Chapter 14
Modal Testing of a Repaired Building After 2010 Chile Earthquake

Manuel Archila, Ruben Boroschek, Carlos E. Ventura, and Sheri Molnar

Abstract A 24 storey reinforced concrete residential building in the city of Concepcion, Chile, was severely damaged during the 2010 M_W 8.8 Maule earthquake. After the earthquake structural elements at the base of the building were repaired in an attempt to restore the structure to its original state. A modal test using ambient vibrations was conducted on this repaired building to determine its dynamic properties. Additional studies using ambient vibrations at near free field locations confirm that ground conditions may have contributed to seismic amplification of the ground shaking at frequencies that were dominant in the seismic response of this high-rise building. This amplification of ground shaking can be considered an important contributing factor to the damage suffered by this building.

Keywords Ambient vibration • Microtremor • Modal testing • Site period • Earthquake damage

14.1 Introduction

On February 27, 2010 at 3:34 am local time a M_W 8.8 megathrust earthquake struck off the coast of Chile causing strong shaking and triggering a tsunami that affected cities along the Pacific Coast of Chile. The city of Concepcion, located at an epicentral distance of 100 km was severely impacted by this earthquake. The aftermath of this earthquake left many high-rise buildings with severe seismic damage, including the collapse of a residential 15 storey building shown in Fig. 14.1. Many studies are still underway to determine the causes of the structural damage of buildings throughout Chile.

Field investigations have led engineers to suggest that walls in high rise Chilean buildings subjected to large axial compressive forces and bending action during the 2010 M_W 8.8 earthquake induced high stresses on the concrete and steel rebars, such that the concrete crushed and rebar buckled under these demands [1]. There is concern that building code provisions in Chile for design and detailing of reinforced concrete walls need to be improved to prevent this type of widespread damage.

After the earthquake, many damaged buildings were repaired to make them safe and allow for re-occupancy. The first and fourth authors visited the city of Concepcion in January 2012 to perform ambient vibration tests on the ground surface and in repaired structures. These ambient vibration tests were conducted to estimate the natural frequency of the subsoil, i.e. site period, and the modal properties of a repaired residential building. This paper presents and discusses selected results of our ambient vibration testing campaign in Concepcion.

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Fig. 14.1 Photo of a 15 storey reinforced concrete building in Concepcion city that collapsed during 2010 Chile earthquake (Photo courtesy of Perry Adebar)

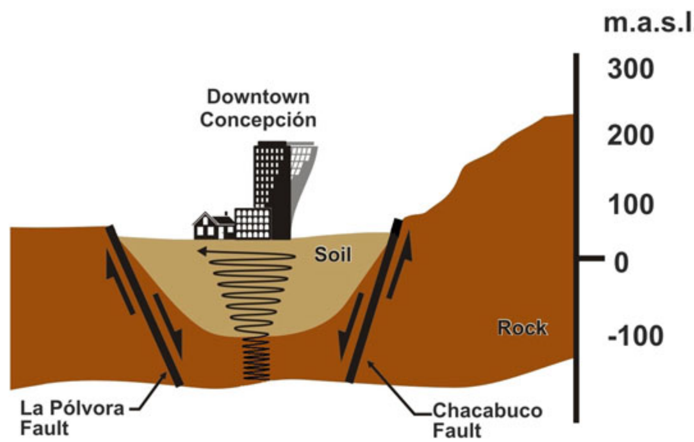

Fig. 14.2 Geologic profile across city of Concepcion and cartoon of seismic amplification in basin deposits (Adapted from [7])

14.2 Ground Conditions at Concepcion City

The city of Concepcion is surrounded by the Bio Bio River to the South, and rock formations elsewhere. A large part of the city of Concepcion is founded on a valley of alluvium sediments. These sediments have settled within a graben (basin) structure. Figure 14.2 shows the La Polvora and Chacabuco Faults, which delineate the graben boundary. This deep deposit of soil under the city has given rise to seismic amplification of earthquake shaking in past earthquakes.

The depth of this deposit varies across the city, decreasing towards the rocky edges of Concepcion and deepening towards downtown Concepcion as shown in Fig. 14.2. This varying profile of soil deposit depth results in different levels of subsoil dynamic amplification and natural frequency of vibration across the region. The subsoil fundamental frequency decreases from the edge of the city towards downtown Concepcion as determined from a campaign of free-field ambient vibration measurements [2].

