lower than 5% for the "2003 Big Bear" event. The three largest events after the "1971 San Fernando" with MTA > 140 cm/s² are the "1987 Whittier Narrow", the "1994 Northridge" and the "1991 Sierra Madre" events. These events produced a significant change of frequency between 20% and 25% using the ambient vibration. The frequencies deduced from the four small earthquakes with MTA < 20 cm/s² ("2001 Beverly Hills", "2002 Yorba Linda", "2003 Big Bear" and "2003 San Simeon") exhibit only light differences compared to the ambient vibration frequencies (less than 10%). By plotting frequencies versus log of the MTA (Fig. 7), we can observe that seismic frequencies are decreasing linearly with the log of the MTA and the seismic frequencies are lower than ambient vibrations frequencies.
Figure 6: Frequency evolution of the longitudinal (circle) and transverse mode (square) as function of the seismic sequence – Milikan Library building.

Figure 7: First (circle) and second (square) modes frequencies from earthquakes recordings and from ambient vibration as function of the Maximum Top Acceleration – – Milikan Library building.

5. CONCLUSIONS

A comparison of structural dynamic characteristics (frequency and damping) derived from ambient vibration and from seismic recordings was conducted. The identification of the dynamic characteristics was based on the Randomdec method for ambient vibration records and on the estimate of ARMA models for seismic records. Among the twelve buildings studied, seven have a structural system made of reinforced concrete elements (shear walls or/and resisting frames) and five have a structural system composed of steel resisting frames. Seismic instrumentation of these buildings is provided by US Geological Survey (USGS) and most of data are available on-line on USGS National Strong Motion Program (NSMP) web site. The main conclusions from this comparison are:

- The frequency values decrease with seismic intensity as expected. However, this dependency is somewhat smaller than expected: the decrease factor does not exceed 40% for RC buildings, and 30% for steel buildings, for high intensity events (PGA over 200 to 500cm/s²).
- For PGA increasing from 0.001g to 0.5g, the seismic frequencies decrease with respect to ambient vibration frequencies, up to a factor of 0.6 for RC buildings and 0.7 for steel buildings.
- Seismic frequencies start to be different from ambient vibration frequencies for PGA around 0.01-0.1 cm/s² for steel buildings and for PGA around 1-10 cm/s² for RC buildings.
- No clear dependence of the damping with the MTA indicator can be seen for RC and steel buildings. Nevertheless, most of the seismic damping values are greater than the ambient vibration damping values for RC buildings.
In conclusion, it is clear that there are differences between the dynamic characteristics derived from ambient vibration records and from strong-motion records. However, our results suggest that frequencies derived from ambient vibrations records could be extrapolated to frequencies determined from earthquake records for RC or steel buildings by knowing the shaking intensity produced by earthquakes. Because damping estimation appears to be much less reliable, this extrapolation cannot be derived for damping values. Because building frequencies directly rule the earthquake design and ambient vibrations records are cheap and easily done, frequencies derived from ambient vibrations records could be an efficient tool in helping to increase the design quality and then the seismic vulnerability.

It should be interesting to have more information on the damping estimation errors, and to compare buildings modal shape derived from ambient vibrations and earthquake records. More data are needed to confirm these observations.

6. REFERENCES


