Wandering of the modal parameters in existing building: application to structural health monitoring and seismic vulnerability analysis.

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SUMMARY:
Ambient vibrations in building is of increasing interest for applications in mechanical engineering, civil engineering and earthquake engineering. With advances in data acquisition systems (number of measurement points, continuous recording, low-noise instrument) and advances in signal processing algorithms, further and better studies can be conducted on civil engineering structures for evaluating their modal parameters and their physical properties. This study is focused on long-term variations of the parameters of frequency and damping obtained in three Lebanon buildings by the method of random decrement. Diurnal and seasonal variations occur due to the effects of temperature on the resonance frequency and partially on damping ratio. These changes, however, confirms the great stability and confidence measurements in buildings: the accuracy of frequency measurements is about 0.1%, while changes are reversible over one year in the order of few %. This information helps to consider the relevancy of analysis of existing monitoring (damage, ageing, and so on) and can better calibrate the mechanical models used for the analysis of seismic vulnerability of existing structures, and thereby help reduce variability of their estimates.

Keywords: ambient vibrations, dynamics of structure, frequency, vulnerability, Lebanon.

1. INTRODUCTION

Since the design forces in structures are frequency and damping dependent (based on the seismic coefficient $C(T,\xi)$ where T is the period of the building and ξ is the damping ratio), these two parameters are the subject of special attention and focus of many research activities. Most losses produced by earthquakes throughout the world are due to deficient seismic behavior in existing buildings in spite of improvements made to seismic codes (Spence et al., 2003). A critical step in seismic risk assessment is therefore to be able to predict the expected damage for a given earthquake in existing structures. One solution is to use fragility curves giving the probability to overpass a damage level for a given seismic intensity. These functions were developped first for high seismic prone regions and then widely applied in-extenso in regions without recent destructive earthquakes that could allow the calibration of the vulnerability curves including the regional specific design. In this way, the vulnerability analysis can be biased and introducing some epistemic uncertainties. Spence et al. (2003) asserted that the adjustment of structural models should assume a large set of unknown parameters influencing the response of existing buildings and introducing a large range of errors and epistemic uncertainties for the establishment of fragility curves, generally due to the lack of structural plans, aging and structural design. Knowing frequency and damping can then reduce the range of errors and epistemic uncertainties for representing the vulnerability as fragility curves (Michel et al., 2012).

New instrumentations and new signal processing methods provide information on ageing effects or after extreme events. The basic idea is that any modification of the stiffness of a system alter its dynamic response (Doeblin et al., 1996; Farrar and Worden, 2007). Variations in these modal parameters can result from a change in the boundary conditions (e.g. fixed- or flexible-base structure), mechanical properties (e.g. reinforcement or retrofitting) or the elastic properties of the material (e.g. Young's modulus). The causes may also be related to non-linear responses of the buildings, transient variations having been observed during seismic excitation due to the non-linear response of the soil-structure boundary (Todorovska and Trifunac, 2006, Todorovska, 2009) or to the closing/opening process of pre-existing cracks within the elements of the reinforced concrete buildings (Clinton et al., 2006; Michel and Gueguen, 2010). Finally, these variations can also be long-term, reversible and slight, as recently observed by Clinton et al. (2006) and Todorovska and Al Rjoub (2006), often correlated to the temporal variations of the atmospheric conditions (temperature, humidity, etc.) Most previous studies conducted in civil engineering structures (e.g., Clinton et al. 2006; Deraemaker et al., 2008; Hua et al., 2007; Nayeri et al., 2008) have shown that temperature is the most significant cause of variability of modal frequencies.

In any cases, since the resonant frequencies are an indicator of the design and the health, their value and their wandering must be the same for identical building, whatever the boundary conditions. Moreover, as shown by Gueguen et al. (2000) and Gueguen and Bard (2005), building vibrations may contaminate the close seismic ground motion, by diffracted back into the ground a piece of vibrating energy through the inertial soil structure interaction. Thus, we can ask whether the building frequencies may depend on the urban environment.

The main purpose of this paper is to analyse the long-term variations in the frequency and damping coefficient of three stand-alone buildings. Since the three buildings are closed and with the same design, the variations of the frequencies must be similar and their behaviour also. After presenting the experiments in section 2, the Random Decrement Technique (RDT) is applied to the data and the variations in frequency are discussed in section 3 and their behaviour during earthquakes also in section 4. Concluding remarks are presented in section 5.