14.3 Site Fundamental Frequency

The fundamental frequency of the soil deposit at different locations across the city of Concepcion was retrieved from microtremor measurements using the H/V ratio analysis technique developed by Nakamura [3]. This processing technique makes use of vertical and horizontal components; this is a cost-effective method to determine the fundamental frequency

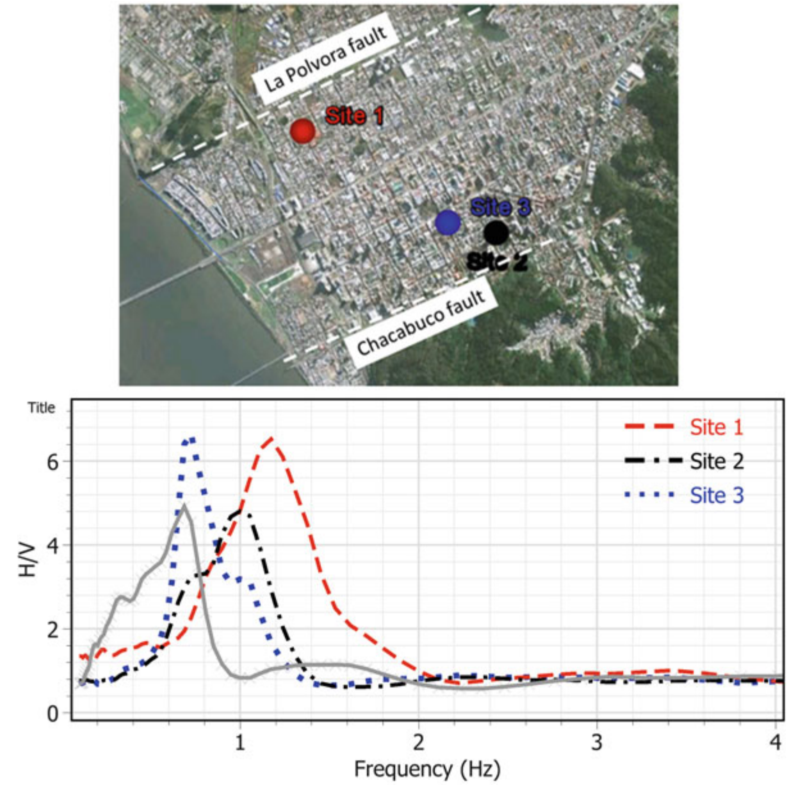

Fig. 14.3 *Top panel*: locations of three free-field ambient-vibration test sites denoted by *coloured circles*. *Bottom panel*: H/V spectral ratios from average ambient vibration and 2010 M_W 8.8 earthquake (*solid line*) recordings

of a soil deposit. The frequency of the peak H/V spectrum ratio is a proxy of the fundamental frequency of the ground.

The microtremor measurements were conducted with a single triaxial seismometer (TROMINO®), which was temporarily installed on the ground to record ambient vibrations for 20 min at a sampling rate of 128 Hz. The spectral ratio of average horizontal to vertical motion was calculated with the Geopsy program [4]. The spectral ratio analyses were performed using 60-s time windows that were 5%-cosine tapered and fast Fourier transformed to 10% proportionally smoothed spectra.

The results from free-field microtremor measurements at three sites are presented in this paper. Figure 14.3 shows site 1 is located south of the La Polvora fault, site 2 is located immediately north of the Chacabuco fault and site 3 is located closest to the centre of downtown Concepcion. Figure 14.3 also shows the average ambient-vibration H/V ratio results for these three sites; site 3 exhibits the lowest peak frequency (0.70 Hz) related to thick basin deposits, whereas sites 1 and 2 exhibit higher peak frequencies (1.16 and 0.97 Hz, respectively) towards the basin edges.

The 2010 M_W 8.8 earthquake was recorded by the strong-motion instrument at site 3. The highest recorded peak acceleration here was 0.40 g, which corresponds to a very strong shaking. The H/V ratios from the ambient vibration measurement (solid line) and the strong motion earthquake record (dashed line) are compared in Fig. 14.3. The average ambient-vibration peak frequency is 0.72 Hz and the strong motion peak frequency is 0.70 Hz. Significant differences are observed in the shape of the H/V ratio curve.

