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Monitoring of the "twin towers" of Bologna in Italy

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Introduction

Non-destructive testing methods, and especially the Acoustic Emission (AE) technique, applied as in situ monitoring systems allow reliable evaluation of the state of conservation of historical masonry buildings and its evolution in time.

In this contribution, in which the preliminary outcomes on the monitoring of the "Garisenda" Tower are discussed, there are also briefly presented the results already obtained from the monitoring of the “Asinelli” Tower, carried out a few years ago by the Authors.

The two Towers, in fact, recognized as the "*twin towers*" of Bologna, represent a remarkable symbol of the City in the Italian Architectural Heritage.

The two towers of Bologna: Asinelli and Garisenda

The Authors of the various histories of the City of Bologna all agree in dating the Asinelli and Garisenda Towers to the early twelfth century.

The Asinelli Tower and the Garisenda Tower in the city centre of Bologna

The Asinelli Tower

The Asinelli Tower was built in 1109 – 1119.

The Tower rises to a height of 97.30 m above the ground, and show a deviation from verticality of 2.38 m.

It has a square cross-section, tapering along its height, the sides measuring ca 8.00 m at the base and 6.50 m at the top.

From the structural standpoint, the tower can be subdivided into four segments, depending on type of masonry.

The Garisenda Tower

The Garisenda Tower, built around the same time, is much smaller (48 metres) but with a steeper leaning (3.22 m) due to an early and more marked subsidence of soil and foundation.

In the middle of the 14th century the Tower, which was 60 m high, was cut by 12 m reaching the current 48 m which it measures today.

The ashlar covering in “selenite” stone of the base dates back to the late 19th century.

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A study on the structural stability of the Asinelli Tower in Bologna

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SUMMARY

This study concerns the structural stability of the Asinelli Tower in Bologna. This building is the tallest and, with the Garisenda Tower, the most undisputed symbol of the City of Bologna. The stability conditions of the tower were analyzed by means of the Acoustic Emission technique. Specifically, this approach was used to analyze the influence of repetitive and impulsive events of natural or anthropic origin, such as earthquakes, wind, or vehicle traffic on the damage evolution of the tower.

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KEY WORDS: acoustic emission; damage evolution; seismic effects; masonry structures; non-destructive monitoring

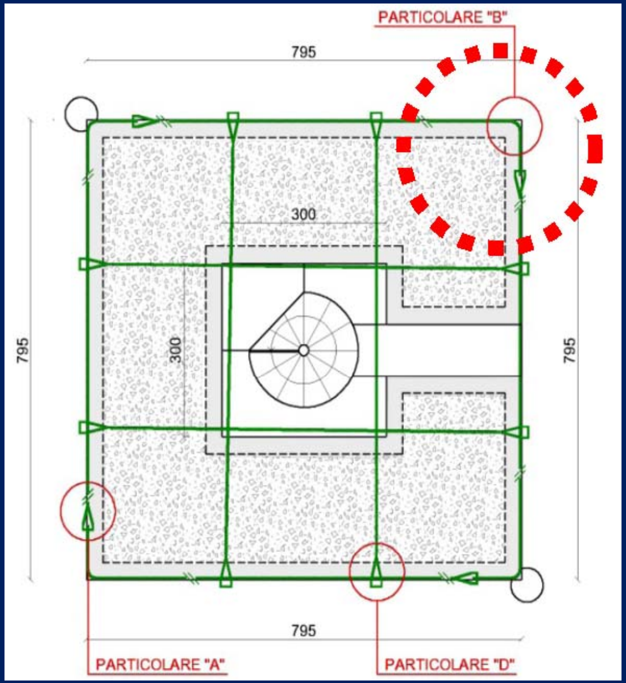
Monitoring planning

AE monitoring on the Asinelli Tower began on 23 September 2010 at 5:40 PM, and ended on 28 January 2011 at 1:00 PM, corresponding to 122 consecutive days.

The data collected during the monitoring period were analyzed to evaluate crack growth and correlate it with the other phenomena considered:

- ***Earthquake frequency in the areas around the city***;
- ***Vehicle traffic in the areas surrounding the tower***;
- ***Wind effects on the tower***.

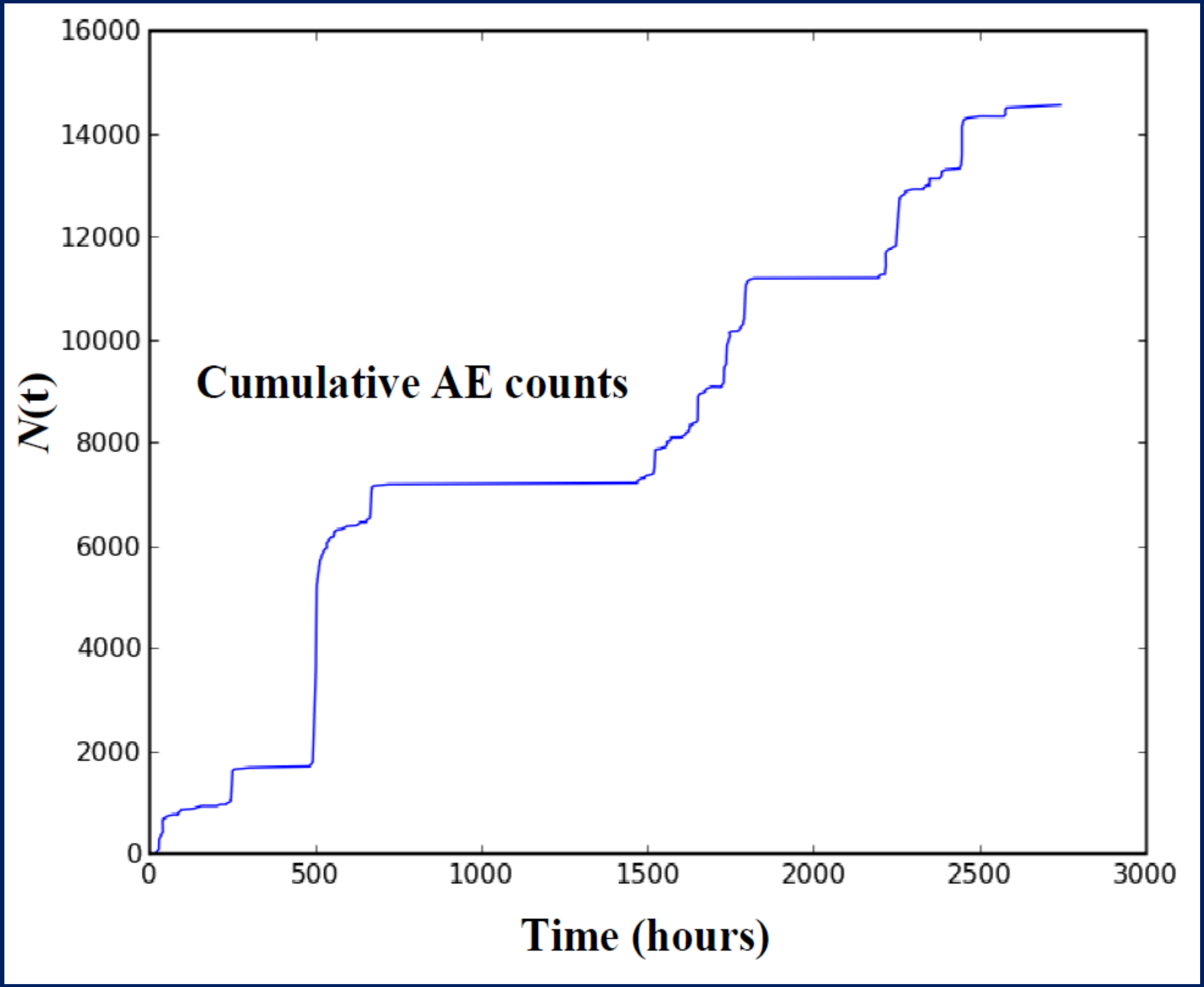
Monitoring by means of the AE Technique



The AE transducers were applied to the north-east corner over the arcade of the tower, in the zones marked with a circle.

Cross-section of the tower at a height of ca 10 m above ground, and arrangement of the AE sensors.

Results of the monitoring process



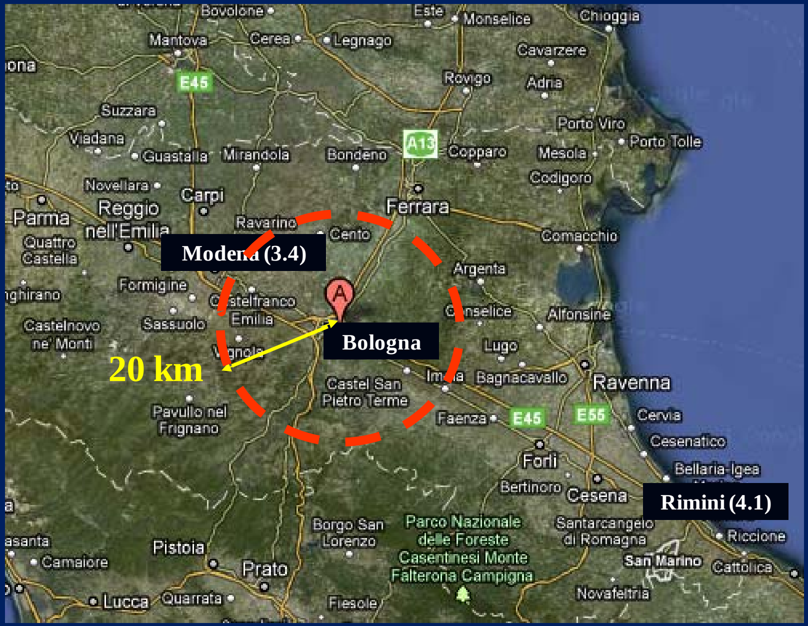
From the curve it can be seen that the masonry was undergoing a damage process.

The discontinuities in the cumulative AE count curve denote the critical moments during which the emission of energy from the microcrack formation process was greatest.

Cumulative AE counts based on the data collected at the north-east corner of the tower, from 5:40 PM of 23 September 2010, to 1:00 PM of 28 January 2011.

AE and earthquakes

During the monitoring period, frequent seismic activities were recorded in the area around the City of Bologna.



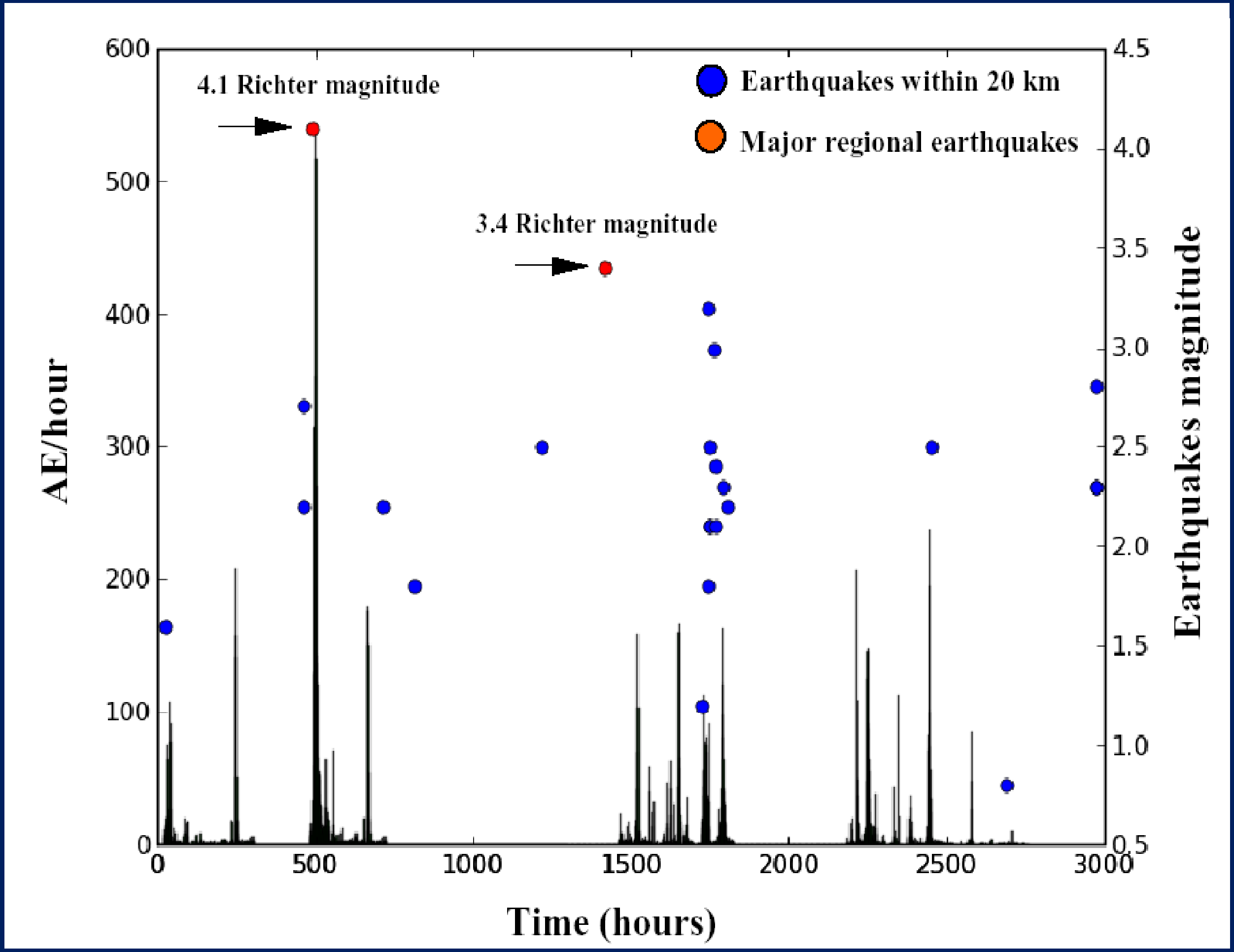
In particular, the following seismic events were considered, the two strongest earthquakes :

- <u>Rimini area on 13 October 2010 at 11:43 PM (4.1 Richter magnitude)</u>;

- <u>Modena Apennines on 21 November 2010 at 4:10 PM (3.4 Richter magnitude)</u>;

and the earthquakes with <u>a magnitude of over 0.5</u> that occurred within a radius of ca 20 km from the centre of the City.

