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Monitoring the response and the back-radiated energy of a building subjected to ambient vibration and impulsive action: the Falkenhof Tower (Potsdam, Germany)

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Abstract

The response of the soil-structure system near the Falkenhof Tower, Potsdam, Germany, has been monitored during the controlled explosion of a bomb dating to World War II. We installed eight 3-component velocimetric stations within the building and three in the surrounding area. We recorded several hours of seismic noise before and after the explosion, allowing the dynamic characterization of the structure both with ambient noise and forced vibration. We then compared the frequencies values and modal shapes of the structural modes evaluated both by analysing in the frequency domain the transfer functions and in the time-domain the different signals. Moreover, we carried out an interferometric analysis of the recorded signals in order to study the structural behaviour and to characterize the soil-structure interaction. Furthermore, we used normalized Short Time Fourier Transform (STFT) for the continuous monitoring of the structural response, in order to highlight possible frequency variations of the structural mode of vibration, and therefore of the structure's behaviour.

To assess structural frequencies and to compare them with those evaluated by transfer functions, we used azimuth-dependent Fourier spectra. We also verified the suitability of the Horizontal-to-Vertical Spectral Ratio (HVSr) for estimating the dynamic characteristics of buildings when only single station seismic noise measurements are available.

Regarding the structure-soil interaction, we identified the presence of a wave field back-radiated from the structure within the low amplitude seismic noise signal. In fact, in the free-field seismic noise recording spectra, peaks at frequencies consistent with those of the first two modes of the structure were recognized.

Keywords: *dynamic identification, soil-structure interaction, ambient vibrations, forced vibrations, rotational HVSR, monitored explosions*

Introduction

The problem of energy back-radiated from vibrating structures has been studied from both theoretical (e.g. Wong *et al.*, 1975) and experimental point of view. Due to the intrinsic difficulties in separating the building-radiated field from the incoming motion during an earthquake, alternative sources have been used: impulsive sources (Kanamori *et al.*, 1991), ambient noise (Chavez-Garcia *et al.*, 2002; Gallipoli M.R. *et al.*, 2004; Cornou C. *et al.*, 2004), or snap-back test on both models (Guéguen. *et al.*, 2002) and real buildings (Mucciarelli *et al.*, 2003; Gallipoli *et al.*, 2006; Ditommaso *et al.*, 2009).

Several authors have used seismic recordings or artificial sources to identify the dynamic properties of buildings (Trifunac, 1972; Hans *et al.*, 2005; Clinton *et al.*, 2006; Kohler *et al.*, 2005 - 2007) and their interaction with the surrounding soil (Safak, 1995 - 1999; Todorovska *et al.*, 2001; Trifunac *et al.*, 2007). However, while there is a vast literature on the effects of a nearby blast (tens of meters) on building behaviour, the use of large explosions (up to some hundred of meters from the target structure) to study dynamic characteristics of a building is not so widespread (Potapov, 1974; Dhakal, 2004; Davoodi *et al.*, 2007; Davoodi *et al.*, 2008).

In this study, we took advantage of the disposal of an unexploded ordnance from WWII near the town of Potsdam, Germany, in a sparsely inhabited area, where only one tall structure is present, to perform an experiment whose aim is twofold:

- 1) To verify if the dynamic characteristics estimated using ambient noise differ from those retrieved using a motion in the range from hundredth- to milli-g.
- 2) To study the propagation of back radiated energy both from ambient noise and the impulsive source.

Experiment description

On the 9th of July, 2008, several kilometres outside of the inhabited area of Potsdam, a bomb dating back to World War II was destroyed. In order to investigate how the seismic signal propagates into and out of a building, and how this could affect the recording in free field, 11 velocimetric stations were installed by the Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences. Eight stations were installed inside a building located in an area near the location of the explosion, while

3 stations were used to monitor free-field motions. In Figure 1 a satellite image shows the area of the experiment. The north-south direction coincides with the direction joining the building and the explosion site, and was used to orient the sensors. Each station is equipped with a 24 Db digitizer and a 1Hz geophone. The sampling rate was set to 100 sample per second.