2. BUILDINGS AND EXPERIMENTS

The three buildings of the present study were constructed in 1995 in the Eastern side of Beirut. The three buildings follow exactly the same construction design, and differ only by the number of stories: 18, 21 and 16 stories for the towers V,W, X respectively. They are distant of about 50 meters from each other and are settled in the same geological formation (see Fig. 1). Buildings are design in RC panels fixed to RC frame elements. The local geology is dominated by limestones and sandstones (Dubertret, 1944). The foundations of the buildings are settled inside the sandstones, at 20m depth. Two stories of parking occupy most of the buried part of the building.

Each tower is instrumented at the top with a Taurus seismic station (Nanometrics) associated to a CMG40 (Güralp) velocimeter. The sensor was aligned with the main orientation of the buildings, that are the same for the three of them (N340°). This sensor has a flat spectrum in the 30 s – 40 Hz frequency band. The sampling frequency is set to 200 Hz. The GPS is continuously on, in order to provide the best time correction to the records of each tower and to be able to compare them within a time accuracy of a few microseconds. The instrumentation started in April 2011, and is still ongoing.

Fourier transforms of one-hour ambient vibrations window recorded at the top of each building are displayed Fig. 2. In this figure, we observe clearly the resonant frequencies of the three towers, the amplitude and frequency variations being related to the building height. As for *non-parametric input only* modal analysis, we assume that the first peak corresponds to the first bending mode (0.72, 0.84, 0.93 and 0.85, 0.71, 0.93 for the W, V and X towers in the longitudinal and transverse directions, respectively). Table 1 summarise the values of the frequencies picked on Fig. 2.

For the three towers, the same fundamental frequency is obtained in the two horizontal directions, i.e. the same lateral resistant is assumed. Considering towers as continuous beams, we observe the classical series of bending frequencies (fundamental and overtones) for shear beam in the three towers (i.e., f2/f1=3, f3/f1= 5, f4/f1=7) in the longitudinal direction. As a consequence, we assume the intermediate frequencies (in italic case in Tab. 1) correspond to torsion mode, observed on the longitudinal direction only for W and V towers, and on both horizontal components for tower X. This

Figure 1. Location of the site of study(right), and external view of one of the towers (left). The geological conditions are visible here and there at the favor of new constructions. They consist of relatively tender Eocene sandstones with a high content of clays lying other the Cretaceous limestones (not visible on this view).

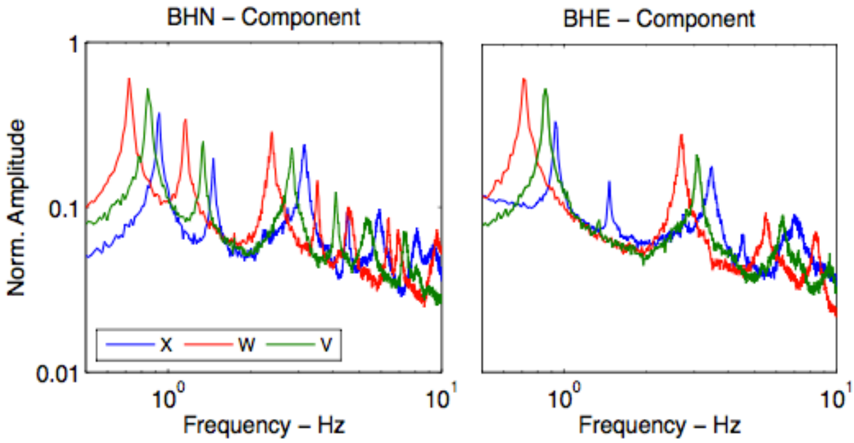

Figure 2. Average normalised amplitude of the Fourier transform computed on one ambient vibrations recording (one hour length) at the top of the three buildings in the longitudinal (left) and transverse (right) direction.

Table 1. Frequency values of the tower V, W, X obtained using ambient vibrations.

	Tower W		Tower V		Tower X	
mode	L (Hz)	T (Hz)	L (Hz)	T (Hz)	L (Hz)	T (Hz)
1	0.72	0.71	0.84	0.85	0.93	0.93
2	*1.16*		*1.34*		*1.46*	*1.46*
3	2.39	2.70	2.83	3.06	3.15	3.48
4	*3.51*		*4.10*		*4.52*	*4.52*
5	4.57	5.49	5.30	6.35	5.92	6.98
6	*6.41*		*7.26*		*8.12*	

difference may be considered as the mark of some variations from the building design of the X tower compared to the two others.