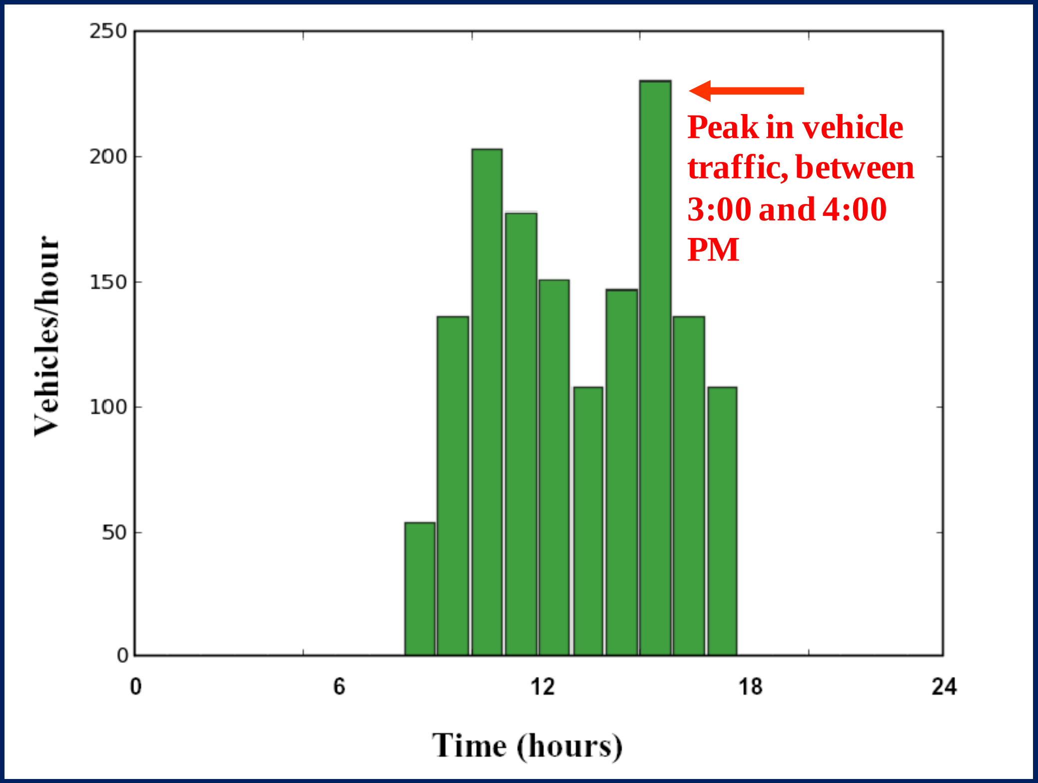
AE and earthquakes

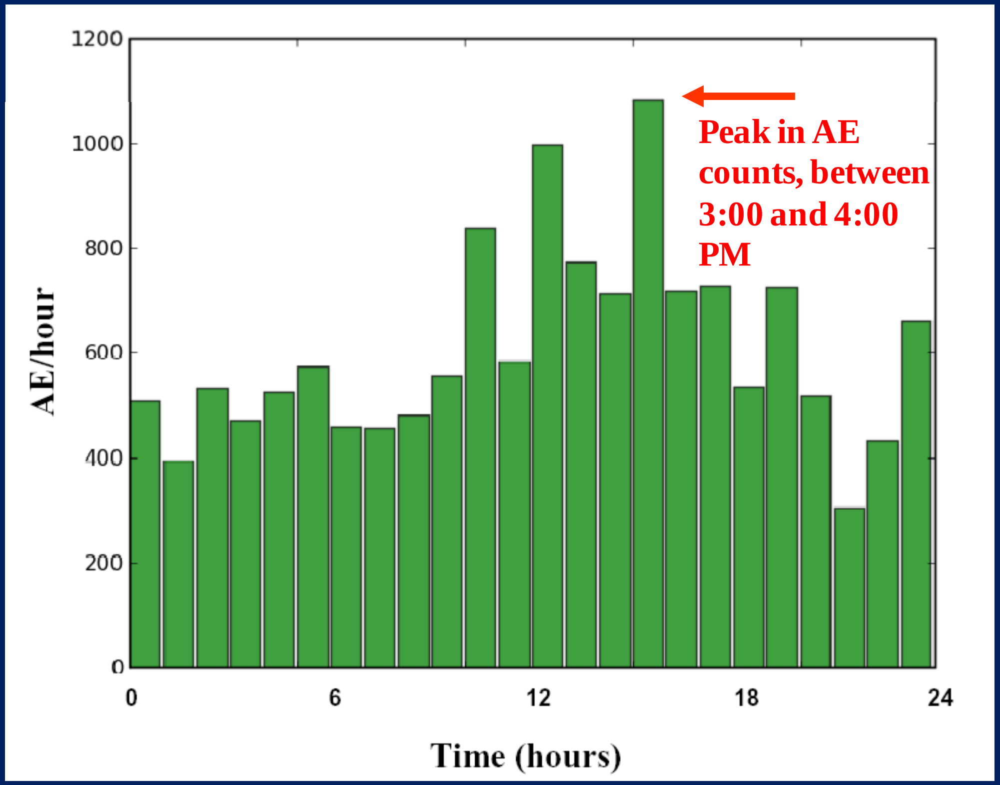


Historic series of the AE differential count and the earthquakes detected within a 20-km radius from the Bologna City centre.

The chart also shows the two strongest regional earthquakes, which occurred in Rimini area and in the Modena Apennines. This chart refers to the entire monitoring period.

AE and vehicle traffic





The comparison between the two distributions reveals as, during the monitoring period, the traffic effects on the damage to the tower were negligible.

As a matter of fact, while the seismic activity has generated AE in each hour of the day, the vehicle traffic has generated increments in AE counts only in specific hours of the days when the traffic has a peak.

AE and wind

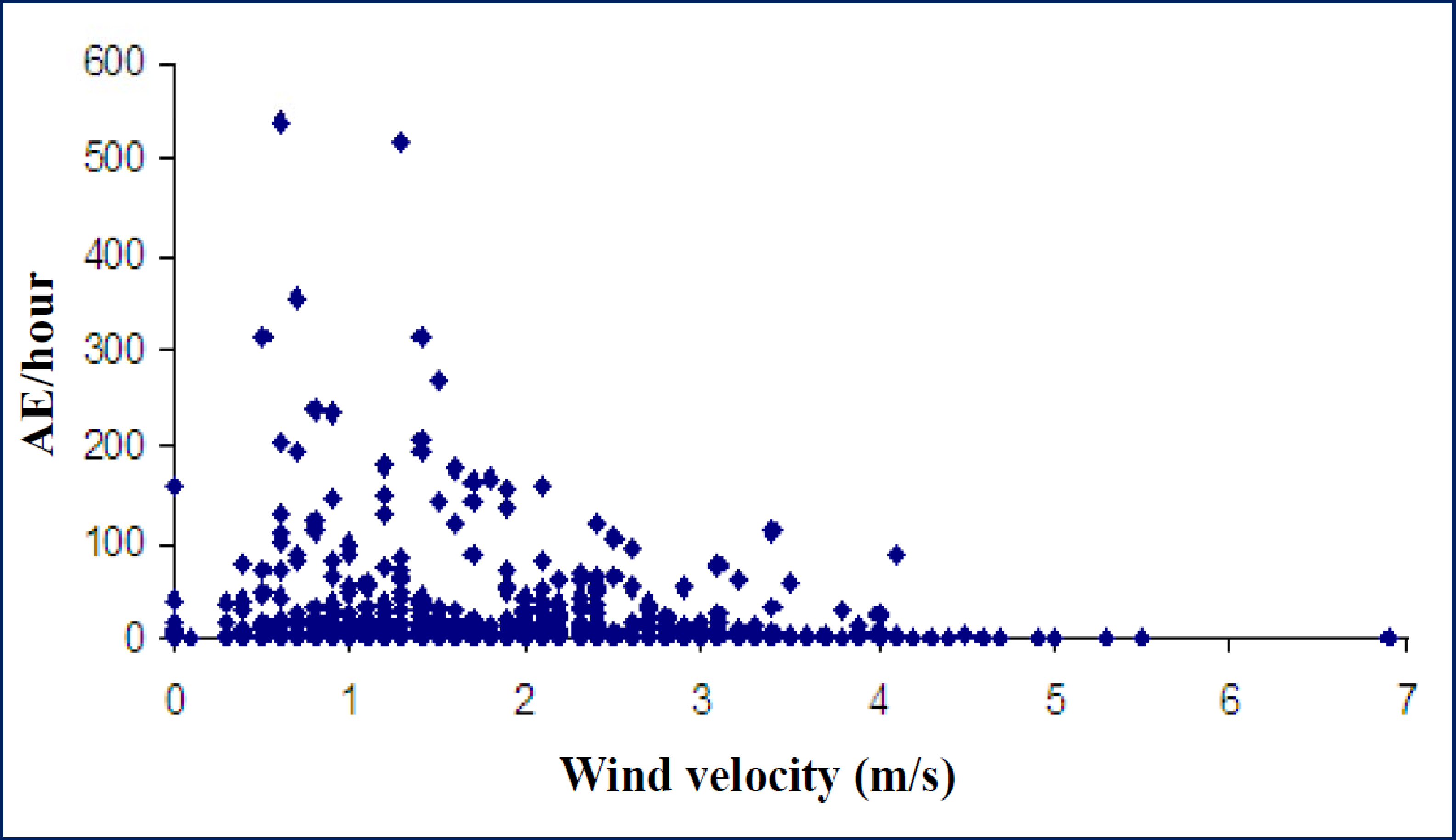


Chart relating the wind velocity and the AE count rate during all the monitoring period (2915 hours).

This graph makes more clear that the two phenomena are completely statistically unrelated.

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Structural monitoring and assessment of an ancient masonry tower

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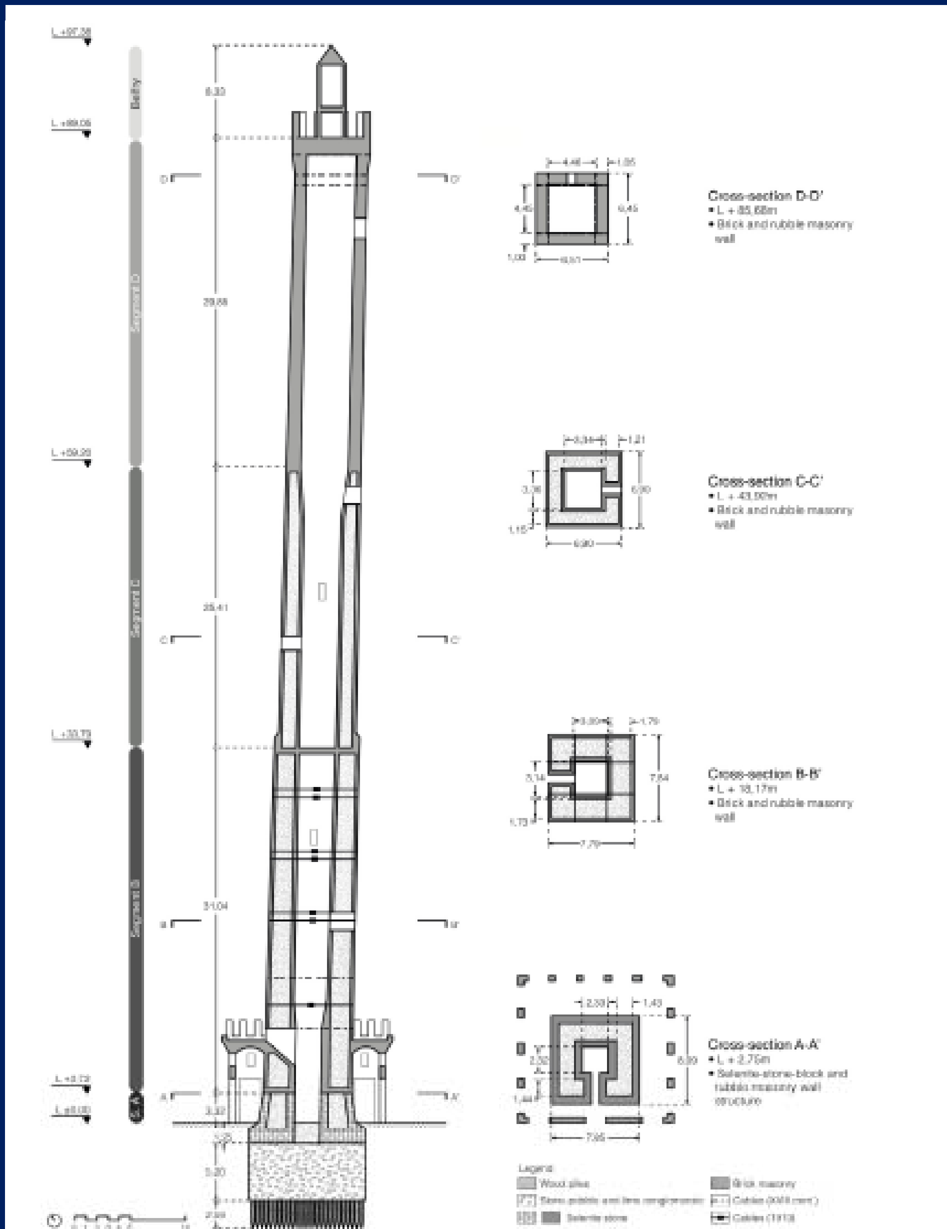
A R T I C L E I N F O