The bomb was exploded about 300 m from the building and the radial direction between the location of the explosion and the building coincides with one of the main structural direction. The bomb had a mass of about 10 kg. The energy released was estimated to be around 40 MJ. The maximum amplitude recorded is similar to what can be expected for a magnitude 3 earthquake at 30 km (see Table 1 for some details on PGA, PGV and PGD).

The building (Figure 2) henceforth referred to as the Tower, is a brick-masonry, bearing-wall structure. It has a square plant (4m x 4m) and is about 16 m high. It is based on sandy ground and has no underground level. The structure consists of 6 storeys used as residential apartments and an additional level for the roof. The inter-storey height is 2.70 m. The thickness of the walls and the characteristics of the stairwell are unknown. Adjacent to the tower, along the NS direction, there is a 2 storey building that was not monitored.

The structure was monitored installing the sensors along two vertical directions, indicated as A and B in the plan view shown in Figure 3. Along vertical direction A, stations were located at all storeys, starting from the ground level, up to the roof, with the only exception being the first floor where access was denied by the owner for privacy reasons. In the vertical direction B, stations were installed at the ground level and at the sixth floor. As shown in Figure 3, vertical direction B coincides with the stairwell, and therefore, is closer to the estimated stiffness centre of the building than vertical direction A. Figure 3, also depicts the position of the stations installed outside the building. Station T1 was located at the bottom of an existing well at 2.5 m depth.

It is worth noting that the installation preceded by several hours the explosion, and that the de-installation of the network was done the day after. Therefore, a large amount of seismic noise data was available for the analysis together with the explosion generated signal.

Data analysis

Figure 4 shows some examples of the recorded signals, from the ground level (top) to the uppermost storey (bottom) of the structure on ± 5 sec around the explosion.

At first glance, there is an effect that might appear inconsistent with general expectations, that is, amplitude decreases with increasing height. As we will discuss later, this is mainly due to the fact that the energy released during the explosion is concentrated in a frequency band outside the eigenfrequencies of the building.

All records were first corrected by the following operations:

- baseline correction;
- trends removal;
- 0.1-30 Hz band-pass filter;
- smoothing with a Tukey window.

The length of the analysed time window pre- and post-explosion is 1600 sec. We divided the seismic noise into 20 sec moving windows with 50% overlap before analysis. The window including the explosion-generated signal was chosen to be 30 sec.

We then estimated the transfer functions for different storeys by calculating the spectral ratio between each station and the station installed in the ground floor of the building, the latter being chosen as the reference. The transfer functions were calculated separately for the vertical direction A and B. However, since the results obtained are very similar, for sake of simplicity we will discuss in the following only the results relevant to direction A.

RESULTS

Identification of the building's dynamic characteristics

The transfer functions calculated using seismic noise signal collected before and after the explosion are identical, as shown in Figures 5 and 7. This result implies that the structural behaviour remains unchanged after the explosion and that, therefore, no damage occurred.

A close look at the transfer functions allows us to identify the first vibration mode of the structure when, along one chosen direction, the amplitude of a peak occurring at a particular frequency increases with increasing storey level. In the case at hand, this

can be observed along the WE direction for the peak occurring at 2.73 Hz (first mode – WE1), and along the NS direction at 2.87 Hz (second mode – NS1). Furthermore, in both horizontal components an increase in the peak amplitude occurs at 6.20 Hz. This evidence indicates the existence of a rotational mode (third mode – R1). Over the frequency range 10 to 15 Hz, there are several peaks that might be attributed to the interaction between the tower and the adjacent structure.

The analysis of the transfer functions (Figure 6) obtained using the explosion signal allows us to identify the main modes of the buildings at frequencies consistent with those estimated by the seismic noise analysis. Moreover, the large amplitudes of the spectral peaks over the frequency range 5 to 20 Hz highlight the interaction between the second translational modes (of the tower) along the WE and NS directions and the adjacent structure. In fact, within this frequency band lies the resonance frequency of the small adjacent structure as assessed by seismic noise measurements (not shown here).

It is worth noting that the main frequencies of the structure (Figure 6) do not change when they are excited by the larger amplitude transient vibrations, confirming the results obtained for ambient noise and impact described in Boutin and Hans (2008). It also highlights that higher modes of the structure are strongly excited by the explosion. This behaviour can be easily explained considering that most of energy released during the explosion, differently from the noise spectrum, is concentrated within 5-20 Hz frequency range (Figure 17).

