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DYNAMIC BEHAVIOR OF A MASONRY TOWER DURING LOW MAGNITUDE SEISMIC EVENTS: RESULTS OF AN EXPERIMENTAL MONITORING CAMPAIGN ON THE ARNOLFO TOWER (FLORENCE, ITALY)

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Abstract

Continuous seismometric monitoring of built structures allows the estimation of structural parameters in ordinary conditions, in the case of anthropic actions inside or outside the structure, and in the case of seismic events of different magnitude, hypocentral distances or epicentral azimuths. Moreover, in the case of buildings of historical and monumental interest, dynamic monitoring is a valid tool to compensate for the lack of information on the mechanical-physical properties of the construction materials, the geometry and the construction history, which can be up to several hundred years old, providing useful indications for the definition of numerical models for the dynamic behaviour simulation. Recognizing how the response in ordinary conditions of historic buildings varies during stresses produced by even small-magnitude seismic events can help in estimating the elastic behaviour of the structure when subjected to larger seismic actions. This study presents data acquired during a long-term experimental campaign conducted on the Torre di Arnolfo of Palazzo Vecchio in Florence. During the campaign seismic events characterized by different source parameters were recorded. The estimation of the dynamic behaviour of the Tower in unperturbed conditions and during earthquakes permitted the assessment of how the dynamic response may vary as a function of magnitude, distance and azimuth of the event. The ultimate target was to understand if and how the results obtained can contribute to providing useful information to define possible damage scenarios produced by seismic events originating in the different seismogenic zones present in the area surrounding the structure under study.

Keywords: Seismometric monitoring, low magnitude seismic events, Masonry Tower.

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1. INTRODUCTION

The continuous evolution of seismic monitoring techniques has allowed a deeper understanding of the dynamic behavior of structures, especially those of historical and monumental importance [1-5]. Real-time monitoring of building vibrations, during seismic events of different intensity, is essential to assess the dynamic structure response and to identify possible vulnerabilities [6-10]. In particular, dynamic monitoring represents a valuable tool for conservation and protection of historical buildings, as it provides crucial information to address the challenges posed by the lack of complete data on the mechanical properties of materials and construction history. Several studies highlight the significance of continuous seismic monitoring in analyzing the dynamic response of structures, not only in ordinary conditions, but also during far/near-field seismic events with different magnitude and epicentral distance [11-14].

The potential for acquiring data on the response of historic buildings to low-magnitude seismic stresses allows to assess the elastic behavior of the structure and to predict damage scenarios in case of more intense events. The analysis of the signals recorded during seismic events of various types offers a more detailed understanding of the vibration modes and the possibility of amplification phenomena due to the structural characteristics and the ground on which the building is built.

This study presents the results of an experimental monitoring campaign conducted on the Arnolfo Tower, one of the highest towers in the historical centre of Florence. Previous studies on this case have focused on the assessment of dynamic properties of the tower-building systems [15, 16]. With the aim to improve the understanding of how collected seismic data can be used to predict damage scenarios for historic structures and improve conservation practices, this paper provides a more comprehensive investigation, focusing on the Tower's behavior during low-magnitude seismic events. A database of seismic events has been collected during a three-year dynamic monitoring campaign on the Tower. The campaign resulted in a dataset of 36 seismic events with magnitude greater than 3.0, collected through two monitoring stations positioned at the foundation and the upper terrace of the Tower. Particular attention was paid to the correlation between the duration and intensity of the seismic oscillation, in order to assess how the effect of the event on the Tower of Arnolfo may vary in relation to the position and distance from the epicentre of the seismic event. This analysis involved the evaluation of spectral response ratios, variation of primary modal frequencies and soil response.

Research on the effect of seismic events on historic structures is not only of academic interest, but also of fundamental importance for the preservation of cultural heritage. Historic buildings, such as the Arnolfo Tower, are subject to unique challenges arising from ancient materials and construction techniques, which, although of great value, may be more vulnerable to the effects of seismic stresses. For this reason, the integration of empirical data and numerical simulations is an effective approach to assess seismic risk and improve intervention strategies for the protection of such buildings.

The analysis of seismic monitoring data collected on the Arnolfo Tower contributes to this goal, offering new insights into the seismic response of historic buildings and providing a study methodology that could be applied to other structures of historical and cultural interest in other seismically active areas.

2. THE ARNOLFO TOWER: MONITORING SYSTEM AND CAMPAIGN

The Arnolfo Tower (Figure 1a) is one of the symbols of the city of Florence. The Tower is a part of *Palazzo della Signoria*, also known as *Palazzo Vecchio* or *Palagio de' Priori*, seat of the government of the city of Florence since the 12th century.

Its construction, attributed to Arnolfo di Cambio, the architect of the Cathedral of Santa Maria del Fiore and the Basilica of Santa Croce, began in 1299.

The Tower, 95 m high, is one of the tallest historic buildings in Florence. The lower part is incorporated in the building itself and rests on a pre-existing medieval tower, the so-called "Torre della Vacca", about 30 m highs (50 Florentine arms), owned by the Foraboschi family [17, 18]. Both the Palazzo and the Tower consist of the same type of multi-leaf masonry formed by regular-sized sandstone blocks. Foundations are largely laid on the remains of the Roman theater of Florentia which can constitute a potential discontinuity. However, the Palazzo and the Tower exhibit good material continuity [16]. The portion of the basement structure included in the building consists of a massive masonry block with a rather regular rectangular plan (4.5 x 7.9 m). A distinctive feature of this tower is that, at the level of the walkway (33.8 m high), the structure stands out about 1.4 m from the façade below, and it's supported by a system of *'beccatelli'* that continues along the entire perimeter of the *Dado Arnolfiano*. Internally of the free-standing section of the Tower, a stairwell system of about 1 meter wide cross vertically through the structure, leading the terrace (69.2 m height) where the belfry is supported by the four massive circular masonry columns.