14.4 Buildings Description and 2010 Chile Earthquake Damage

14.4.1 Building 1

A modern 12 storey reinforced concrete which exhibited severe damage in structural and non-structural components is shown in Fig. 14.4. The construction of this building was finalized in 2006. This building was located within a distance of 80 m from measurement site 1 described above. The building has an L-shape and comprises two separate building towers, one

Fig. 14.4 Damage observed in 12-storey reinforced concrete building

Fig. 14.5 Elevation of 24 Storey Building and ambient vibration measurements

tower has approximate plan dimensions of 28 m long by 12 m wide and the other is 35 m by 12 m. The structural system provided to withstand earthquakes was shear walls.

The pictures in Fig. 14.4 show that the windows of the panoramic elevator suffered extensive damage. Partial collapse of the roof structure above the elevator was observed. The base of the walls above ground showed extensive cracking in horizontal and diagonal patterns. This building was considered inhabitable after the earthquake and has been slated for demolition. No access was allowed to this building; however the fundamental frequency of a shear wall building can be estimated using a rule of thumb described in equation 1.

$$fn = \frac{1}{(Tn)} = \frac{1}{(0.075N)} = \frac{1}{(0.075 * 12)} = 1.11\ Hz \tag{14.1}$$

where N is equal to the number of storey above ground level. Comparing the fundamental frequency of site 1 of 1.16 Hz and the estimated fundamental frequency of this building, it is clear that seismic amplification of motion could take place due to resonance. This correlation confirms that ground conditions played an important role on the seismic damage caused by the earthquake which rendered the building inhabitable.

14.4.2 Building 2

A 24 storey repaired reinforced concrete building for residential occupancy was subject to modal testing. The building has 23 stories above ground level and one basement storey. The approximate plan layout dimensions are 40 m by 15 m. The structural system to withstand earthquake and gravity loading is comprised of slender reinforced concrete walls. Figure 14.5 shows pictures from the building and the ambient vibration tests performed on the ground (site 2) and the building.

The building had been opened only for a month before the Chile earthquake of February 27, 2010. Residents evacuated the building as the shaking was very strong. No apparent damage was observable on this building from the outside, however

Table 14.1 Summary of modal properties

Mode	Frequency (Hz)	Damping ratio (%)
Mode 1	0.61	1.901
Mode 2	0.66	1.783
Mode 3	0.85	1.893
Mode 4	2.79	1.551
Mode 5	3.10	2.004
Mode 6	3.46	1.694

posterior inspection of the structure showed that the walls at the base of the building were severely damaged. The structure was subsequently repaired.

14.5 Description of the Modal Test on Building 2

14.5.1 Testing Technique

Output-Only Modal analysis (OMA) techniques were used in this study [5]. The modal properties sought were natural frequencies, mode shapes and damping ratios. Input excitations were not recorded and ambient vibrations were recorded only. The Enhanced Frequency Domain Decomposition (EFDD) method available in the program ARTeMIS v. 4.1 [6] was used to process the data.

14.5.2 Test Setup

The test was conducted using a set of 3 triaxial high-resolution accelerometers (TROMINO®), the same sensors as used for the free-field microtremor measurements. The internal clocks of the sensors were synchronized to a common reference time through a Global Positioning System (GPS). A reference sensor was located at the roof of the building and two roving sensors were placed at each one of the following floors: 1, 5, 9, 13, 17, 20 and 23. Because there was no satellite visibility from inside the building, the accelerometers were synchronized at the roof level with satellite visibility readily available. After synchronization, the accelerometers were placed inside of the building to perform the corresponding measurement at different floor levels. Recordings of ambient vibrations were taken for periods of 20 min at each floor using a sampling rate of 512 Hz. An illustration of the different test setups is shown in Fig. 14.6.

14.6 Modal Model

The model was developed using the seven different setups depicted in Fig. 14.6. The peak picking method was used to select frequencies from the singular value decomposition plot shown in Fig. 14.7. Six modal frequencies were identified. The summary of the modal properties obtained are listed in Table 14.1. The fundamental frequencies of the translational modes are 0.61 and 0.85 Hz in the transverse and longitudinal directions, respectively. The damping ratios range between 1.5% and 2.0% which is expected at the ambient vibration level. The corresponding modal shapes are presented in Fig. 14.8, only floors where measurements were taken are shown for clarity.