Using frequency-domain analysis, several peaks that could be related to higher modes of the structure were identified in the transfer functions estimated by the seismic noise and explosion data analysis. By performing a time domain analysis, filtering the signal around these peaks, it was then possible to assign the corresponding frequencies to the higher modes (the fourth at 12.22 Hz in the NS direction and the fifth one at 12.95 Hz in the EW direction) of the structure.

On the contrary, a clear spectral peak at 22.10 Hz indicating the second rotational mode of the structure (VI mode) is easily identified in the transfer functions of both the seismic noise and the explosion signal.

Summarizing, the spectral ratio analysis allowed us to identify six frequencies of vibration of the tower (Table 2) at 2.73, 2.87, 6.20, 12.22, 12.95 and 22.10 Hz.

The time-frequency analysis (normalized Short Time Fourier Transform, STFT) of signals starting before and ending after the explosion (Figures 8 and 9) confirms that during the explosion, while the resonance frequencies of the building do not vary, a strong interaction between the tower and the adjacent structure takes place. In fact, only during the explosion (between 50 and 55 sec) along the two main orthogonal directions were the frequencies of vibration of the small adjacent structure strongly excited.

Calculating the STFT over narrow-band filtered signals recorded at different levels inside the building allows us to confirm the interaction between the two structures. As an example, Figure 10 shows the results obtained by filtering the signal with a pass-band filter (5-9 Hz) around the peak at 7.5 Hz. The spectral amplitude at 7.5 Hz clearly decreases with increasing distance between the storey and the adjacent building, therefore confirming that this frequency cannot be ascribed to being a mode of vibration of the tower, but is due to the interaction between the two structures. Similar results, not shown here for sake of brevity, were obtained for the other peaks at 10 and 18 Hz shown in Figure 6. These results show that a frequency-time analysis can help in better understanding the dynamic characteristics of a building rather than a simple frequency domain analysis which is not able to follow the time-dependent variation of the seismic input and of the related building response. In particular, in this case, the use of seismic noise alone cannot constrain the effect of the adjacent building on the tower's behaviour.

Thanks to the large available data set, we set out to verify if single station noise measurements processed according the HVSR technique might be suitable for multi mode identification in the structure. The main frequencies of vibration were evaluated by rotating the horizontal component of the recorded motion and then performing both a spectra and a HVSR analysis. Both analyses were carried out by only considering the recordings collected on the topmost storey (Figure 3) along the vertical direction A. Figures 11 and 12 show the Fourier spectra of the horizontal component after rotation for the back-azimuth, and the corresponding HVSR, respectively.

Figures 11 and 12 show that both methods allow an estimation of the frequencies of vibration in agreement with those obtained by the standard spectral ratio method. It is worth noting that simple rotational HVSR allows us to identify the structural frequencies highlighting the peaks related to the first three main modes of vibration. However, note that the relative amplitudes of the HVSR peaks might be different from those estimated by the transfer function method due to the amplification of the vertical component of the motion in the building. Please, also note, that we verified during the measurements that no-strong source of noise was acting inside the building.

Figure 13 shows the structural modal shapes evaluated by the transfer function and the time domain analysis, with both techniques providing consistent results. The modal shapes derived using the eigenfrequencies previously estimated are consistent with the expected one for the kind of structure at hand. That is, the first 3 modes have nearly linear shapes with increasing level. Interestingly, the slope of the modal shape for higher modes changes after the second level in the building, indicating that there is a vertical change in the global stiffness (mainly along the NS direction) of the structure due to the adjacent small building.

Furthermore we also attempted to estimate the first two modal shapes by using HVSR. In order to characterize the modal shapes using this HVSR technique, at the second level, a linear interpolation was necessary because the signal recorded at this level was not reliable due to a malfunctioning of the sensor Z component. Interestingly, the HVSR results are consistent with those obtained by the transfer function and the time domain analysis. Using H/V ratio it is possible that the estimate of both resonance frequencies and modal shapes can be biased, if the vertical component has large spectral amplitudes in the range of frequencies close to the main frequencies of horizontal vibration. For example this can happen when the independent membrane vibrations of the floor can be large. It is therefore advisable, when H/V measurements are carried out, to place the instrumentations as close as possible to structural elements like columns, beams and walls.