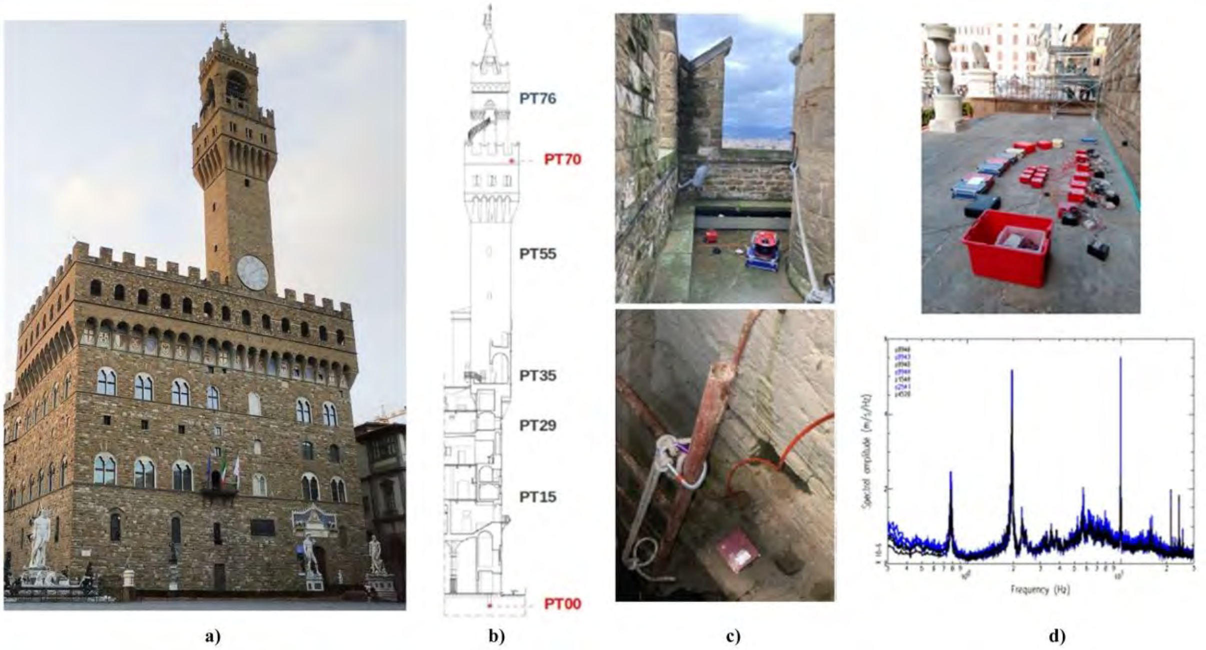


Figure 1. a) Palazzo Vecchio and Arnolfo Tower; b) Location of the seismic station along the Tower; c) examples of installation, terrace station (PT70 top figure) and one of the stations inside the Palazzo (PT00 bottom); d) Huddle Test, installation and comparison of the spectra recorded by all the seismic stations.

The monitoring campaign on the Arnolfo Tower was performed from December 2021 to the end of October 2023. At the beginning only two seismometric standalone stations were installed along the Tower (red in Figure 1b).

The base station (PT00) has been installed at the bottom of the Tower, inside the so called "Arengario" room at the entrance courtyard of the palace (Figure 1b,c). The seismometer was located about 3m below the ground level. The top station (PT70) was located at about 70 m in the terrace right below the bell chamber (Figure 1b,c). During the execution of the experiment other measuring points on the Tower were covered. Five more stations have been installed at the height of 15, 29, 35, 55 and 76 m respectively. All the seismic stations were equipped with 2.0 Hz three-axial velocity sensors coupled to 24-bit DAS, produced by SARA electronic instruments. The X axes were North oriented, corresponding to the in-plane direction after a rotation of 12° clockwise from N. All the devices were connected to GPS. Data were recorded at 100 sps in continuous mode, they have been corrected for the instrumental response before the analysis. The sensors were subjected to a Huddle Test to verify the correspondence of the recordings (Figure 1d).

3. EFFECTS OF EARTHQUAKES AND AMBIENT SOURCES

During the monitoring campaign, 36 earthquakes with magnitude stronger than 3.0 occurred up to about 190 km from Florence were recorded at least by the two main stations (PT00 and PT70). The earthquakes are well distributed both in distance and back-azimuth from the station, Figure 2 and Table 1.