Keywords:
Acoustic emissions
Finite element analysis
Fracture mechanics
Damage
Masonry

A B S T R A C T

The Asinelli Tower in Bologna is taken as a case study to define a general methodology for the analysis of historical masonry towers. The difficulties that are typically encountered in building finite element models of increasing complexity are addressed, proposing a general procedure. A formulation accounting for masonry anisotropy due to existing damage and cracking is presented, which is more effective in describing the dynamic behavior of the tower, compared with results available in the literature. In addition, acoustic emission monitoring results are presented and compared to the numerical simulations. The structural assessment of the tower is carried out with respect to different actions like seismicity, wind and urban traffic.

Asinelli Tower Finite Element Modelling



Vertical section and cross-sections of the structure

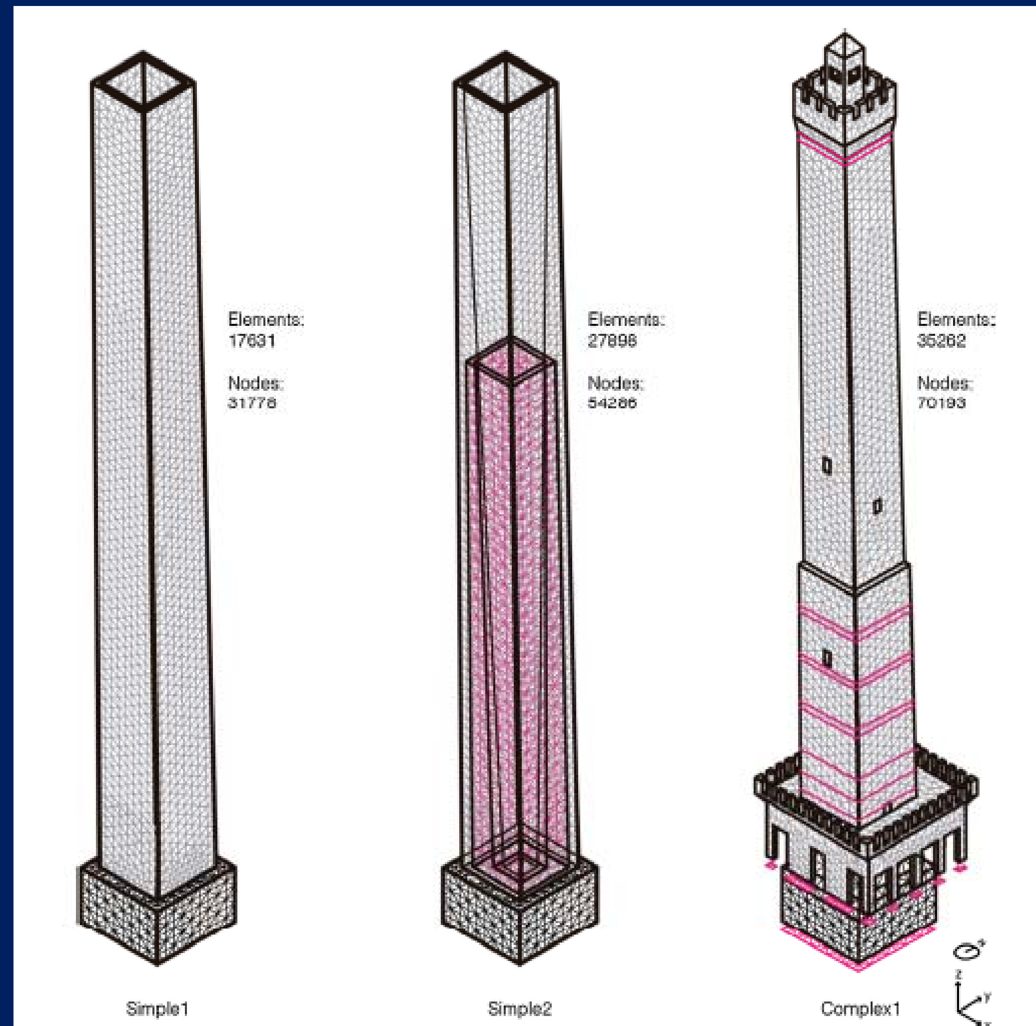


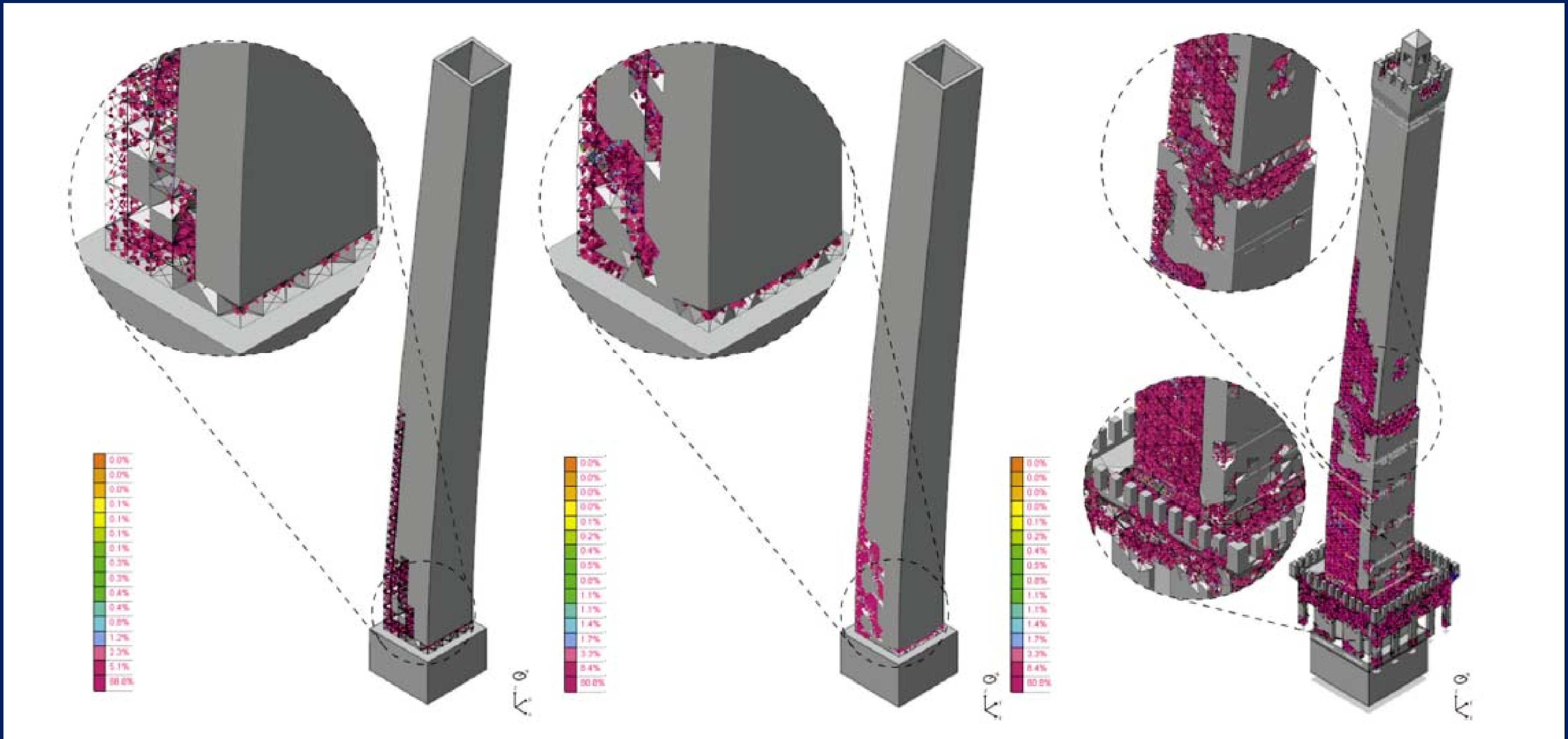
Fig. 2. *Simple1*, *Simple2* and *Complex1* models.

FE models with increasing levels of complexity

Numerical results

The seismic analysis outcomes are in agreement with the increase of AEs recorded during monitoring due to seismic events.

The AE monitoring takes benefits of numerical simulations both in the design phase (optimal sensor placing) and for the interpretation of results.



In the more complex model cracking energy distributes in a much realistic way compared to simplified models, since various discontinuities on the Tower have been modeled: openings, merlons, steeple, and so on.

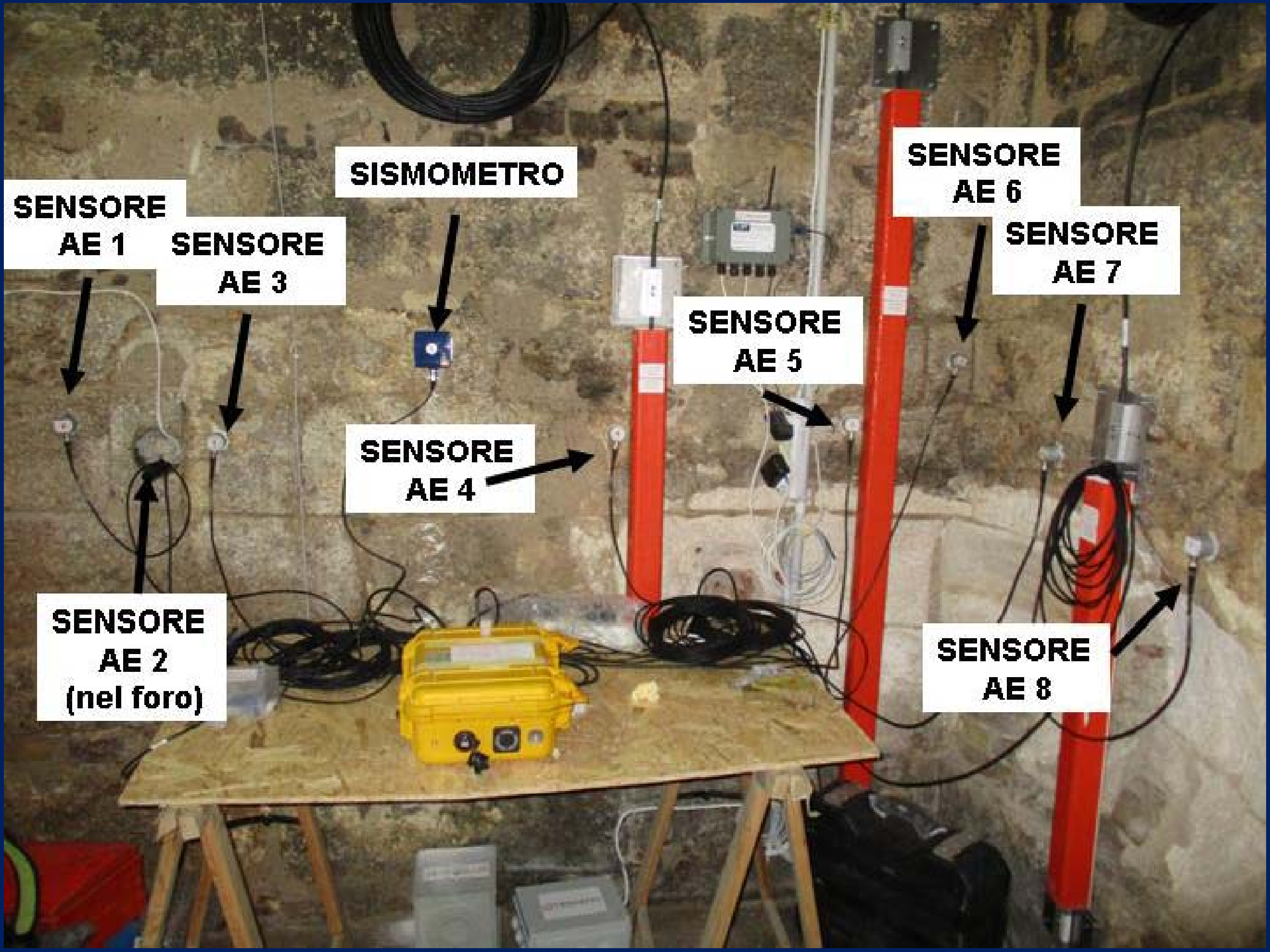
Monitoring of the Garisenda Tower

The equipment installed in the Torre Garisenda cell consists of an AE devise provided of 8 channels, connected to 8 piezoelectric sensors.