3. WANDERING OF THE FREQUENCIES USING THE RANDOM DECREMENT TECHNIQUE

An effective solution to track frequency and damping variations over time is to apply the random decrement technique, RDT. By stacking a large number of windows with identical initial conditions, ambient vibrations remain stationary and the impulse response of the structure is revealed. Vandiver et al. (1982) and Asmussen et al. (1999) provide details on the theory of RDT and its mathematical formulation that can be simplified by:

$$RDT\,(\tau) = \frac{1}{N}\sum_{i=1}^{N} s(t_i + \tau)$$

where N is the number of windows with fixed initial conditions, s is the ambient vibration window of duration τ, and t_i is the time verifying the initial conditions. The choice of initial conditions is a key point in ensuring the stability of the Random Decrement signature. The null displacement and positive velocity conditions proposed by Cole (1973) and verified by Asmussen et al. (1999) were used in the present work. The number of windows N is also critical to obtain a stable and relevant damping estimation. In our case, we optimised the parameters of the RDT by testing the τ and N values for providing the smallest dispersion. in the results. Before the RDT processing, a fourth-order band pass filter was applied to the raw data, centred on the expected fundamental frequency with a 10% frequency band. The RDT signature of the mode is exponentially damped and its period is computed by averaging the time lapse between two upward zero crossing points.

Figure 3 shows in black the variations of the frequency values for the Tower V in the longitudinal direction. The six first modes were considered and a sliding average window is applied for giving the smoothed wandering of the frequencies in yellow. We observe small fluctuations in time, the main variations are visible simultaneously on all modes (arrows B1 and B2). Nevertheless, we observe also some fast and transient variation (A1, A2 and A3) only on modes 2 and 3, assuming to be first and second torsion modes. Since the general trend of the variations are observed whatever the modes, this observation let us suppose that bending modes (modes 1, 3 and 5) do not react in the same way as torsion mode in case of specific external forcing.

The same trend is also observed when we compare the frequency variations for the three buildings. Figure 4 displays the frequency variations of the three towers for the first and second modes. We observe at the same time (B1 and B2 arrows) the same variations whatever the buildings and the direction (T direction not shown in this paper). As previously mentioned, the second mode (torsion) shows a fast variation only observed on this mode but simultaneously on the three towers. In order to explain the variations of frequency we observe, we plot (Fig. 5) a zoom of the frequency variation (20 days) for tower V in the longitudinal direction, compared to the external temperature recorded 10 km far away (Beirut Rafic Hariri International Airport station) . We observe that the fast transient variation of the torsion mode corresponds to an increase of the temperature, this external forcing having no effect on the bending mode. Moreover, the phases of the temperature and the torsion mode variations are in phase while they are in opposite phase for bending mode. Thus, torsion and bending modes do not have the same behaviour with respect to the temperature, confirmed by the same trend on the three towers, only for extreme forcing.

These observations lead to assume that :

(1) the three buildings have the same behaviour and the same frequency variations in time, confirming the relevancy of the frequency assessment of building using ambient vibrations.

(2) for buildings having the same design, the RDT is robust enough for detecting small variations, not always related to damages.