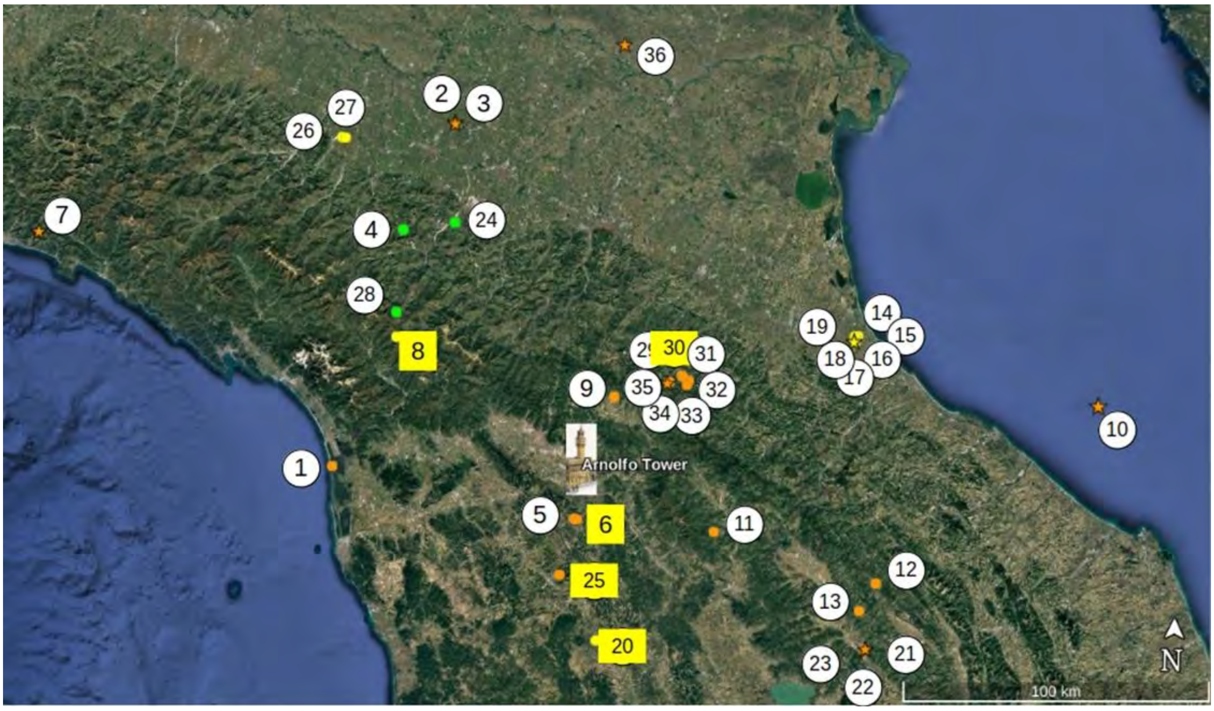
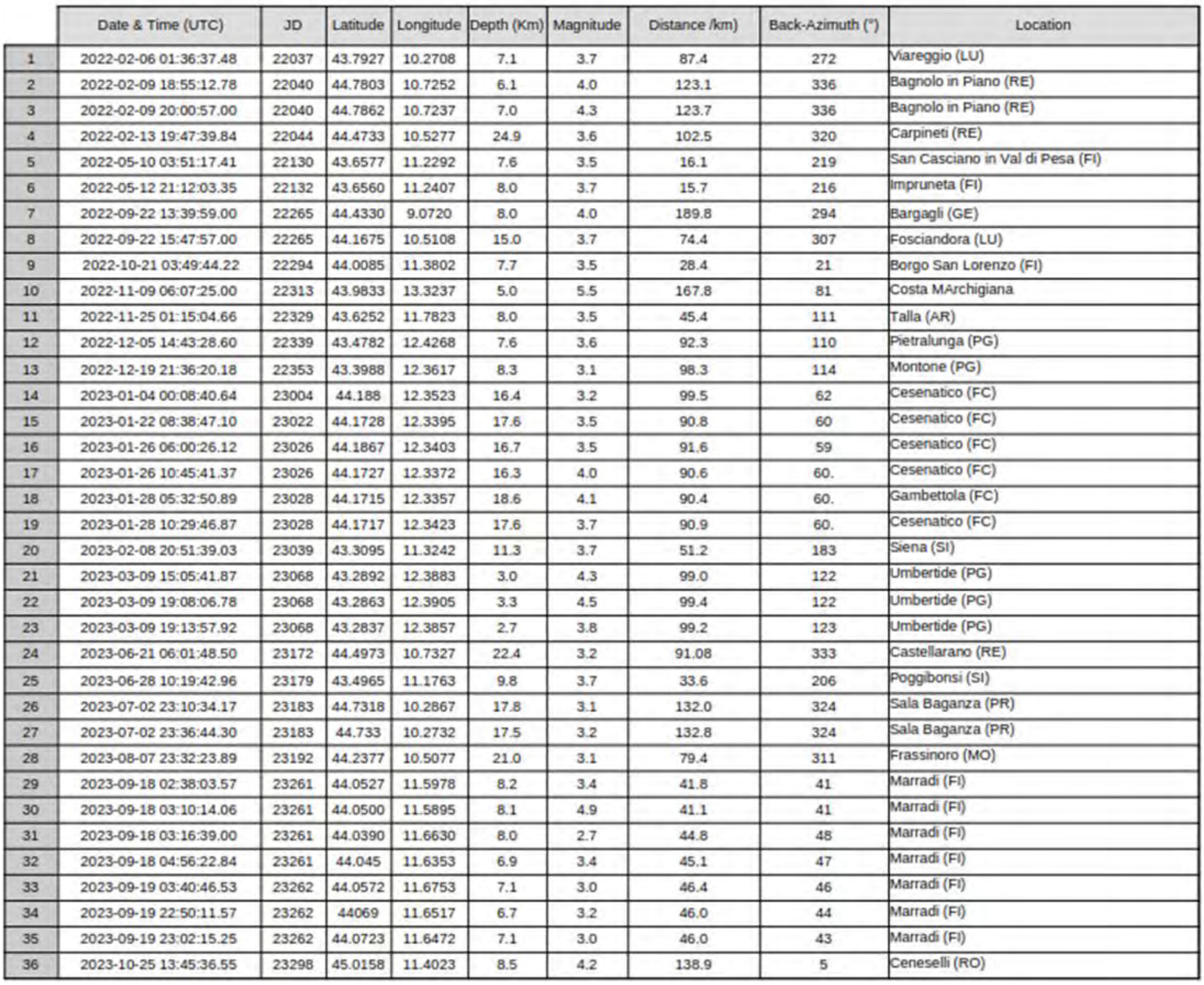


Figure 2. Map of the earthquakes recorded by the main monitoring station (PT00; PT70) during the experimental campaign. The events also recorded in the National Seismic Network station located in Florence inside the “Osservatorio Ximeniano” are highlighted in yellow.

On February 2022 and in October 2023 two seismic sequences occurred in the vicinity of Florence, the former in the Impruneta area, about 15 km from the center of Florence, the second in the area of Mugello, where in 1919 occurred the last strong earthquake occurred in the Northern Appenines (I_o X MCS, with estimated intensity VI in Florence). Both the seismic sequences produced hundreds of small seismic events, the Impruneta sequence at about 15 km from Florence exhibits a maximum magnitude equal to 3.7 (ML), the Mugello sequence maximum magnitude was 4.9. The highest magnitude events are: *i*) Bagnolo in piano (RE) 02/09/2022, M=4.3, epicentral distance 123 km, backazimuth 336°; *ii*) Costa Marche, 11/9/2022, M=5.5, epicentral distance 168 km, backazimuth 81°; *iii*) Umbertide, 03/09/2023, M=4.5, epicentral distance 99 km, backazimuth 122°; *iv*) Marradi, 09/18/2023, M=4.9, epicentral distance 41 km, backazimuth 41°. The backazimuth is measured clockwise from the direction corresponding to geographic North. Figure 2 shows the distribution of events recorded by the Tower stations. In yellow are highlighted those also recorded in the National

Seismic Network station located in Florence, inside the “Osservatorio Ximeniano” about 500 m from the Arnolfo Tower.