With this system it is possible to perform a real-time analysis of the signals coming from the PZT sensors and extract the parametric data. The sampling rate is fixed in 5 MS/s at 16 bits.

Equipment (mod. AEmission) installed at the Garisenda Tower with a pair of piezoelectric sensors

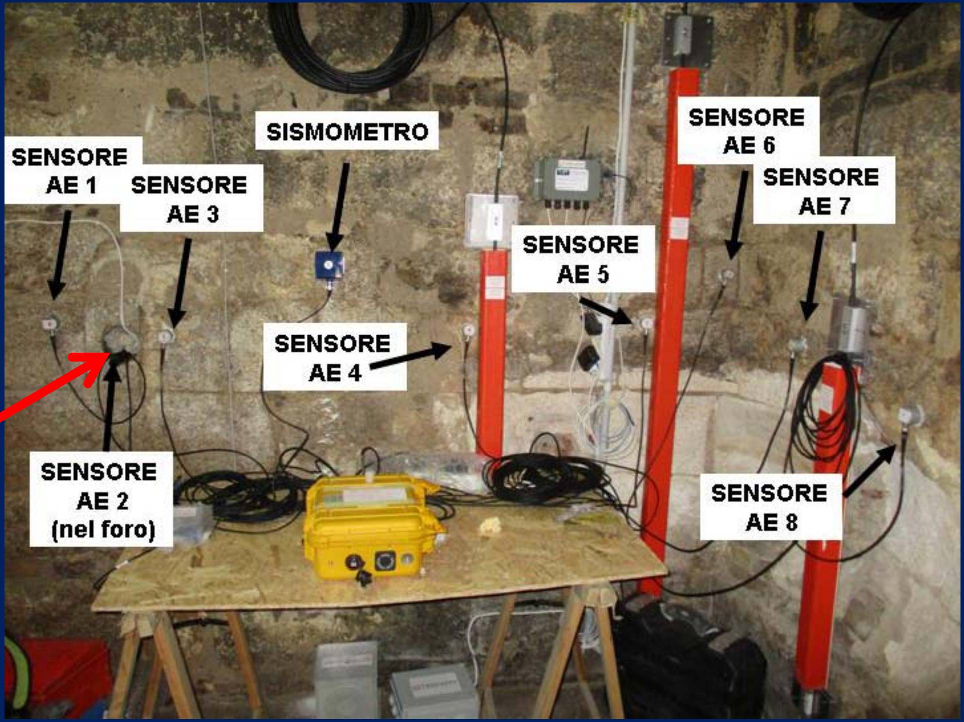
The piezoelectric sensors have been fixed to the inner wall of the Tower, composed of blocks of “selenite”, by means of a high-strength glue which, ensures excellent grip even in particularly critical environmental conditions.



Arrangement of the AE sensors inside the Garisenda Tower cell

On one of the Tower's cell walls an hole, with a diameter of 10 cm and a depth of 140 cm, was drilled by technicians of the Municipality of Bologna, in order to obtain specimens of "selenite" to be tested in the laboratory. The hole was made at a height of about 120 cm from the floor.

Drilled hole



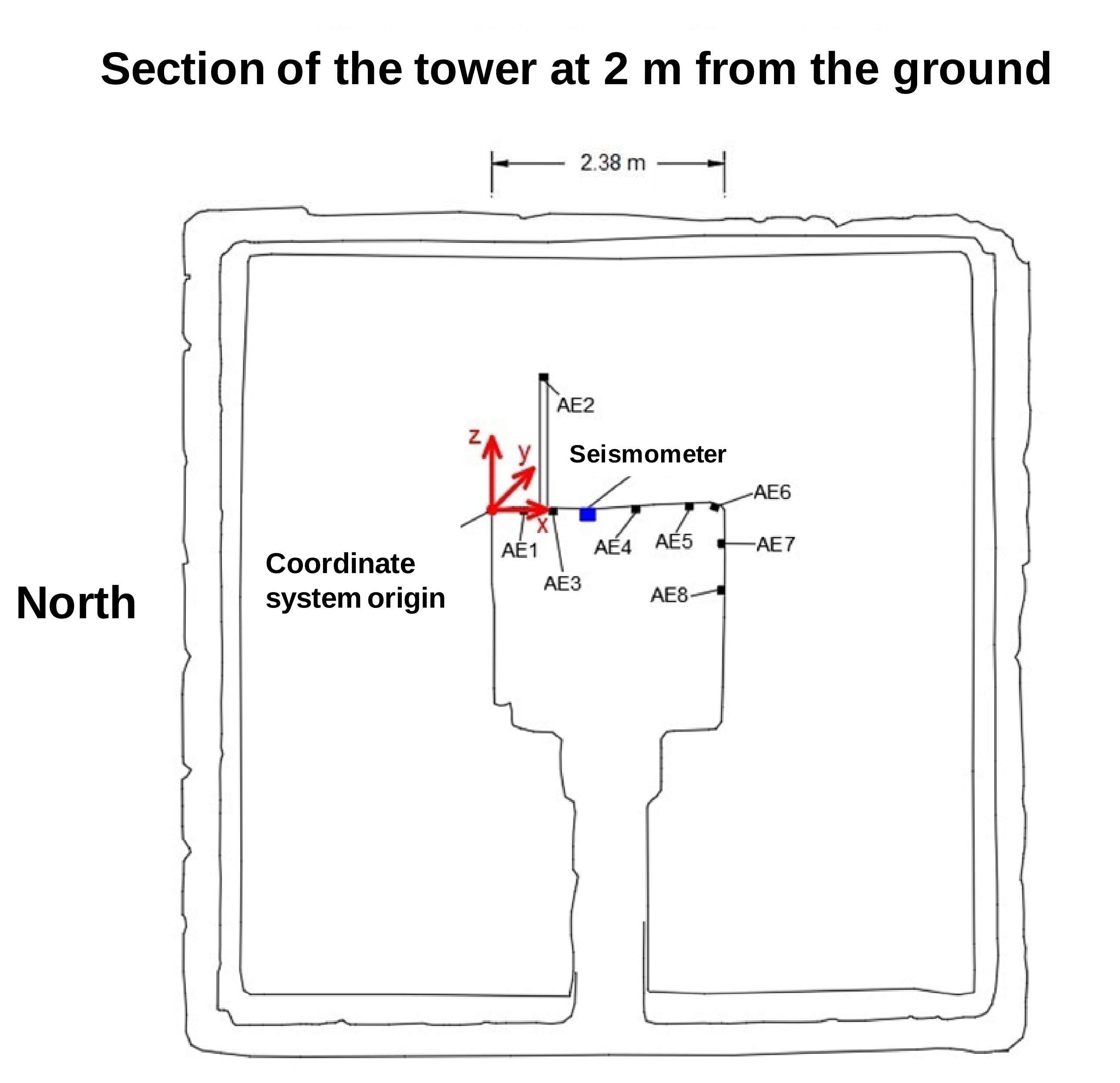
Two AE sensors have been positioned respectively to the left and right of the hole, another inside it, while the remaining five along the so-called "*unloading arch*" formed inside the walls of the Tower.

The current acquisition started at 12:24:00 (UTC) on May 31st, 2019, and ended on July 15th, 2020 (10:55:00 UTC), date of the last survey.

The signals threshold was set at 0.8 mV.

Table 1. Sensors number and their coordinates in cm

SENSORE	X	Y	Z
#1	34	122	0
#2	51	111	140
#3	65	118	0
#4	153	123	0
#5	210	124	0
#6	237	141	0
#7	238	123	– 43
#8	238	120	– 93



Plan of the Tower

Origin of the coordinate system and arrangement of the AE sensors

Compression test on selenite specimens

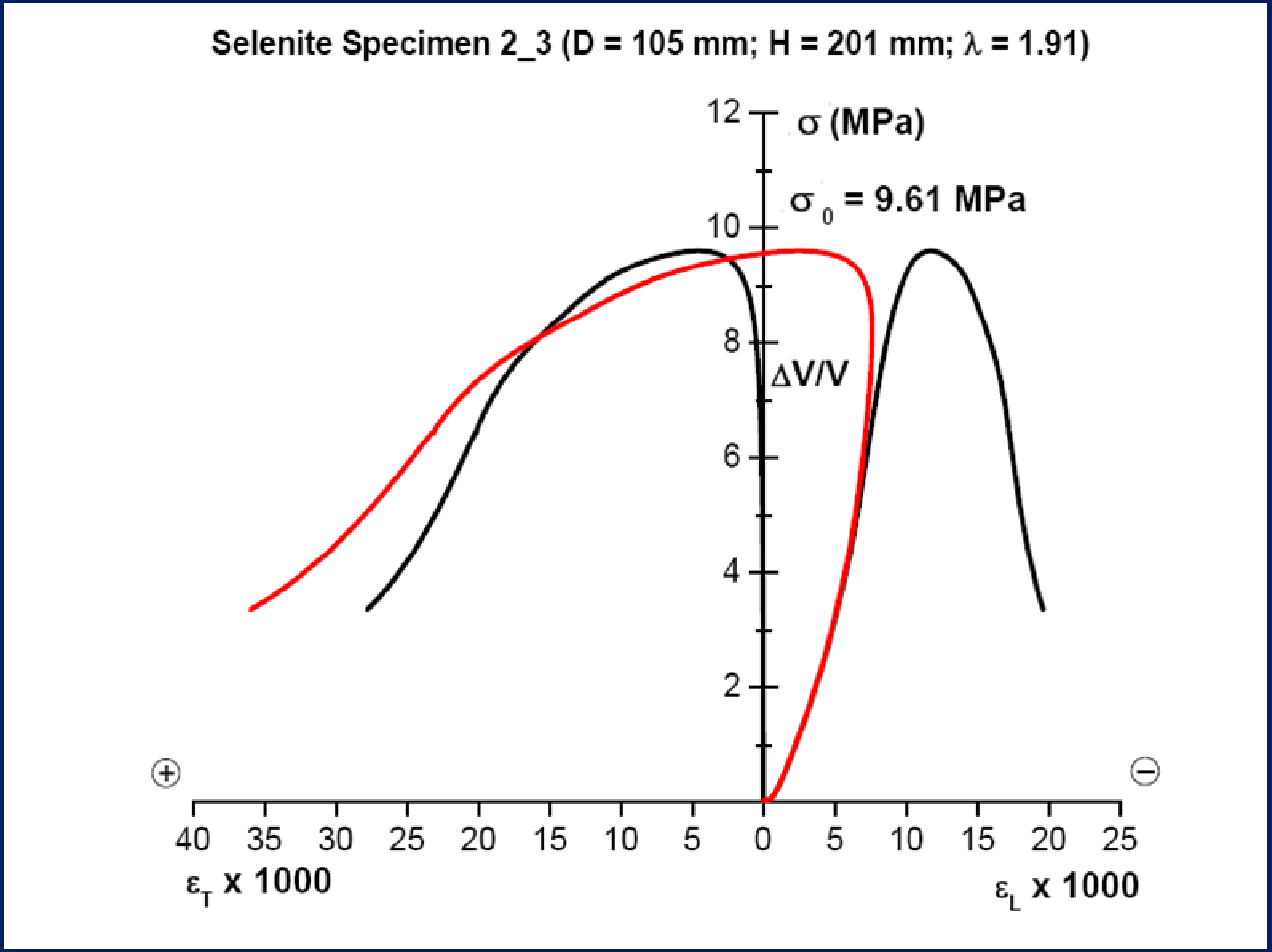
To test the capability of piezoelectric sensors on detecting AE data from "selenite" specimens in compression, laboratory tests were performed.

The tests were carried out by controlling the transverse displacement obtained by a circumferential deformometer. Simultaneously the vertical and horizontal strains, and the volume variation were measured.

Compression test on a specimen with slenderness 2.
Note the circumferential deformometer and the AE sensors applied to the specimen external surface

From the compression tests carried out in the laboratory it can be seen that substantial AE signals begin to appear when the compression stress in the specimens is on average between 1.0 and 2.0 MPa.

This means that the selenite masonry at the base of the tower must at least be stressed by that pressure to emit AE signals.