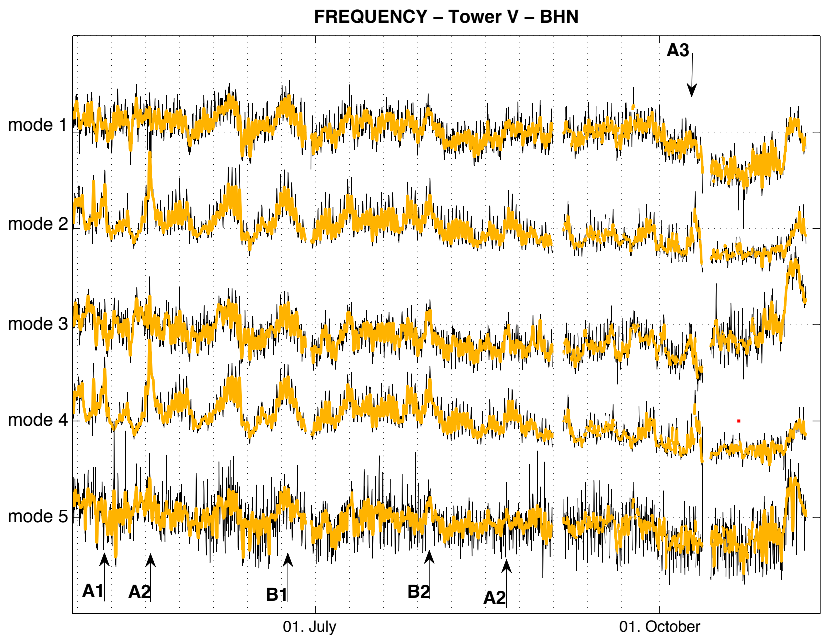

Figure 3. Frequency variations of the five first modes considering the longitudinal direction of the V tower. Yellow lines correspond to the smoothed variation, computed as the mean value of the frequency within a sliding windows (5 hours length). Value (Y-axis) are in Hz.

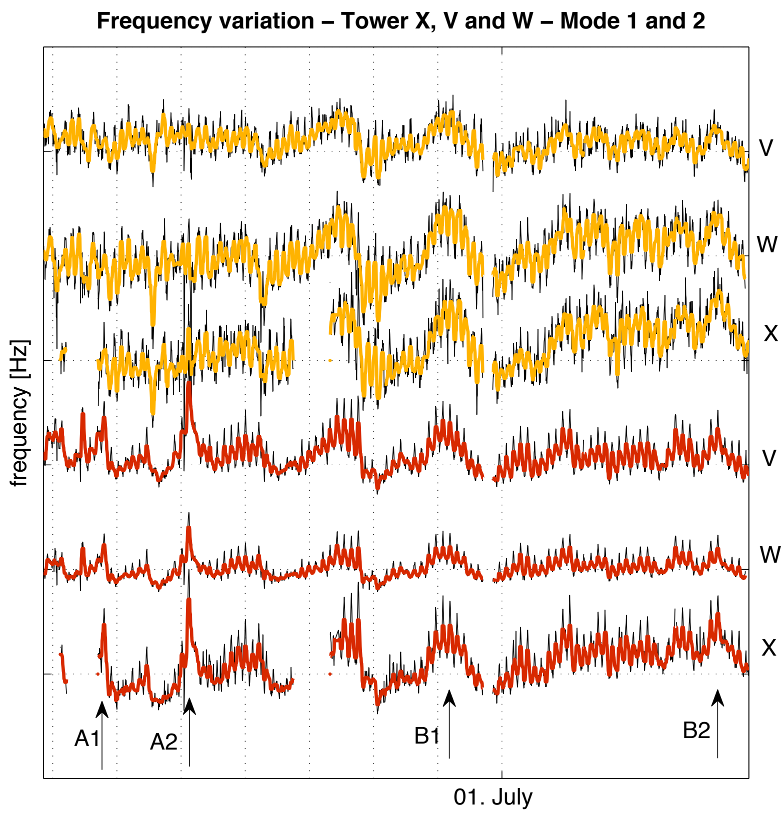

Figure 4. Frequency variations (black lines) for the three towers considering the first (bending, yellow line) and second (torsion, red line) modes. Thick lines correspond to the smoothed variation, computed as the mean value of the frequency within a sliding window (5 hours length). Value (Y-axis) are in Hz.

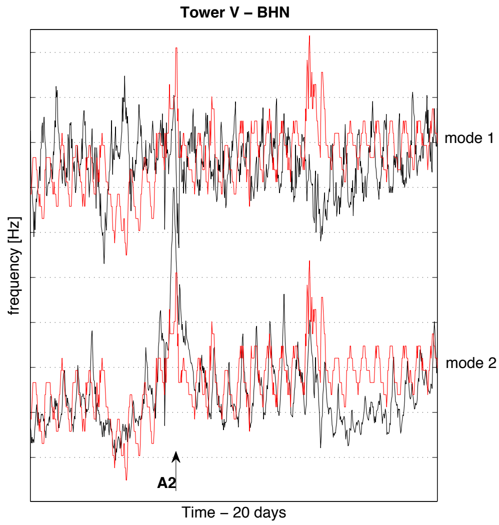

Figure 5. Zoom (20 days) of the frequency variations (black lines) for the longitudinal direction of the V tower considering the first (upper row) and second (lower row) modes, compared to the external temperature (red line) recorded at 10 km far away, at the Beirut airport. Value (Y-axis) are in Hz.

(3) torsion and bending modes usually react in the same way, except during strong forcing not clearly defined in this study.