	Date & Time (UTC)	JD	Latitude	Longitude	Depth (Km)	Magnitude	Distance /km)	Back-Azimuth (°)	Location
1	2022-02-06 01:36:37.48	22037	43.7927	10.2708	7.1	3.7	87.4	272	Viareggio (LU)
2	2022-02-09 18:55:12.78	22040	44.7803	10.7252	6.1	4.0	123.1	336	Bagnolo in Piano (RE)
3	2022-02-09 20:00:57.00	22040	44.7862	10.7237	7.0	4.3	123.7	336	Bagnolo in Piano (RE)
4	2022-02-13 19:47:39.84	22044	44.4733	10.5277	24.9	3.6	102.5	320	Carpineti (RE)
5	2022-05-10 03:51:17.41	22130	43.6577	11.2292	7.6	3.5	16.1	219	San Casciano in Val di Pesa (FI)
6	2022-05-12 21:12:03.35	22132	43.6560	11.2407	8.0	3.7	15.7	216	Impruneta (FI)
7	2022-09-22 13:39:59.00	22265	44.4330	9.0720	8.0	4.0	189.8	294	Bargagli (GE)
8	2022-09-22 15:47:57.00	22265	44.1675	10.5108	15.0	3.7	74.4	307	Fosciandora (LU)
9	2022-10-21 03:49:44.22	22294	44.0085	11.3802	7.7	3.5	28.4	21	Borgo San Lorenzo (FI)
10	2022-11-09 06:07:25.00	22313	43.9833	13.3237	5.0	5.5	167.8	81	Costa MArchigiana
11	2022-11-25 01:15:04.66	22329	43.6252	11.7823	8.0	3.5	45.4	111	Talla (AR)
12	2022-12-05 14:43:28.60	22339	43.4782	12.4268	7.6	3.6	92.3	110	Pietralunga (PG)
13	2022-12-19 21:36:20.18	22353	43.3988	12.3617	8.3	3.1	98.3	114	Montone (PG)
14	2023-01-04 00:08:40.64	23004	44.188	12.3523	16.4	3.2	99.5	62	Cesenatico (FC)
15	2023-01-22 08:38:47.10	23022	44.1728	12.3395	17.6	3.5	90.8	60	Cesenatico (FC)
16	2023-01-26 06:00:26.12	23026	44.1867	12.3403	16.7	3.5	91.6	59	Cesenatico (FC)
17	2023-01-26 10:45:41.37	23026	44.1727	12.3372	16.3	4.0	90.6	60.	Cesenatico (FC)
18	2023-01-28 05:32:50.89	23028	44.1715	12.3357	18.6	4.1	90.4	60.	Gambettola (FC)
19	2023-01-28 10:29:46.87	23028	44.1717	12.3423	17.6	3.7	90.9	60.	Cesenatico (FC)
20	2023-02-08 20:51:39.03	23039	43.3095	11.3242	11.3	3.7	51.2	183	Siena (SI)
21	2023-03-09 15:05:41.87	23068	43.2892	12.3883	3.0	4.3	99.0	122	Umbertide (PG)
22	2023-03-09 19:08:06.78	23068	43.2863	12.3905	3.3	4.5	99.4	122	Umbertide (PG)
23	2023-03-09 19:13:57.92	23068	43.2837	12.3857	2.7	3.8	99.2	123	Umbertide (PG)
24	2023-06-21 06:01:48.50	23172	44.4973	10.7327	22.4	3.2	91.08	333	Castellarano (RE)
25	2023-06-28 10:19:42.96	23179	43.4965	11.1763	9.8	3.7	33.6	206	Poggibonsi (SI)
26	2023-07-02 23:10:34.17	23183	44.7318	10.2867	17.8	3.1	132.0	324	Sala Baganza (PR)
27	2023-07-02 23:36:44.30	23183	44.733	10.2732	17.5	3.2	132.8	324	Sala Baganza (PR)
28	2023-08-07 23:32:23.89	23192	44.2377	10.5077	21.0	3.1	79.4	311	Frassinoro (MO)
29	2023-09-18 02:38:03.57	23261	44.0527	11.5978	8.2	3.4	41.8	41	Marradi (FI)
30	2023-09-18 03:10:14.06	23261	44.0500	11.5895	8.1	4.9	41.1	41	Marradi (FI)
31	2023-09-18 03:16:39.00	23261	44.0390	11.6630	8.0	2.7	44.8	48	Marradi (FI)
32	2023-09-18 04:56:22.84	23261	44.045	11.6353	6.9	3.4	45.1	47	Marradi (FI)
33	2023-09-19 03:40:46.53	23262	44.0572	11.6753	7.1	3.0	46.4	46	Marradi (FI)
34	2023-09-19 22:50:11.57	23262	44069	11.6517	6.7	3.2	46.0	44	Marradi (FI)
35	2023-09-19 23:02:15.25	23262	44.0723	11.6472	7.1	3.0	46.0	43	Marradi (FI)
36	2023-10-25 13:45:36.55	23298	45.0158	11.4023	8.5	4.2	138.9	5	Ceneselli (RO)

Table 1. List of the earthquakes recorded by the main monitoring station (PT00; PT70) during the experimental campaign.

3.1. Top-Base Vibration Amplification and Duration Effects

For each event, the seismograms of the recordings from the top (black) and the base (blue) of the Tower have been analysed. For the sake of brevity, the event records shown in Figures 3 and 4 refer to some of the most representative ones. The numbers correspond to those reported in the list of events (Table 1). The comparison demonstrates that, during the majority of the seismic events recorded by the two stations, a clear effect of significant amplification of the vibration and its duration is observed along the horizontal components. Seems to be related to the propagation along the structure of transverse (S) and waves which produce a reverberation effect of the oscillation that prolongs the duration of the seismogram at the top station.

The effect does not seem to be directly related to the source parameters of the event (magnitude, depth, epicentral distance or back azimuth).

Events originating from the same azimuthal sector (e.g. 2, 3, 26, 27, 28 or 29, 30, 31, 32, 33, 34, 35), with comparable magnitude and distance (e.g. 20, 25 or 13, 24 or 17, 18) or with similar seismic distance (e.g. 2, 3, 26, 27) exhibit different behaviors. The amplification of the oscillation appears to be less consistent in the case of impulsive events (5, 6, 6b, 9), for which however a prolongation of the durations is recorded, evidently influenced by the damping of the building. In the case of vertical components, an amplification effect on the amplitude of the oscillations is generally observed, which is particularly evident for impulsive events, while resonance phenomena that produce a prolongation of the duration of the oscillation are not so often present.

Figure 5 shows the relation between the duration ratios between PT70-PT00 with magnitude, distance or back-azimuth for each motion component. The distribution of top-base duration ratios shows no functional relationship with magnitude, distance or back-azimuth.