Compression test results

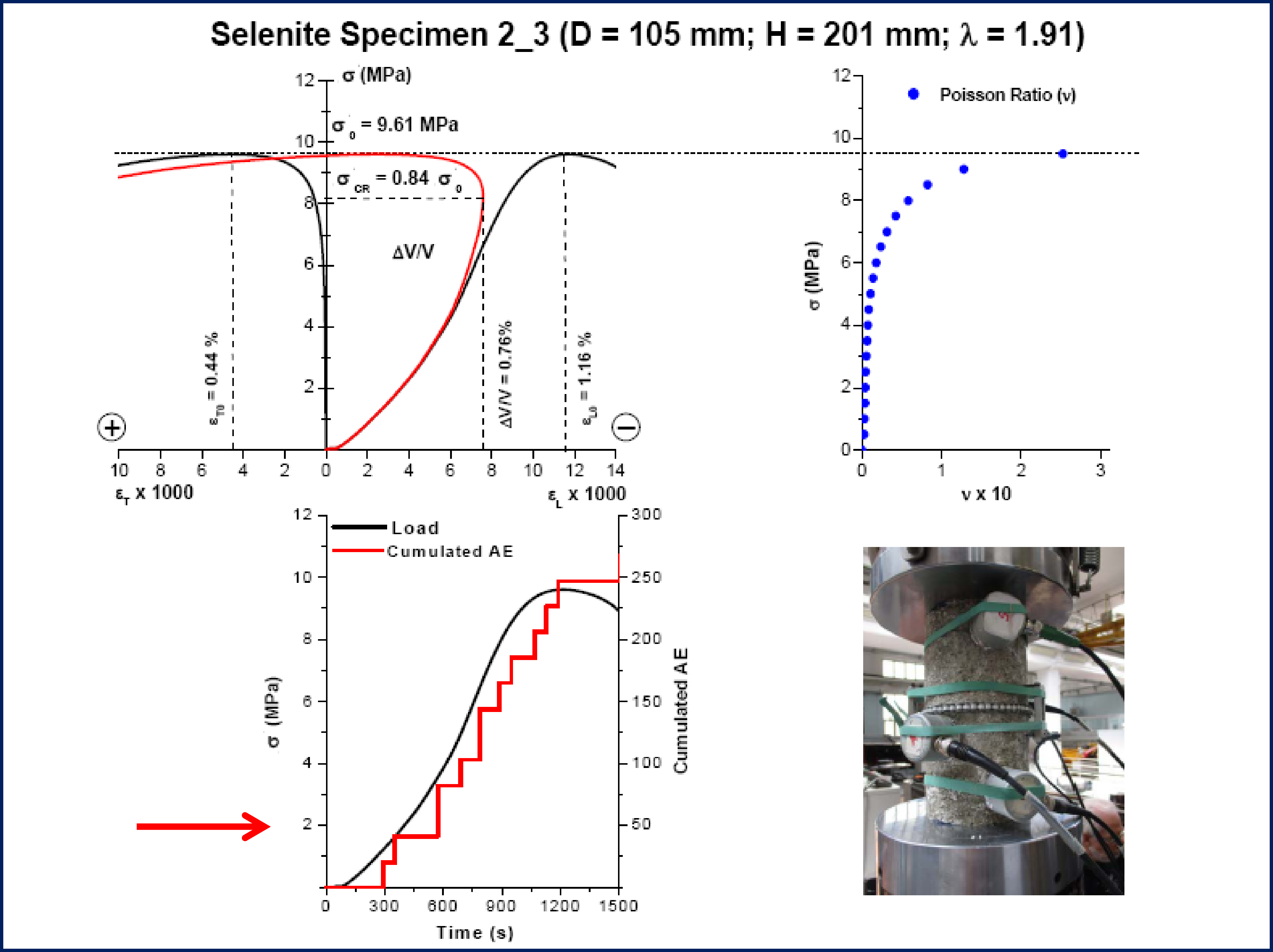
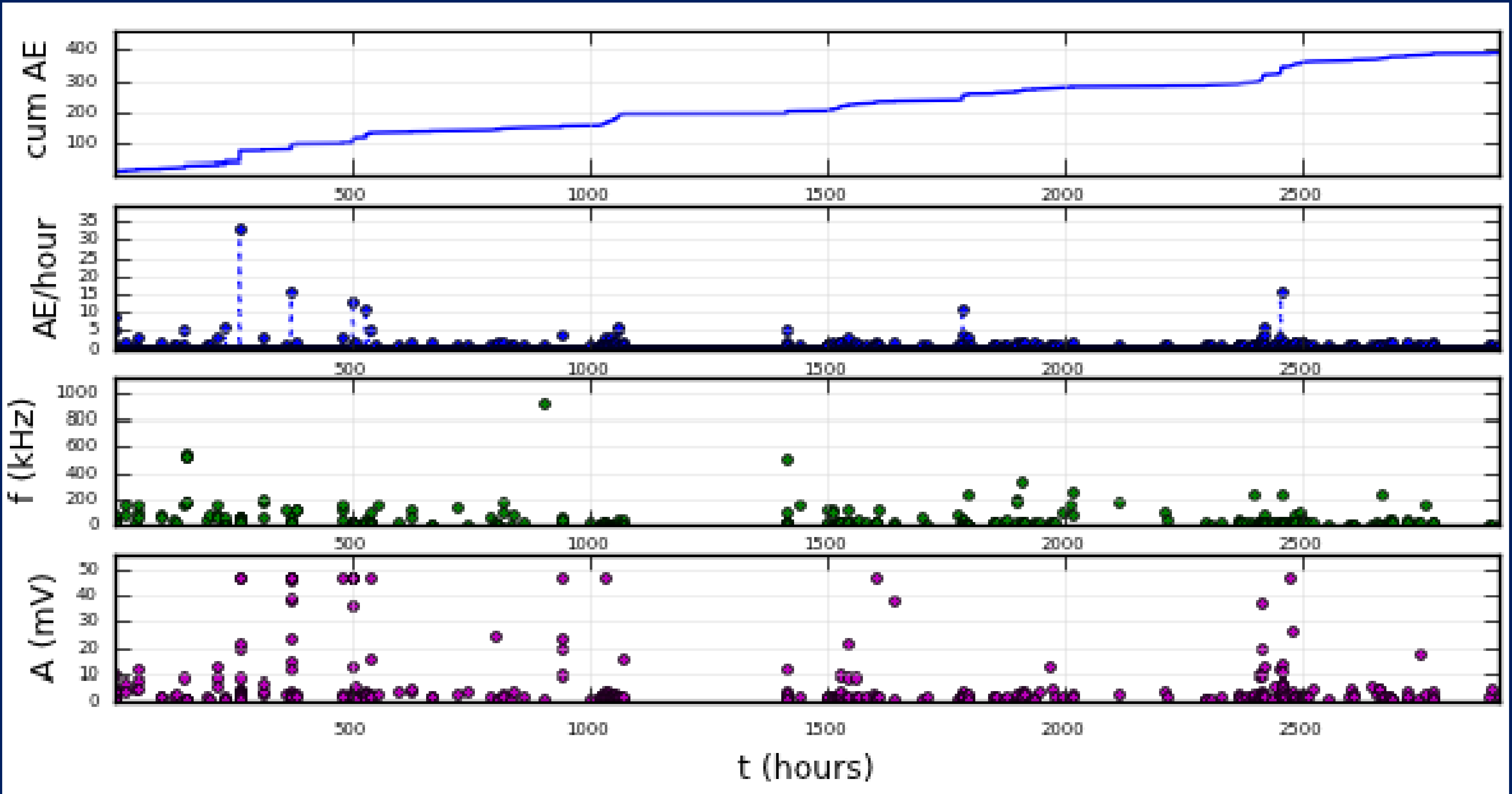
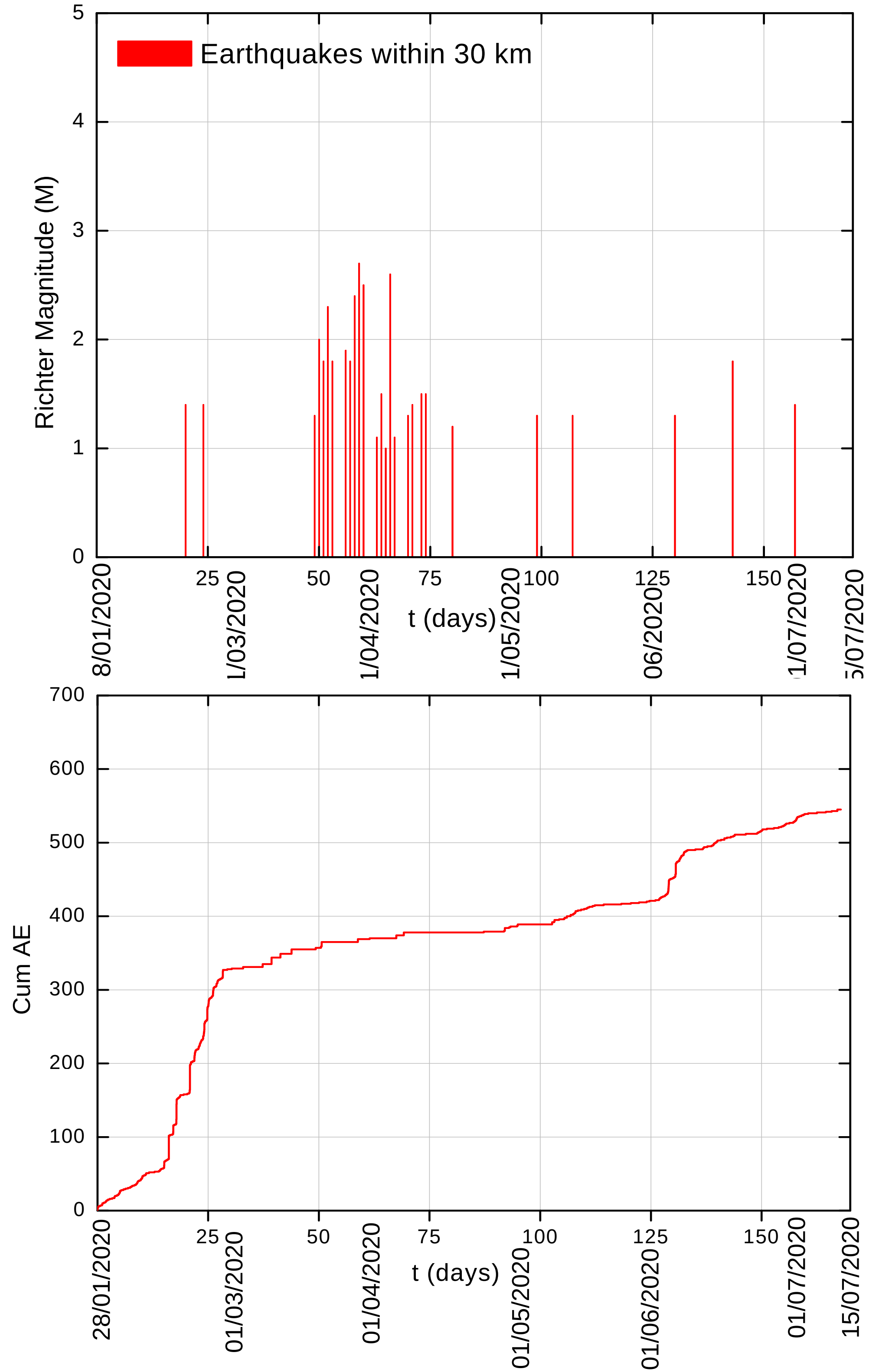


Chart of the AE data obtained along the first monitoring period from May 31st, 2019, to September 30th, 2019