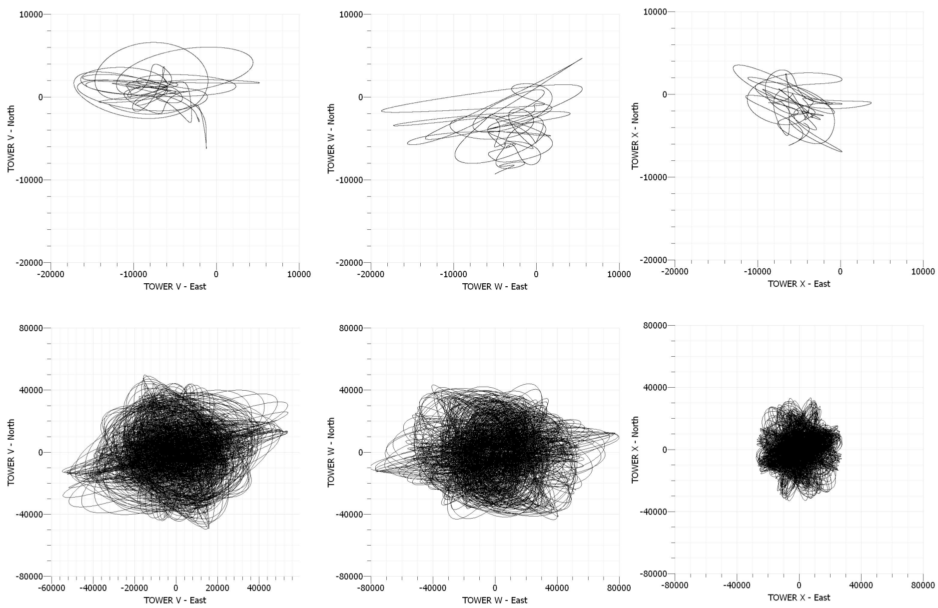

Figure 6. Ambient noise recording in the three towers. Upper row: filtered below 0.05 Hz. Lower row: Filtered around the fundamental frequency (0.6-1 Hz). Amplitude are in counts.

4. BUILDING-BUILDING INTERACTION UNDER NOISE AND EARTHQUAKE VIBRATIONS

4.1. Noise vibrations in the three towers

Figure 6 shows a typical recording of ambient noise in each tower. For the sake of comparison with the records of one regional earthquake in the following section, the motion is filtered in two bands: below 0.05 Hz and around the fundamental frequency of the three towers between 0.6 and 1 Hz. The duration presented here is 10 minutes. No clear ensemble behavior is evident from the analysis of these plots in the Longitudinal (North) - Transverse (East) plan. The three towers move randomly, without any clear ensemble motion even for long period as the 20 s presented herein, in opposition with intuitive expectation.

4.2 Recordings of the 2011 October 10 Van earthquake (Turkey, Mw=7.1, R=800 km) in the three towers.

Figure 7 shows the polar plots of the motion associated with the arrival of the 2011 Van earthquake, located in Eastern Turkey. The upper row presents the motion of the towers filtered below 0.05 Hz. At this period, the three towers experience the same ground motion in terms of amplitude and phase. That is to say that they behave as a single object. The lower row shows the same motion bandpass filtered between 0.6 and 1 Hz. This band allows for a focus on the fundamental frequency of each tower. Surprisingly, the motions are this time very different one from each other. If the towers V and W have comparable vibrations, the tower X appears to behave in a different way. This is apparently surprising because the three buildings share the same construction design, and should behave the same way, neglecting the small effects of the number of stories. One possible explanation besets in an interaction between the buildings that have close but different fundamental frequencies. Since fundamental frequencies are closed, beatings may occurred and provided some disturbances in the building response. This should be confirmed with further analysis on the data, e.g. computing cross-correlation.

5. CONCLUSIONS

The three buildings tested in this paper share the same structural design. The long-term variations of their fundamental frequencies are identical, wanderings being explained by air temperature variations. bending and torsion modes have different behaviors, although the same trends are observed in the three towers. The small variations observed are less than 0.1 %, and the Random Decrement Technique provides an effective tool for monitoring the structural dynamics of existing buildings. Further works could be expected using damping also for explaining the variations observed.

Under seismic noise, building motions appear independent one from the others, at low and high frequencies. On the contrary, under earthquake ground motion the three building move as an unique ensemble at low frequency, traducing the global effect of the long-period ground motion. Surprisingly, we observe out-of-phase response of the three towers at their fundamental frequency, even if their fundamental frequency are very close (0.7 to 0.9 Hz).