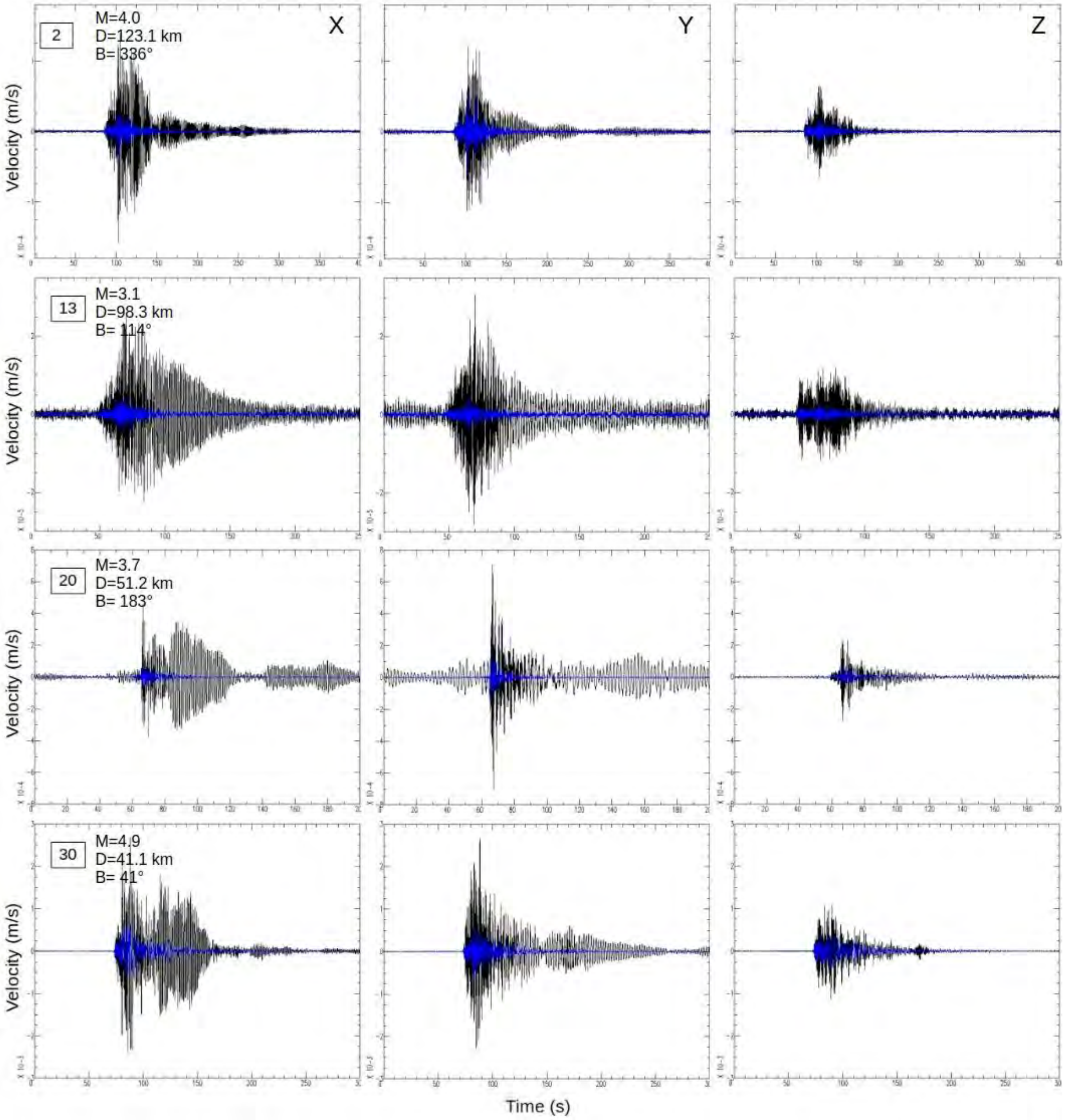


Figure 3. Seismograms recorded at the top (PT70, black), superimposed to the waveforms recorded at the base (PT00, blu). The numbers correspond to the earthquakes highlighted in the map, 2, 13, 20, 30.

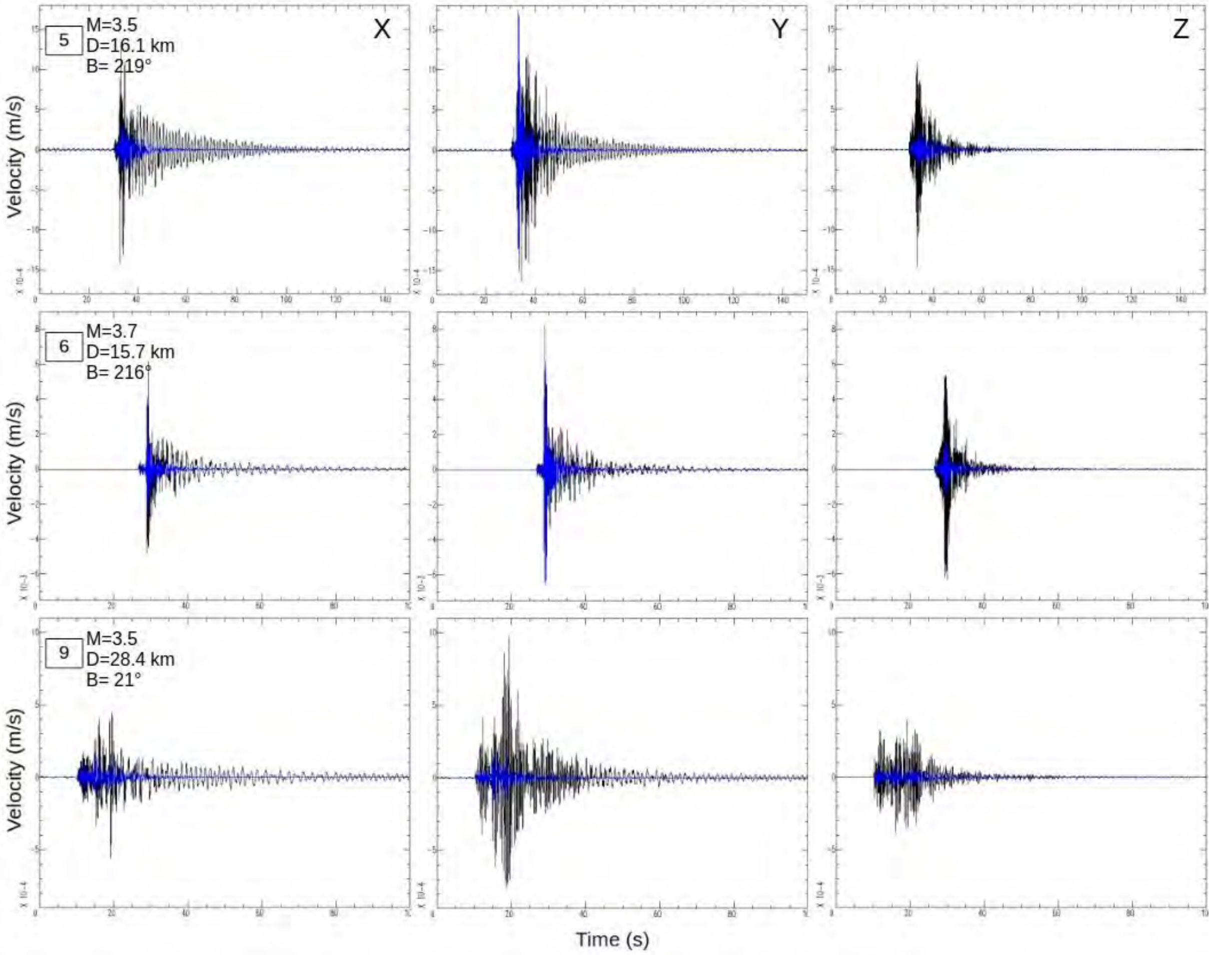


Figure 4. Seismogram recorded at the top (PT70, black), superimposed to the waveforms recorded at the base (PT00, blu). The numbers correspond to the earthquakes highlighted in the map, 5, 6, and 9.