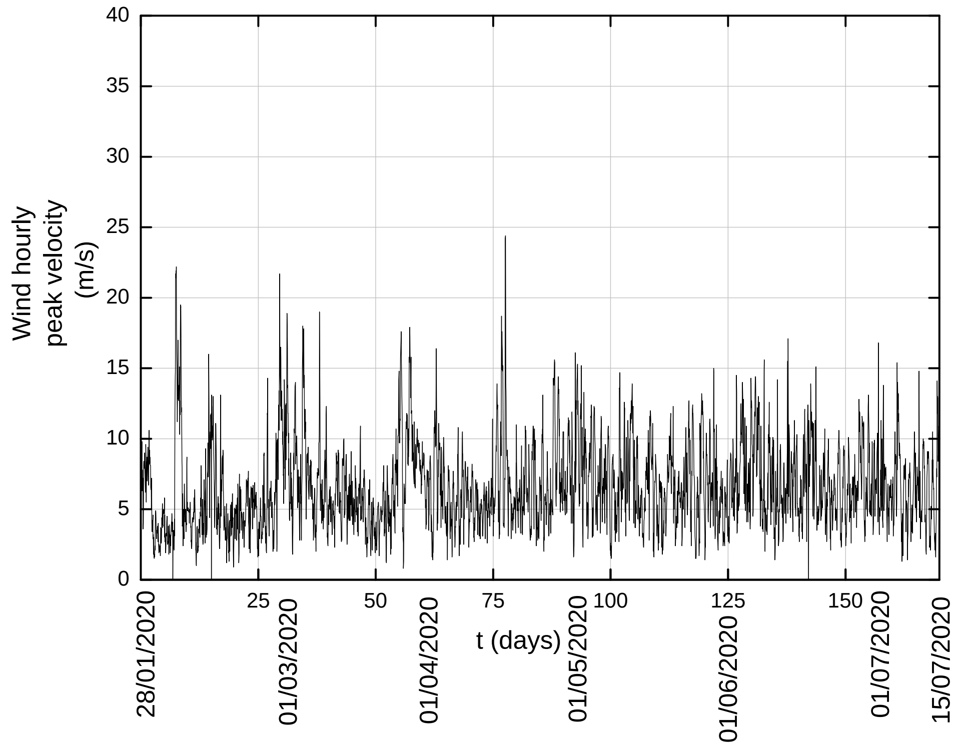


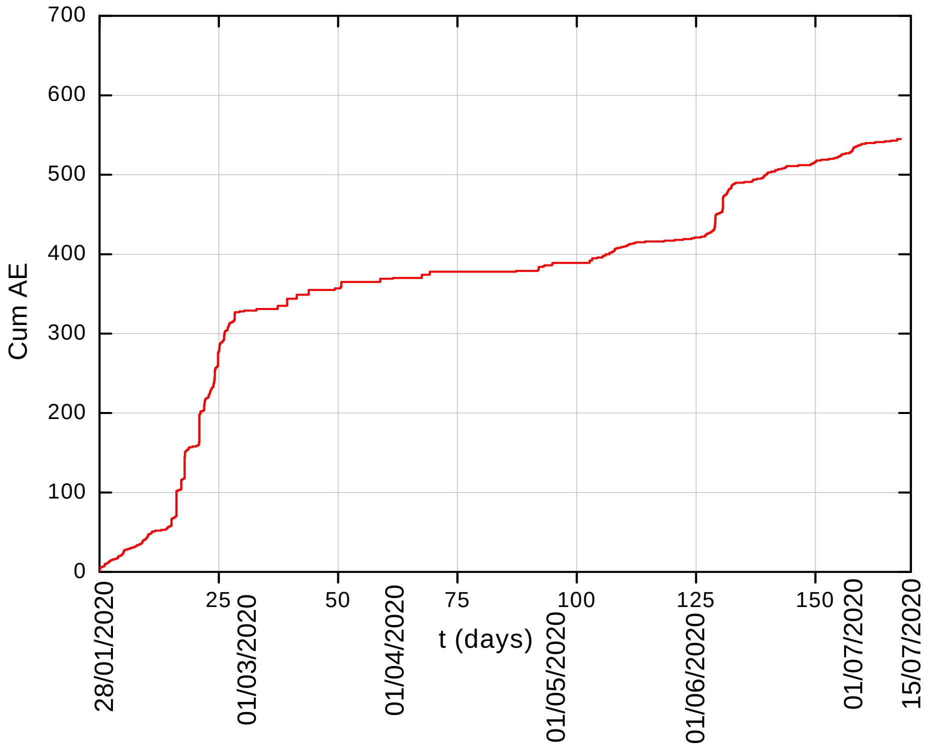


AE cumulative count and earthquakes detected within a 30-km radius from the Bologna City center.

During the monitoring period from May 31st, 2019, to July 15th, 2020 date of the last survey, there were no high Richter scale magnitude earthquakes in the Bologna region.

Considering a time window from January 28th, 2020 to July 15th, 2020, it can be see how the earthquakes did not have influence on the AE trend.



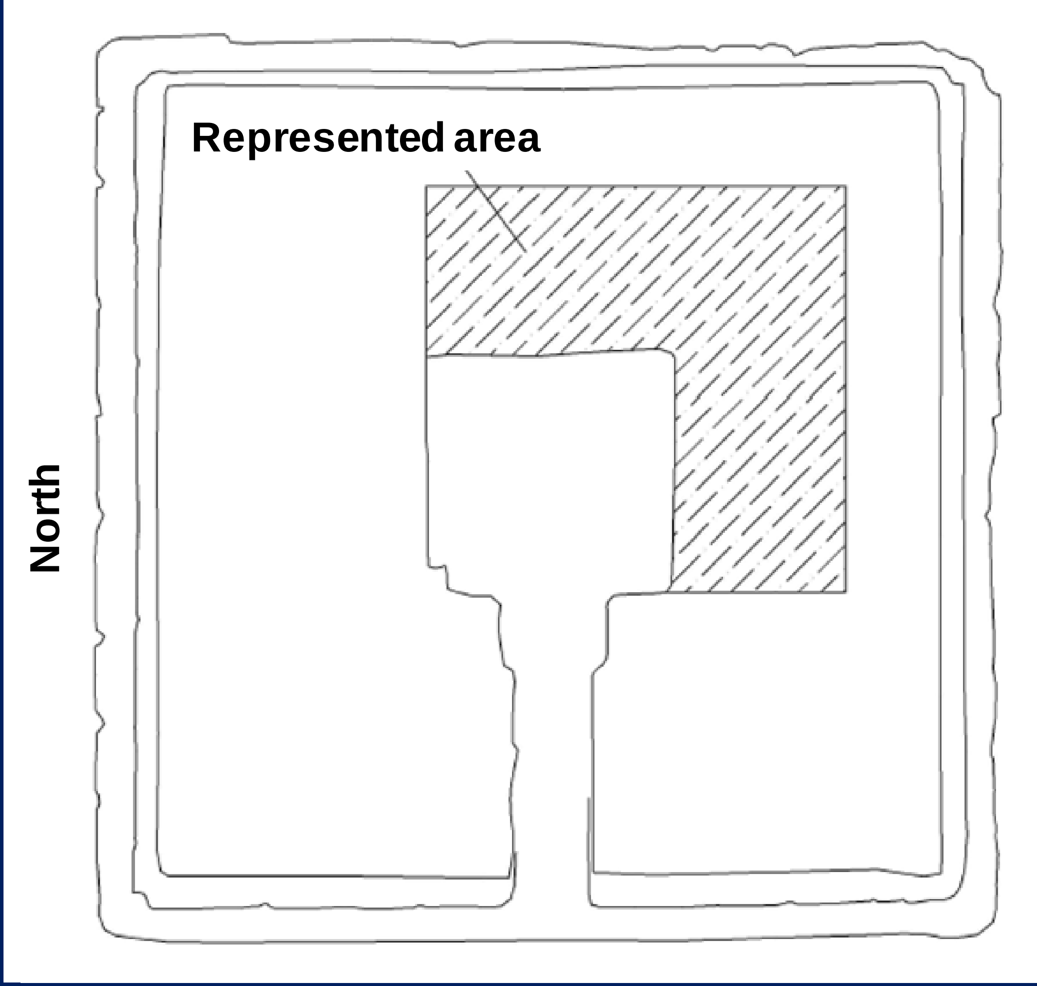


AE cumulative count and wind velocity detected around the Garisenda Tower.

Considering the same time window from January 8, 2020 to July 15th, 2020, it can be see how the wind velocity did not have influence on the AE trend.

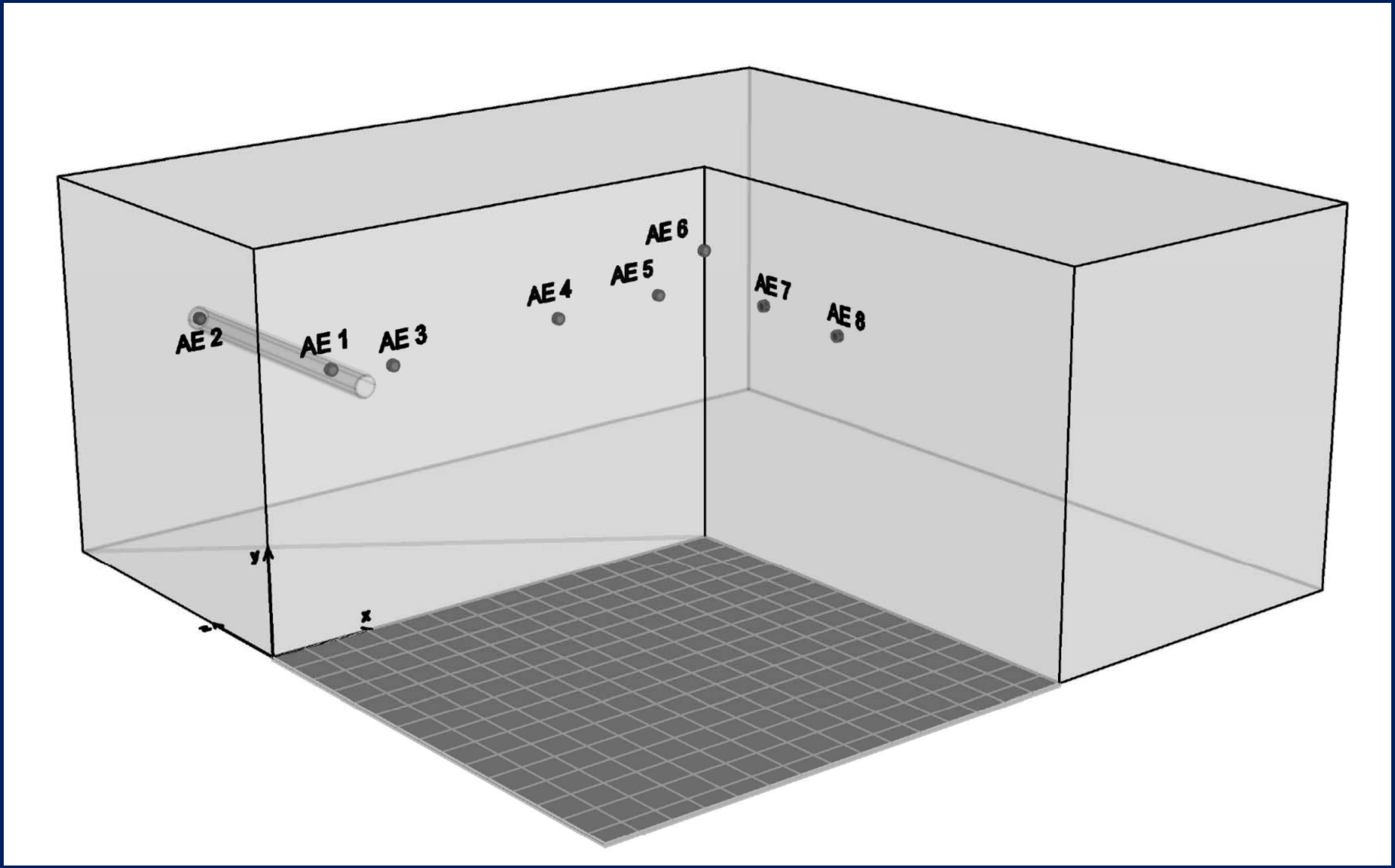
AE sources location

Representation of the sensors coordinates and AE sources throughout all the monitoring period

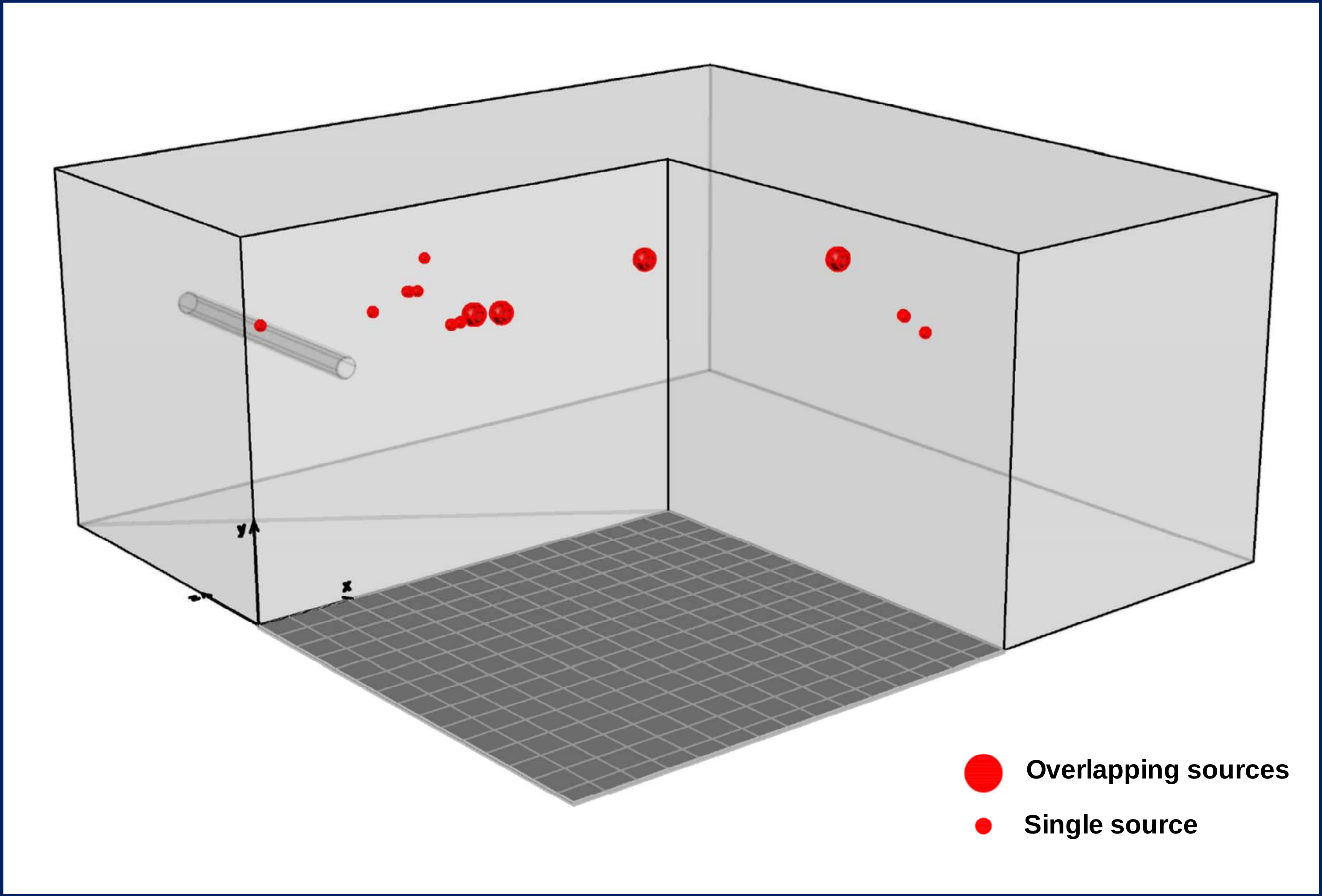


Plan of the Tower

The area represented in axonometry is highlighted with a hatching



Axonometry with the representation of the sensors positions



Axonometry with the representation of the AE sources

Other monitoring devices installed in the Garisenda Tower cell

In the Garisenda Tower, six optical cables were also installed by the Firm "Smart Monitoring Italia" (OSMOS Group - SMI Srl), to measure, in real time, the vertical displacements of the tower basement.