Further works must be done for improving the analysis of the three towers response, explaining the differences between torsion and bending modes wandering and the seismic response of nearby buildings. This may have impact on urban planning and understanding the lateral variability of damages observed at short distance.

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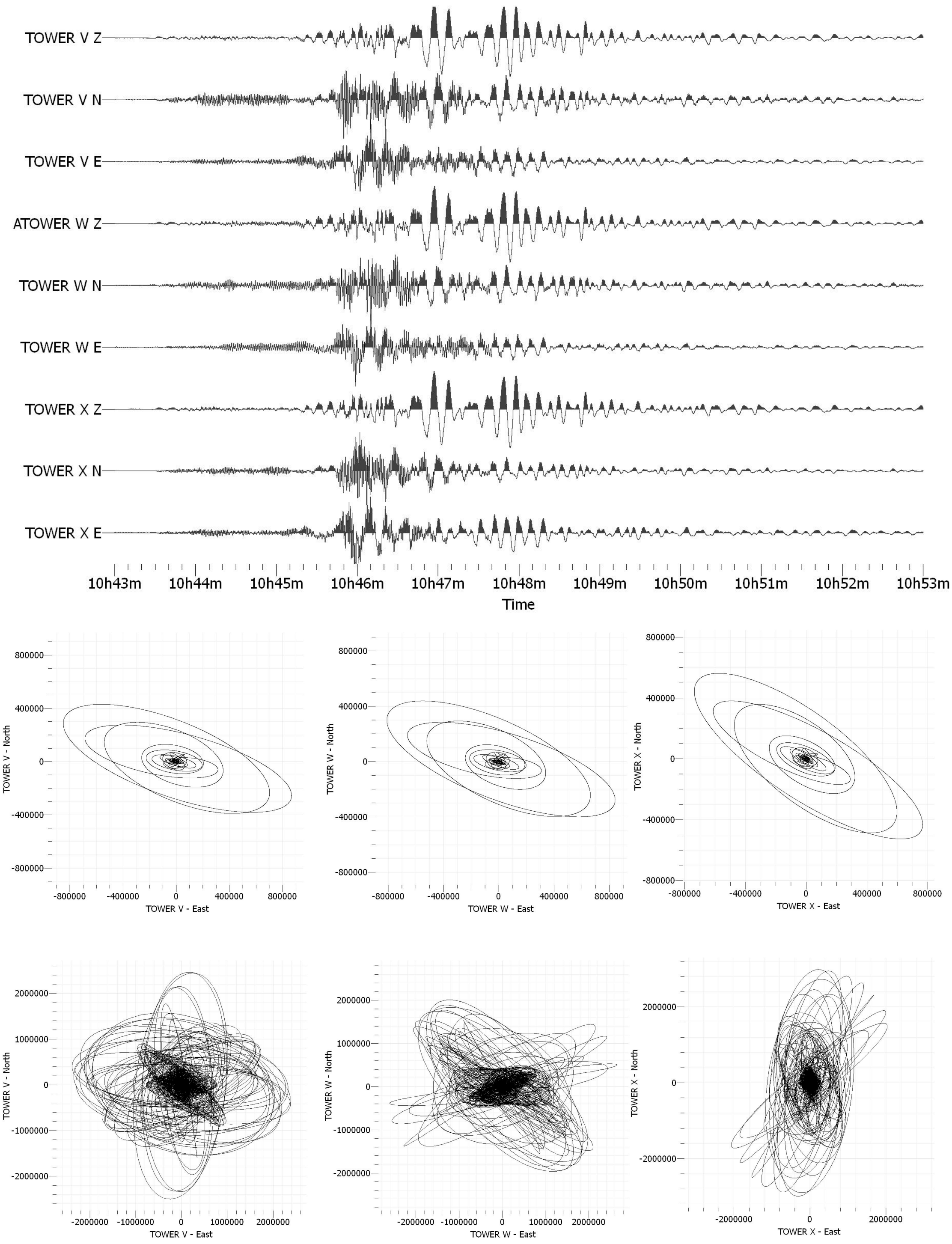

Figure 7. The records of the Van earthquake in the towers. Upper row: the 9 traces of the Van earthquake recorded in the towers. Middle row: the motion filtered below 0.05Hz. The three towers behave as an ensemble. Lower row: the motion filtered around the fundamental frequency of each building. The amplitude remains of the same order, but the motion look more independent from each other. Amplitude are in counts.

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