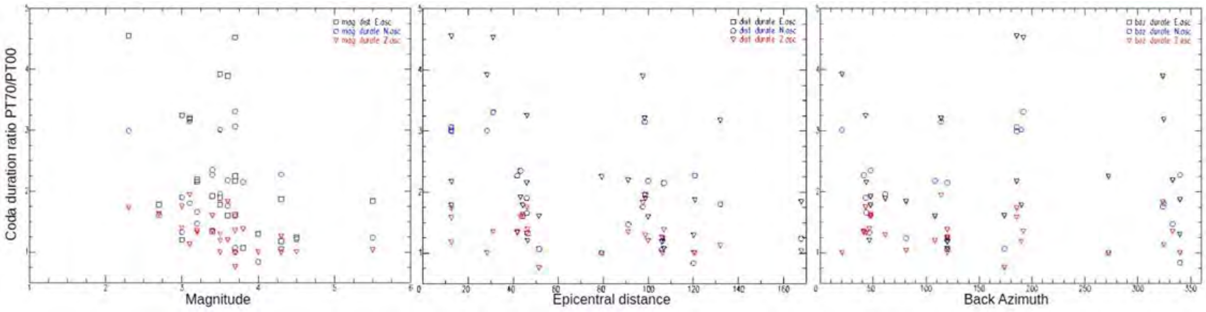


Figure 5. Correlation between the duration ratios between PT00-PT70 with magnitude, distance and back-azimuth for each motion component.

3.2. Spectral response ratio

The Spectral ratios between homologous components at the top and base stations (SSR, Standard Spectral Ratio) have been calculated for all recorded events. The SSR ratios demonstrate the frequency content at the top in comparison to that recorded at the base of the Tower. Given that the signal at the base represents the seismic input, it can be considered representative of the empirical response function of the system.

The SSR ratios analysis allows to identify some peculiarities of the structure's response to the seismic input common to most of the seismic events recorded inside the Tower.

Along the horizontal components, practically for all seismic events and independently from the source parameters, it is possible to recognize the spectral peaks corresponding to the modal frequencies identified through the analysis of free vibrations, both those at low frequency associated with oscillation modes of the Tower (0.49 Hz and 0.80 Hz) and those above 1 Hz that would seem to be linked to the modes of the Palazzo dei Priori. Some events do not show low frequency content, they are the seismic events characterized by a shorter epicentral distance (5, 6, 6b, 9), corresponding to the areas of San Casciano in Val di Pesa, Impruneta and Borgo San Lorenzo. These events, with magnitudes ranging from 3.5 to 3.7, correspond to the most impulsive ones, for which the duration of the most energetic phase of the seismogram on which the spectral ratio is calculated corresponds to a few seconds (from 1.5 to about 4 s).

As regards the vertical component (Z, in red), excluding the impulsive and closest events, a spectral peak centered on a frequency of 6 Hz dominates over all the other events, which could likely be associated with an axial mode of the Tower. The events that present low-frequency peaks in the SSR ratio seem to correspond to the events that show greater amplification and prolongation of durations.

For sake of brevity the SSR spectra of the most energetic events (M $\geqslant$ 4.0) were averaged to obtain average spectral ratios on all the motion components. Figure 6 indicates the frequencies of the main peaks on each component.

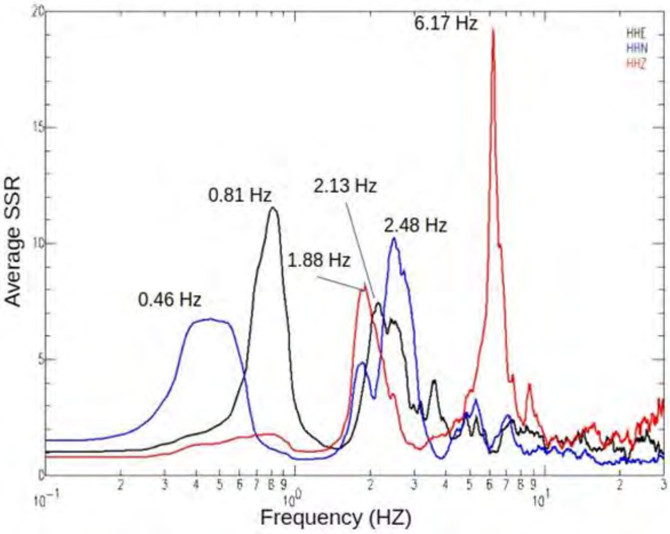


Figure 6. Frequencies of the main peaks on each component, averaged to obtain mean spectral ratios over all motion components, obtained from the SSR spectra of events with magnitude M $\geqslant$ 4.0.

The trends of the average SSR ratios on the largest magnitude earthquakes were compared with the average spectra calculated on free vibrations of the structure, calculated on approximately 50 consecutive days of recording. Figure 7 shows an excellent agreement between the results from the earthquake analysis and the spectral analysis of the free vibrations of the structure. On the horizontal components, a good correlation is found between the frequency peak identified through the two independent datasets, the peak value detected through the earthquakes is significantly higher than that obtained for free vibrations. Further investigation will be needed to understand the causes of this discrepancy.

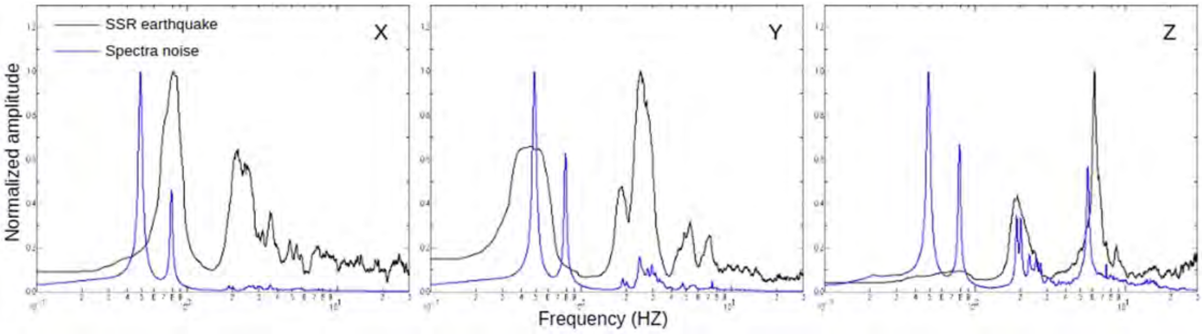


Figure 7. Comparison of mean SSR ratios on larger magnitude earthquakes and mean spectra calculated on free vibrations of the structure, calculated over approximately 50 consecutive days of recording.

3.3. Time variation of modal Frequencies

To evaluate the effect produced by the seismic events on the modal frequencies of the Tower, the temporal trends of the main modal frequencies were estimated on the days in which the most significant events were recorded.

The spectra were calculated on all the 240 s intervals present on the daily recording. The temporal trends of the modal frequencies were superimposed on the daily waveforms.