Moreover, a seismometer was fixed at a height of about 150 cm from the floor basement. This device is capable of acquiring movement speeds greater than or equal to 0.127 mm/s.

Both the optical cables an the seismometer have internal clocks synchronized with UTC (Coordinated Universal Time) time reference.

Thanks to this arrangement, the AE signals distribution can be related with the data measured by the optical cables and the seismometer, in order to obtain possible correlations between the actions generated by the environment and the Tower damage.

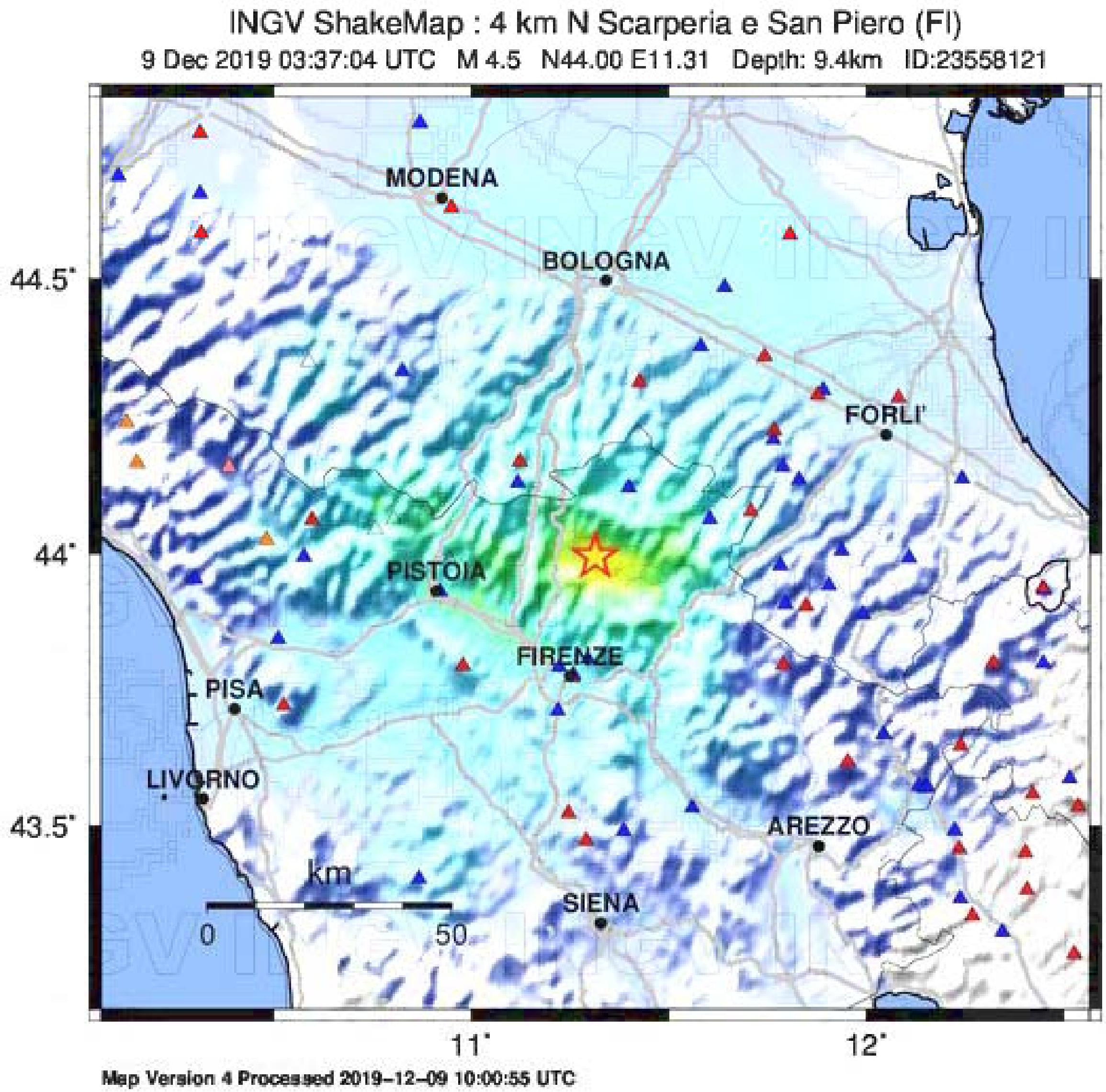
Comparison of the AE data with those obtained from the seismometer relating to a seismic event of December 9th, 2019

On December 9th, 2019 at 03:37:04 UTC (04:37:04 Bologna City local time) an earthquake with a Magnitude Moment (Mw) equal to 4.5 degrees on the Richter scale was recorded in Italy, as measured by the seismic stations of the National Institute of Geophysics and Volcanology (INGV), http://terremoti.ingv.it/.

The earthquake epicenter was located in the Municipality of Scarperia and San Piero (FI), North Latitude 44.00 and East Longitude 11.31.

The earthquake epicenter was about 60 km from the location of the Garisenda Tower.

The seismic event induced vibrations which were also recorded by the seismometer fixed on the front wall of the tower cell (XY plane) at a height of about 150 cm from the floor.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.06	0.2	0.8	2.0	4.8	12	29	70	>171
PEAK VEL.(cm/s)	<0.02	0.08	0.3	0.9	2.4	6.4	17	45	>120
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Faenza and Michelini, 2010, 2011

Furthermore, considering the ground shaking map elaborated by the INGV, it can be seen that in the Bologna area the peak speed of the ground shaking was evaluated between 0.08 and 0.3 cm/s with a peak acceleration between 0.2 and 0.8 % g.

This value is consistent with what was observed at the Garisenda Tower where, through the seismometer, a transverse component equal to 0.063 cm/s, and a peak acceleration of 0.5% g was detected.

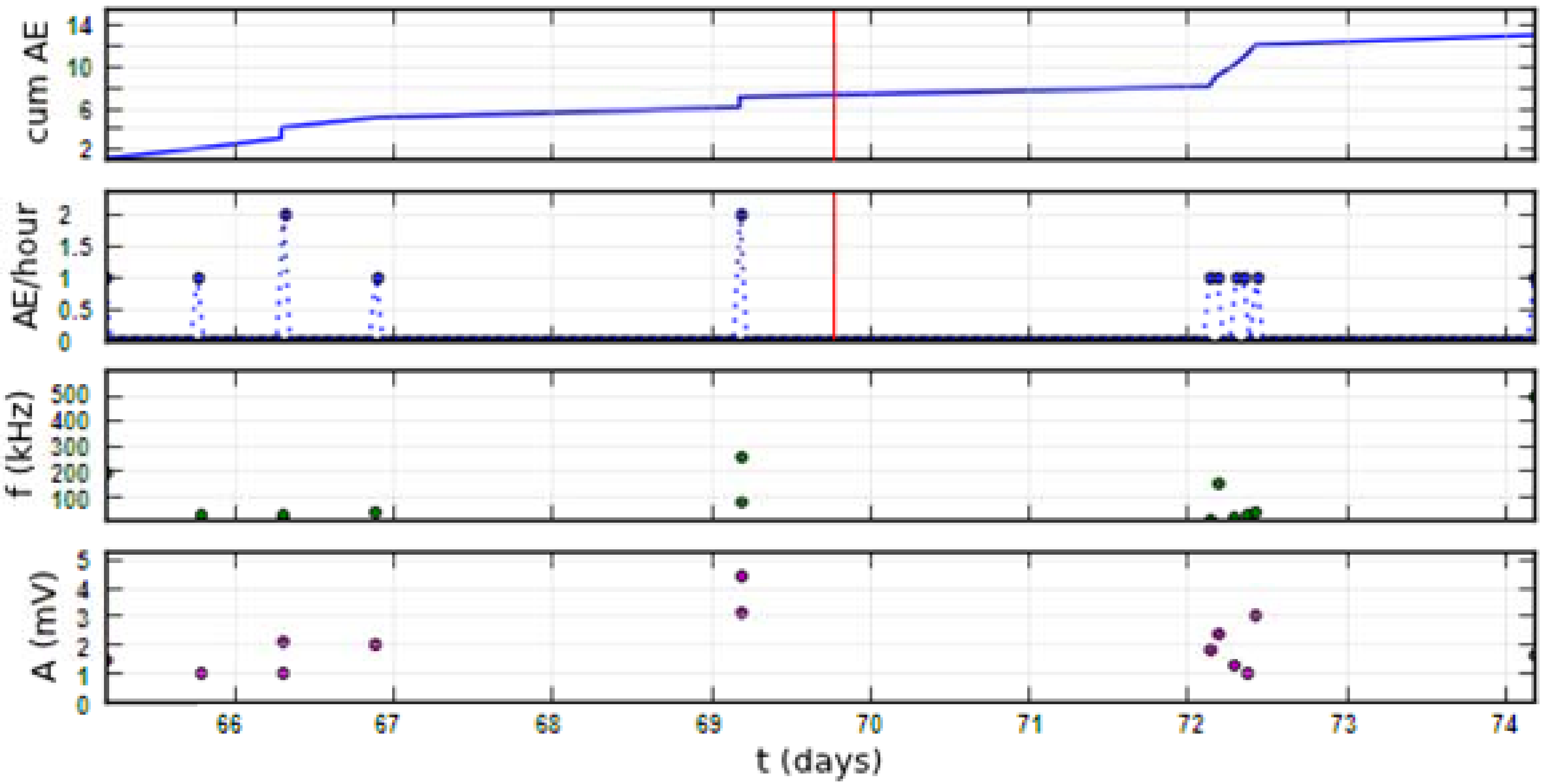
To evaluate the impact of the earthquake on the formation of micro-cracks in the basement of the Tower, a graph is shown below that represents the distribution of the AE signals in a time window of nine days, centered at the moment of the earthquake.

From this graph it can be seen that, in the periods around the earthquake, there are no anomalies in the signals detection .

The interval in question is rather characterized by a reduced number of detected AE signals, if compared to periods of more intense activity.

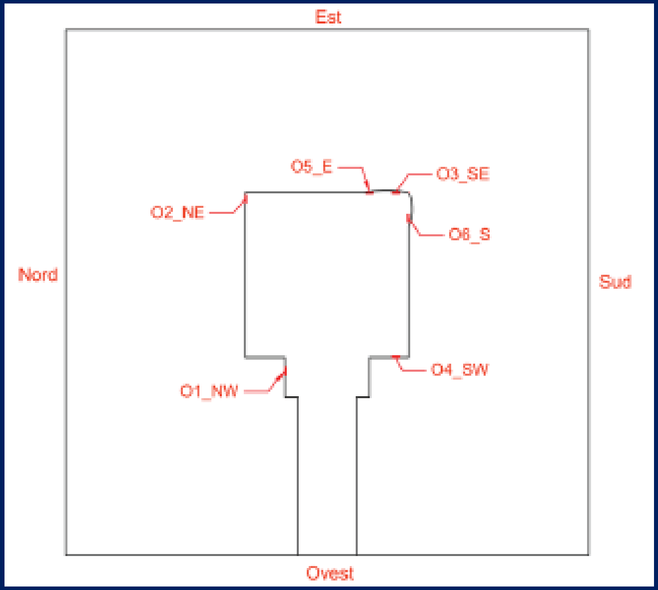
Nine-day wide window centered on the moment of the earthquake occurrence

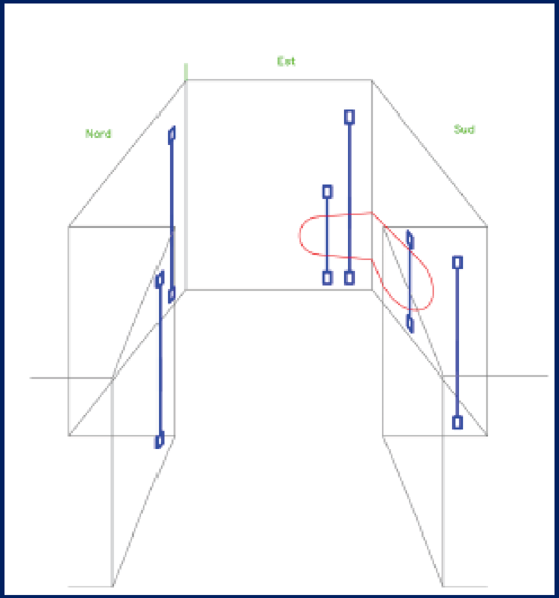
December 4th, 2019, 3:30 pm – December 13th, 2019, 3:30 pm