The fundamental frequency of the soil profile at site 2 where the building is located was determined to be 0.97 Hz (Fig. 14.2), and the dominant frequencies of vibration of the repaired building range between 0.61 Hz to 0.85 Hz. The frequencies are comparable and confirm that ground conditions also played an important role on seismic amplification of demands on the building that led to the severe earthquake damage observed.

There is no information available regarding the condition of the building before the 2010 M_W 8.8 earthquake. The building blueprints are not publicly available, and this prevents creation of any computer model to estimate the dynamic properties of the original building. Notwithstanding it is clear that the ambient vibrations measurements show that torsion is present in the dominant modes which might be a consequence of the earthquake damage.

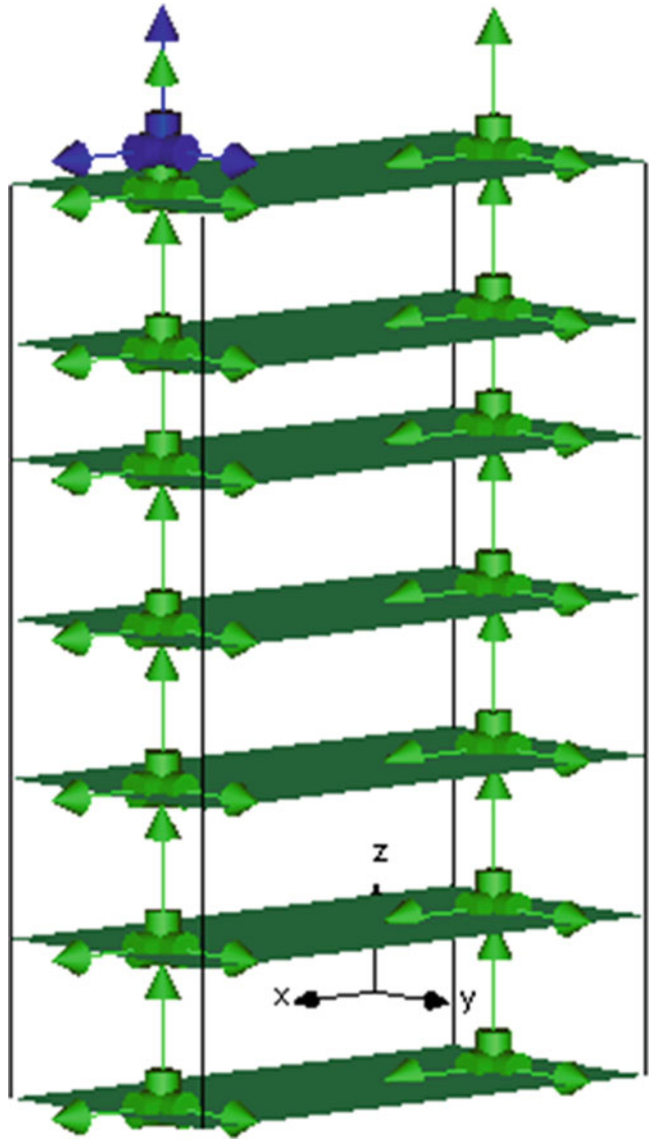

Fig. 14.6 Location of sensors over building height

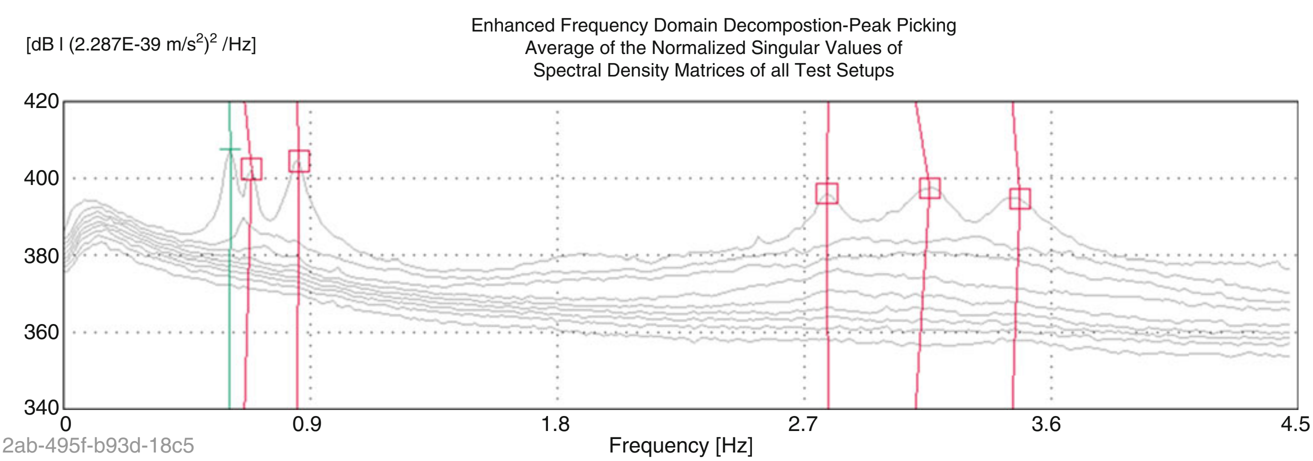

Fig. 14.7 Plot of Singular Value Decomposition of the average of all measurements

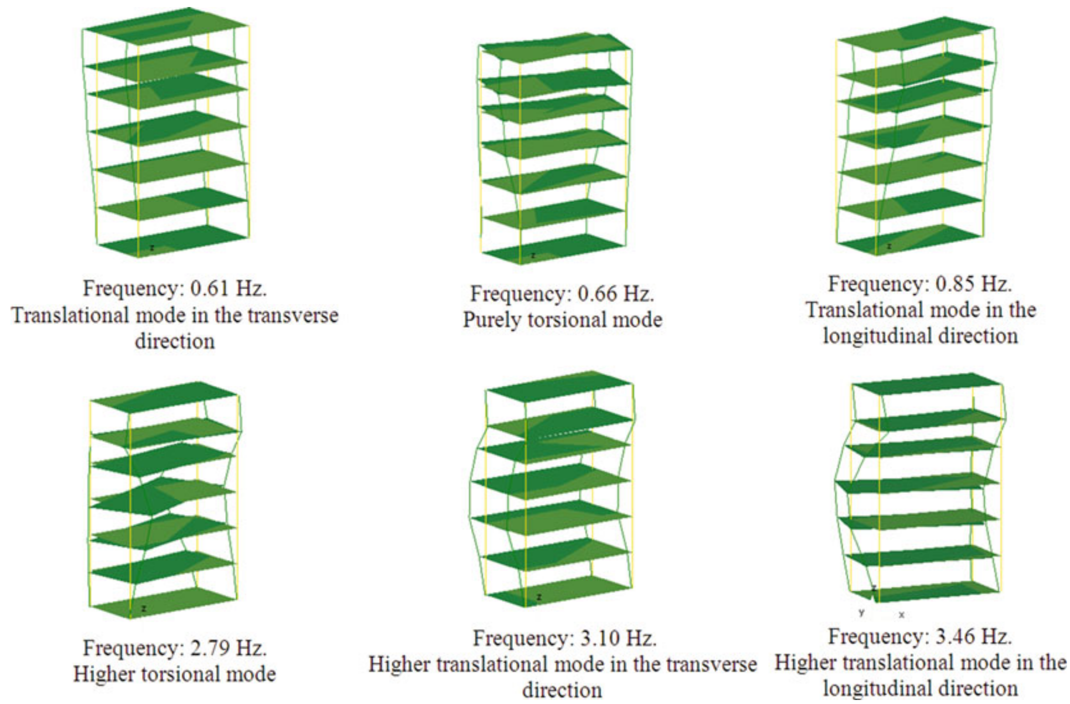

Fig. 14.8 Modal shapes of repaired high-rise building

14.7 Remarks

The estimates of the fundamental frequency of the ground at different locations across the city of Concepcion correlated well with the dominant frequencies of vibration of surrounding buildings which experienced severe damage during the 2010 M_W 8.8 earthquake. This close relation confirms that ground conditions had an important role in amplifying the seismic demands that were exerted upon high rise buildings.

The mode shapes retrieved from the ambient vibration measurements of the 24 storey repaired building were strongly influenced by torsional vibration. There is no evidence available to confirm if this condition of torsional response corresponded to the original state of the building or was inflicted by the earthquake damage. As an engineering practice in active seismic regions ambient vibrations should be performed on structures to monitor mode shapes throughout their different states, undamaged, damaged and repaired, to assess severity of damage and confirm the effectiveness of repairs in restoring the structure to its original condition.

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