Figure 8 show the temporal trend of the main modal frequency (F0), relative to the out-of-plane direction (Y), and of the corresponding spectral amplitude; the signals inside each box are the seismograms of the recorded events. Only some events produce a temporary reduction in the modal frequency, although they are not of particularly high magnitude. The extent of the effect is quantified on values of the order of a few percentage points of the value of the modal frequency both in the case of some events with a magnitude greater than 4.0, and for events with a lower magnitude if the epicentre of the event is sufficiently close to the Tower. Table 2 shows the events that have produced a reduction in the modal frequency.

	Date & Time	Latitude	Longitude	Depth (Km)	Magnitude	Distance /km)	Back-Azimuth (°)	Location
6	2022-05-12 21:12:03.35	43.6560	11.2407	8.0	3.7	15.7	216	Impruneta (FI)
10	2022-11-09 06:07:25.00	43.9833	13.3237	5.0	5.5	167.8	81	Costa MArchigiana
11	2022-11-25 01:15:04.66	43.6252	11.7823	8.0	3.5	45.4	111	Talla (AR)
23	2023-03-09 19:13:57.92	43.2837	12.3857	2.7	3.8	99.2	123	Umbertide (PG)
30	2023-09-18 03:10:14.06	44.0500	11.5895	8.1	4.9	41.1	41	Marradi (FI)

Table 2. List of events that produced a reduction in modal frequency.

3.4. Soil spectral properties assessment

The station located at the base was used to characterize the foundation soil of the Palace and the Tower, in order to investigate the possibility that double resonance effects could be generated and that these are the cause that determines the significant prolongation of the durations recorded at the top of the Tower. To do this, recordings of ambient seismic noise were used, as far as possible free of particularly energetic transients. HVSR (Horizontal to Vertical Spectral Ratio) spectral ratios were calculated according to the methodology introduced by Nakamura (1989) [19]. Figure 9 shows the average HV spectral ratio over 20 of the monitoring days.

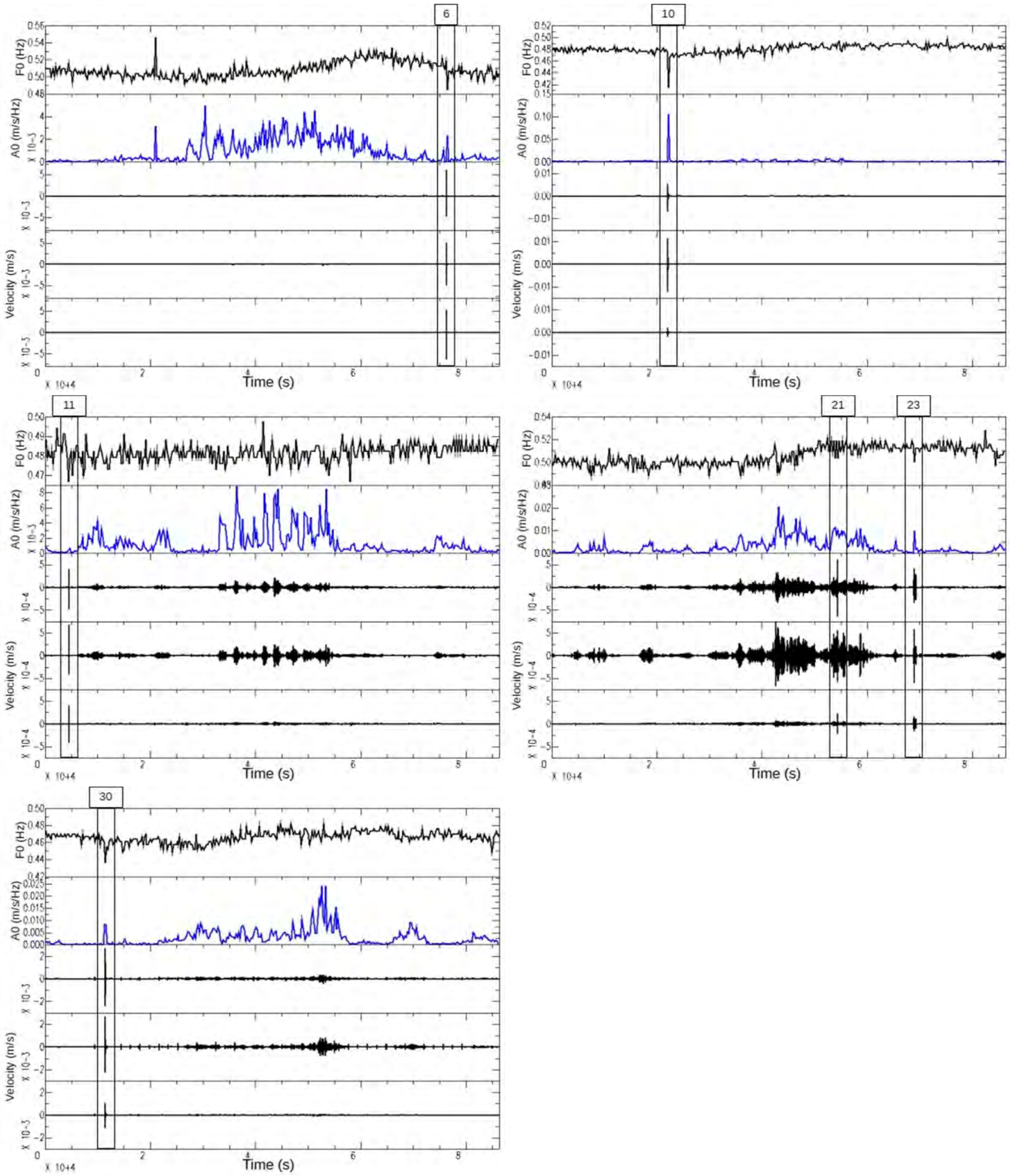


Figure 8. Temporal trend of the main modal frequency (F0), relative to the out-of-plane direction (Y), and of the corresponding spectral amplitude.