Finally, we estimated the damping of the structure by using the method proposed in Mucciarelli and Gallipoli (2007). Damping was also evaluated for signals recorded by

station L1 located outside of the building. The damping value calculated for the Tower, with both signals in good agreement (~3%) and the estimated damping consistent with the small amplitude ground motion analysed. On the contrary, the damping values estimated from seismic noise (~6%) and the explosion signal (~3.5%) are different. Since one might expect higher damping in the case of larger amplitude ground motion, this result might indicate that the estimated damping is an effective one biased by the larger amount of energy radiated back to the soil by the Tower during the explosion.

Building-soil interaction

In order to verify if the Tower returned a significant amount of energy back into the ground, the rotational HVSR were also calculated for the recordings of station L1 (Figure 3) in the ambient noise window.

The results, reported in Figure 14, show that the first and second modes of the building can be tracked in the signal recorded at 10 meters distance outside it.

In order to study the structural behaviour and soil-structure interaction, an interferometric analysis (e.g. Curtis *et al.*, 2006; Snieder and Safak, 2006) was performed using signals recorded in the tower and at station L1. The signal at different levels was deconvolved for the signal recorded at the top of building using a regularized Tikhonov deconvolution (Tikhonov and Arsenin, 1977; Bertero and Boccacci, 1998; Parolai *et al.*, 2009). Figure 15 shows the results where we compared the analysis performed with seismic noise and the explosion signal. While there is good agreement between the results provided by both analyses for the WE and NS components, the results obtained for the Z component show discrepancies. However, this might be explained by taking into account that at each level of the Tower, the mass was different, implying different frequencies of vibration of the floor. In this case, each floor has exhibited a membrane behaviour, depending from masses and stiffness. Stiffness was the same at each floor, while masses were very different.

It is worth noting, for example on the WE component of the explosion signal recordings, the differences between the simple pulse in the acausal part of the Green's function and the long lasting oscillation in the causal one due to the

structural response. Also in the deconvolved wavefield the dominance of higher modes in the explosion signal is highlighted.

These analysis are in good agreement with the modal analysis presented in Figure 13. Performing a spectral analysis of the deconvolved traces depicted in Figure 15 (here not shown), it is possible to find the structural eigenfrequencies and the related modes (Figure 13); e.g. the ringing of the WE component, during the explosion (Figure 15), is a frequency related to the V mode ($f=12.95$ Hz) showed in Figure 13.

Finally, we investigated the possibility of detecting the fingerprint of soil-structure interaction using the FFT of the signals recorded on the ground surrounding the structure before the explosion. Figure 16 clearly shows two spectral peaks: one occurring at the same frequency of the fundamental mode of the structure, and another one at 22.10 Hz, the second rotational mode of the Tower. Thus, confirming the results of the rotational HVSR analysis, we see that ambient vibrations already indicate the capability of the structure to modify the free-field ground motion. This ability, however, disappears with distance. At station T2, located 25 m away from the building, the peak due to the fundamental period of the structure has vanished.

We also see that the amplitude of the peak at 22.10 Hz decreases with increasing distance for stations located outside of the tower (Figures 16 and 18) while it varies within the building, depending on the storey. Therefore, it is believed to be due to the structure and not to an external source.

Figure 17 shows the spectra of the signal generated by the explosion recorded at the free-field stations. The transient energy is concentrated within the 5-20 Hz frequency band, therefore at frequencies higher than the lower modes of the structure. This might explain why only the higher modes (third and fourth) were excited (Figure 17) and released back to the soil a large amount of energy.

The Fourier spectra of the signal recorded after the explosion are shown in Figure 18. Spectra are again similar to those calculated for seismic noise collected before the explosion with the first and fourth modes of the structure easily identified by a large peak in the spectra of all stations.