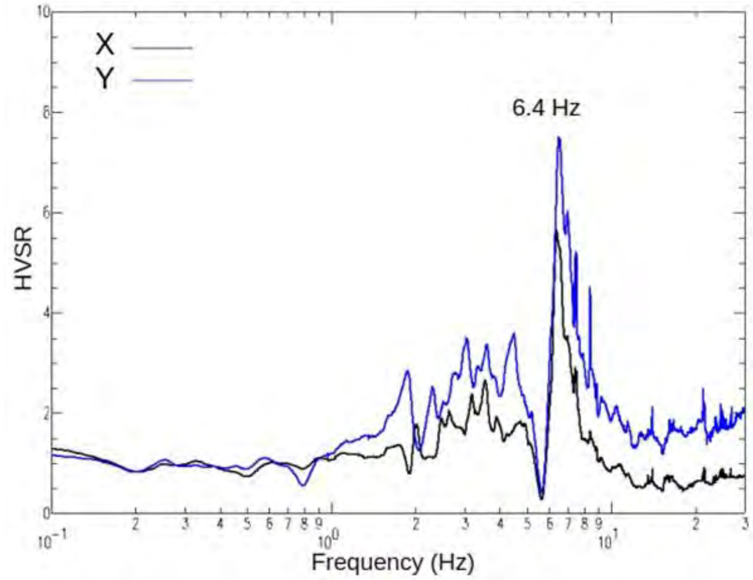
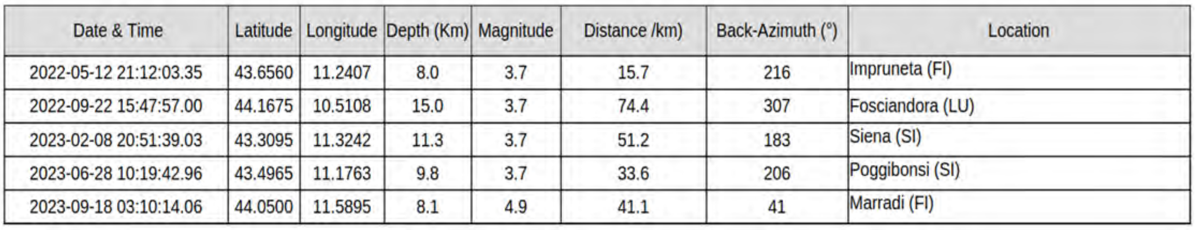


Figure 9. HVSR of station PT00 in X and Y directions.

The average HVSR shows a clear spectral peak centered on a frequency of 6.4 Hz which fits well with the results of the seismic microzonation performed in the urban area of Florence (https://www.regione.toscana.it/-/risultati-delle-indagini-nella-provincia-di-firenze). In particular, a measurement point reported in the map of the fundamental frequencies of the soil, located about 250 m away from the Arnolfo Tower, indicates a HVSR frequency peak centered on 6.7 Hz with an amplitude of 4.7, values that do not differ much from those identified by the analysis on the signals recorded at the base of the Tower.

Some seismic events recorded during the monitoring of the Tower were recorded by the seismic station installed inside the "Osservatorio Ximeniano" of Florence, just over 500 m away from the Tower. The selected earthquakes are indicated in Table 3.



Date & Time	Latitude	Longitude	Depth (Km)	Magnitude	Distance /km)	Back-Azimuth (°)	Location
2022-05-12 21:12:03.35	43.6560	11.2407	8.0	3.7	15.7	216	Impruneta (FI)
2022-09-22 15:47:57.00	44.1675	10.5108	15.0	3.7	74.4	307	Fosciandora (LU)
2023-02-08 20:51:39.03	43.3095	11.3242	11.3	3.7	51.2	183	Siena (SI)
2023-06-28 10:19:42.96	43.4965	11.1763	9.8	3.7	33.6	206	Poggibonsi (SI)
2023-09-18 03:10:14.06	44.0500	11.5895	8.1	4.9	41.1	41	Marradi (FI)

Table 3. List of events recorder to the seismic station of Ximeniano Observatory.

The homologous component spectral ratios (SSR) were calculated between the seismograms recorded at the base of the Tower and inside the "Osservatorio Ximeniano". The Figure 10 shows the average of the SSR spectral ratios on all the selected events. On all the components the SSR spectral ratio does not differ much from a unit value, this would seem to indicate that the two sites present extremely similar spectral characteristics and that the base station of the Tower does not show particular amplifications on frequencies that could be in resonance with the modal frequencies of the Tower.

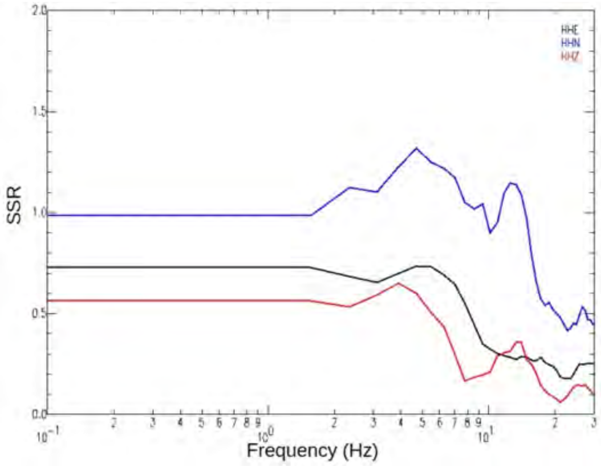


Figure 10. Average of the SSR spectral ratios on all the events recorder to the Ximeniano station.

4. CONCLUSIONS

In this study, the analysis of data acquired during a long-term seismic monitoring campaign conducted on the Arnolfo Tower is presented, with the aim of analyzing the effect of low magnitude seismic events, on the dynamic response of the structure. Recordings from seismic stations located along the Tower permitted the evaluation of the variations in the dynamic response of the Tower as a function of various seismic parameters, including magnitude, distance and azimuth of the event. Continuous monitoring for about two years, has allowed to record numerous seismic events distributed with a good azimuth coverage, over a magnitude range between 3.0 and 5.5 and epicentral distance between about 15 and 190 km. The analysis enabled the observation of the structure response to impulsive and far-field events, highlighting phenomena of amplification and prolongation of the duration of the oscillations.

In summary, the following findings are highlighted:

- The comparison between the seismograms recorded at the base and at the top of the Tower, as expected, reveals a significant shaking amplification and a resonance effect that prolongs the duration of the oscillation. This effect appears to be unrelated to the source parameters of seismic events, as no clear correlation is observed in the distribution of the ratios between the durations at the top and at the base with respect to magnitude, epicentral distance or back-azimuth. Only impulsive near-field events do not inhibit spectral peaks that can be associated with the fundamental harmonics of the Tower.
- The analysis of the time variation of the modal frequencies during seismic events indicates that some earthquakes results in a temporary reduction in the modal frequency of the Tower which appears correlated with the duration of the ground shaking. This suggests that the propagation of the seismic wave inside the Tower tends to cause a temporary reduction in the stiffness of the structure, which returns to its initial values at the end of the event.
- The HVSR (Horizontal to Vertical Spectral Ratio) analyses on the base station highlight the presence of a spectral peak centered on 6.4 Hz, consistent with the microzonation analyses of Florence. This suggests a rigid soil conditions with a thin alluvial cover that could extend only few meters in depth. Consequently, there are no conditions of triggering double resonance phenomena on the Tower or on the Palazzo della Signoria. Furthermore, the spectral comparison between the base

station of the Tower and the station of the National Seismic Network installed inside the Osservatorio Ximeniano, at about 500 meters, shows no significant differences in the recorded signals.

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