Finally, Figure 19 shows one example of the results obtained by calculating the spectral ratio between the recordings of the explosion at the closest station (L1) and the most distant one (T25). The radiated energy is visible also in the vertical component because the building-radiated wave field is a mix of body and Rayleigh

waves (Guèguen *et al.*, 2000, Mucciarelli *et al.*, 2003; Gallipoli *et al.*, 2006). Amplification peaks occur close to the main frequencies of vibration of the building. This result is consistent with the findings of Mucciarelli *et al.* (2008) and Ditommaso *et al.* (2009), who noticed that, although the soil-structure interaction in inhabited areas might act in general as a dampener for the recorded wavefield (Semblat *et al.*, 2008), there is a shift of energy that concentrates at frequencies close to the frequencies of the buildings yielding to local peaks of amplification in the Fourier spectrum.

Discussion and conclusion

The analysis of ambient and transient vibrations performed with different techniques showed that there was no change in the resonant frequencies of the structure investigated. In this case, the dynamic characteristics estimated using ambient noise does not differ from those retrieved using ground motion in the range from centi- to milli-g.

However, in the case of the presence of adjacent buildings, we showed that seismic noise analysis on a single building might not fully explain the structural behaviour. With regards to this, we also show that a frequency-time analysis is more informative than standard time domain or frequency domain investigations.

The presence of the Tower proved to be able to modify the free-field ground motion. It is important to note that the frequencies most affected during the ambient noise recording were those around the fundamental periods, because the structure of the noise reveals a broad peak in the same range of frequency. During the explosion, more energy is carried at higher frequencies, thus exciting the higher modes of the structure, whose contribution to the back-radiation also increases. While the global effect is a decrease in energy due to the added damping of the structure, in the frequency band close to the building's eigenfrequencies, there is a strong increase in spectral values. We believe that the modification of motion observed could be interesting for the effect they may have on accelerometric stations located inside or nearby stand-alone buildings. A more quantitative modelling of this effect is described in Ditommaso *et al.*, (2009).

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Table and Figure caption

Table 1: Peak ground parameters close to the Tower.

Table 2: Main frequencies of vibration of the structure.

Figure 1: Satellite site image showing the relative location of the monitored building and the site of the explosion.

Figure 2: Monitored building.

Figure 3: Instrumentation plan view.

Figure 4: Example of the recorded signals at the L1 station and along vertical A.

Figure 5: Transfer functions evaluated from noise recordings before the explosion.

Figure 6: Transfer functions evaluated from the signal recorded during the explosion.

Figure 7: Transfer functions evaluated from recordings after the explosion.

Figure 8: STFT evaluated during the explosion at the top floor – WE direction.

Figure 9: STFT evaluated during the explosion at the top floor – NS direction.

Figure 10: STFT of the filtered signal (5 – 9 Hz) recorded at each level of the building – NS Direction.

Figure 11: Rotational Fourier spectra.

Figure 12: Rotational HVSR.

Figure 13: Modal shapes with respect to level. Note the change in slope after the second level for the higher modes.

Figure 14: Rotational HVSR evaluated for L1 station.

Figure 15: Comparison of the interferometric analysis of signals recorded within the building and at the station L1 (Level 0) using noise (right) and explosion signals (left). Signal recorded at Level 3 (Z Component) was not reliable due to malfunctioning of the sensor.

Figure 16: Spectra evaluated with noise before the explosion.

Figure 17: Spectra evaluated during the explosion.

Figure 18: Spectra evaluated with noise after the explosion.

Figure 19: Spectral ratio between the L1 and T25 stations (vertical component).

Table 1

PGA (g)		
z	ns	we
0.00032987	0.00052496	0.00032522
PGV (m/s)		
z	ns	we
3.7668E-05	5.5438E-05	3.7887E-05
PGD (m)		
z	ns	we
6.7034E-07	5.3751E-07	7.4905E-07

Table 2

I Mode (WE1) Translational WE	II Mode (NS1) Translational NS	III Mode (R1) Rotational Z	IV Mode (NS2) Translational NS	V Mode (WE2) Translational WE	VI Mode (R2) Rotational Z
f (Hz)	f (Hz)	f (Hz)	f (Hz)	f (Hz)	F (Hz)
2,73	2,87	6,20	12,22	12.95	22.10

Figure 1

Figure 2

Figure 3

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Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

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