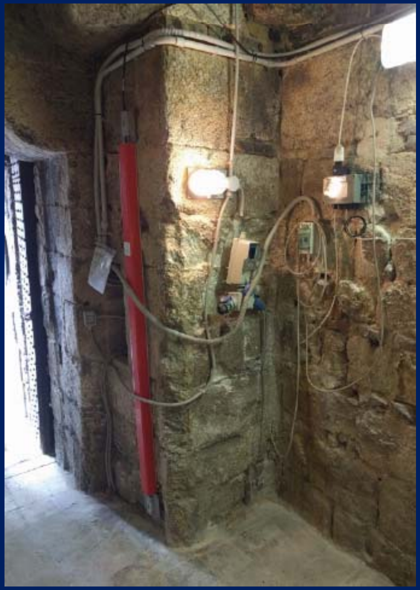


The earthquake (Mw = 4.5) of December 9th, 2019 (03:37:04 UTC) is represented by a red bar

Arrangement of the optical cables inside the cell of the Tower







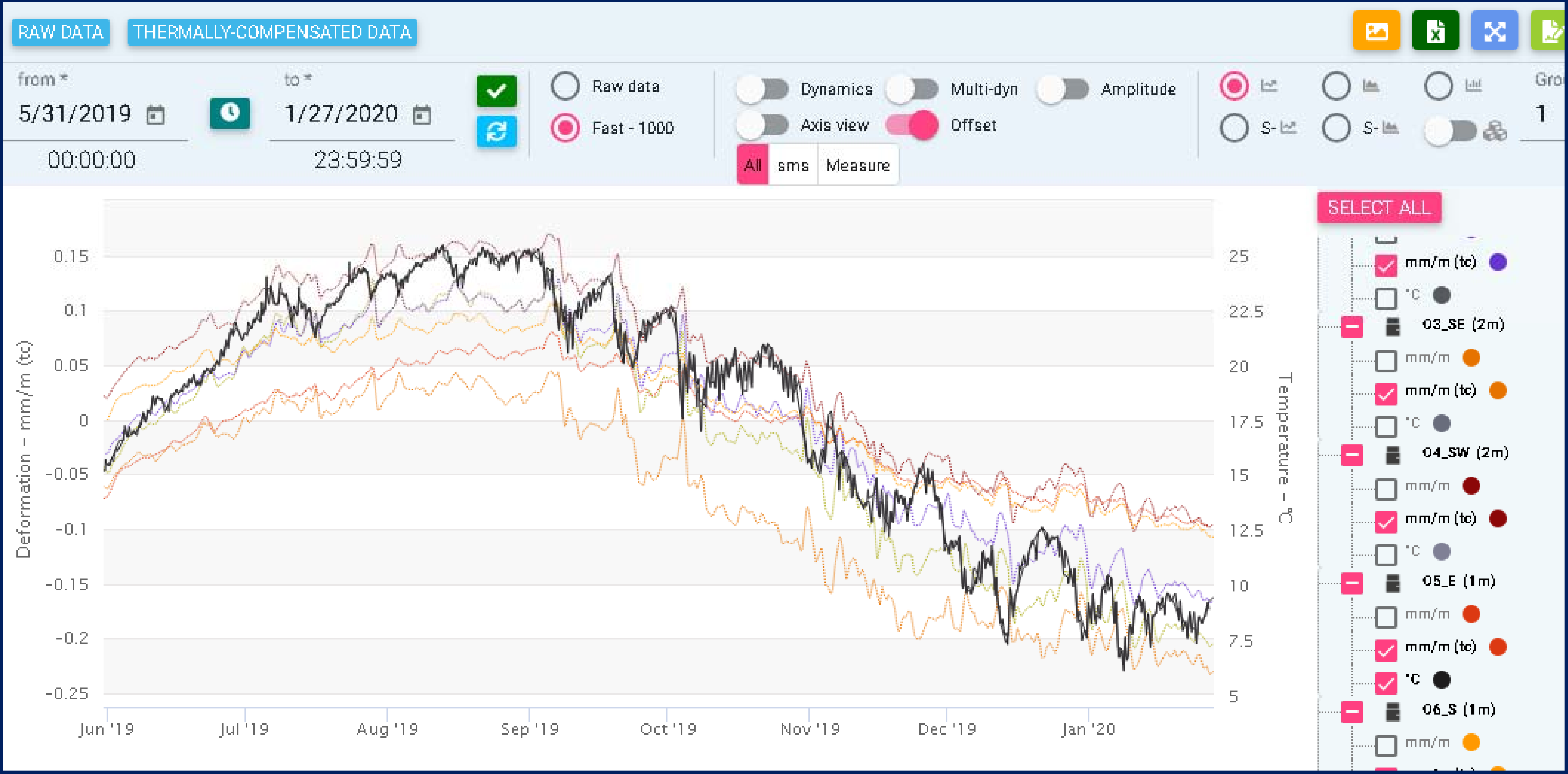
South-west side

East side

North-west side

Strain trends purified from the contribution of thermal variations detected by the optical cables The black line curve expresses the temperature trend

Period from May 31st, 2019 to January 27th, 2020

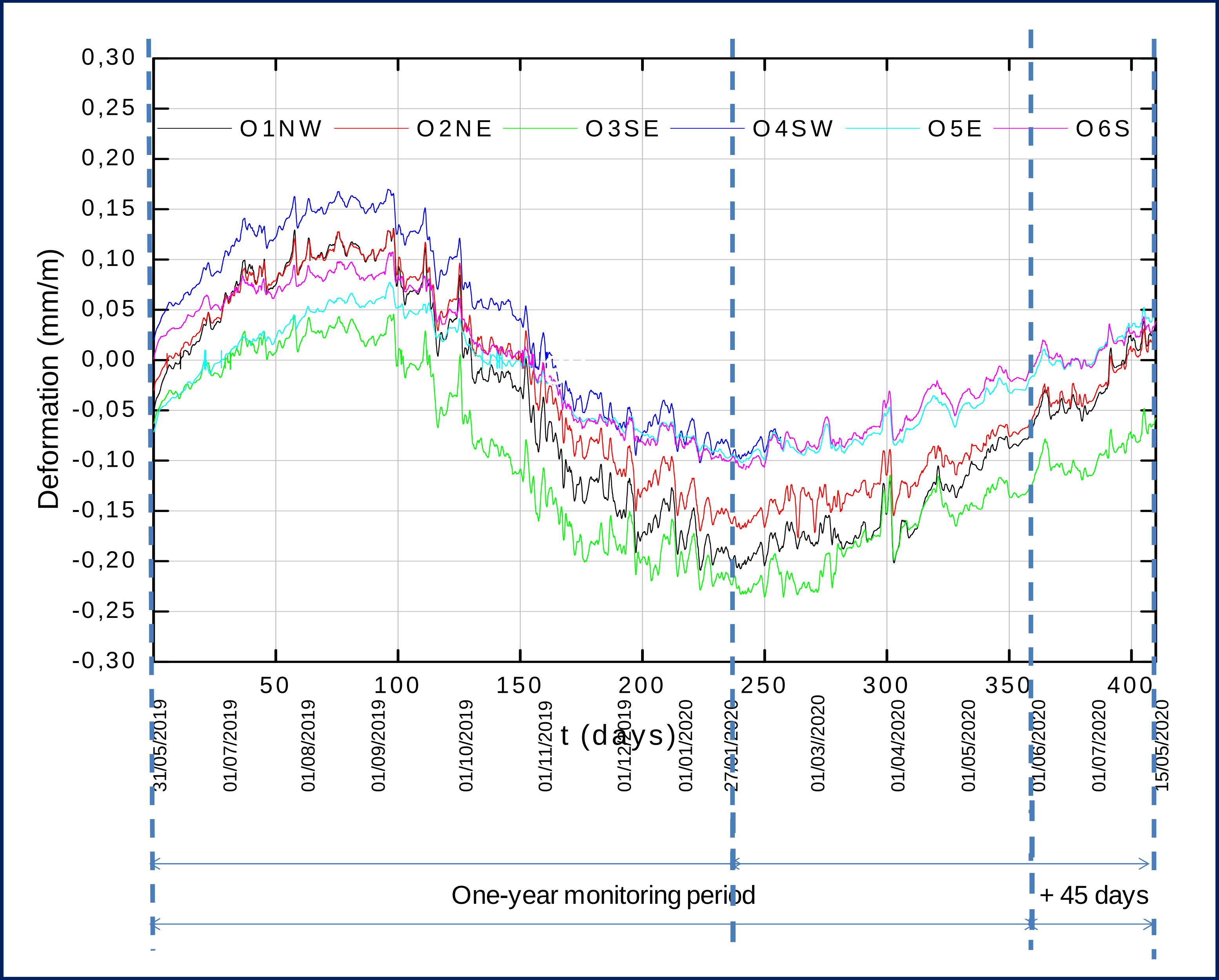


Strain trends purified from the contribution of thermal variations detected by the optical cables
The black line curve expresses the temperature trend

Period from January 28th, 2020 to July 15th, 2020

Strain trends detected by the optical cables represented during all the monitoring period

Period from May 31st, 2019 to July 15th, 2020, date of the last survey

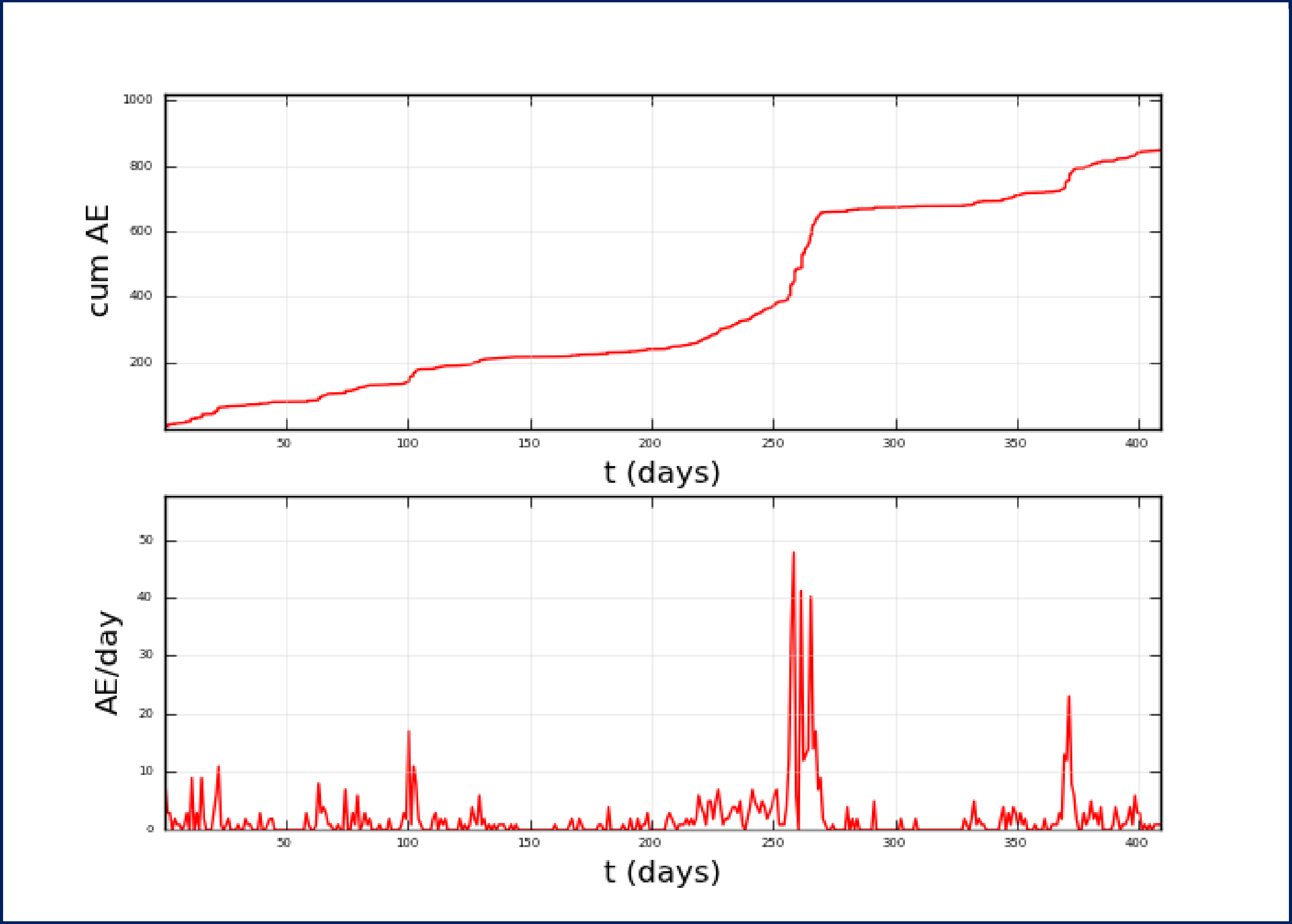


The variations in the strain trends are clearly due to seasonal thermal excursions.

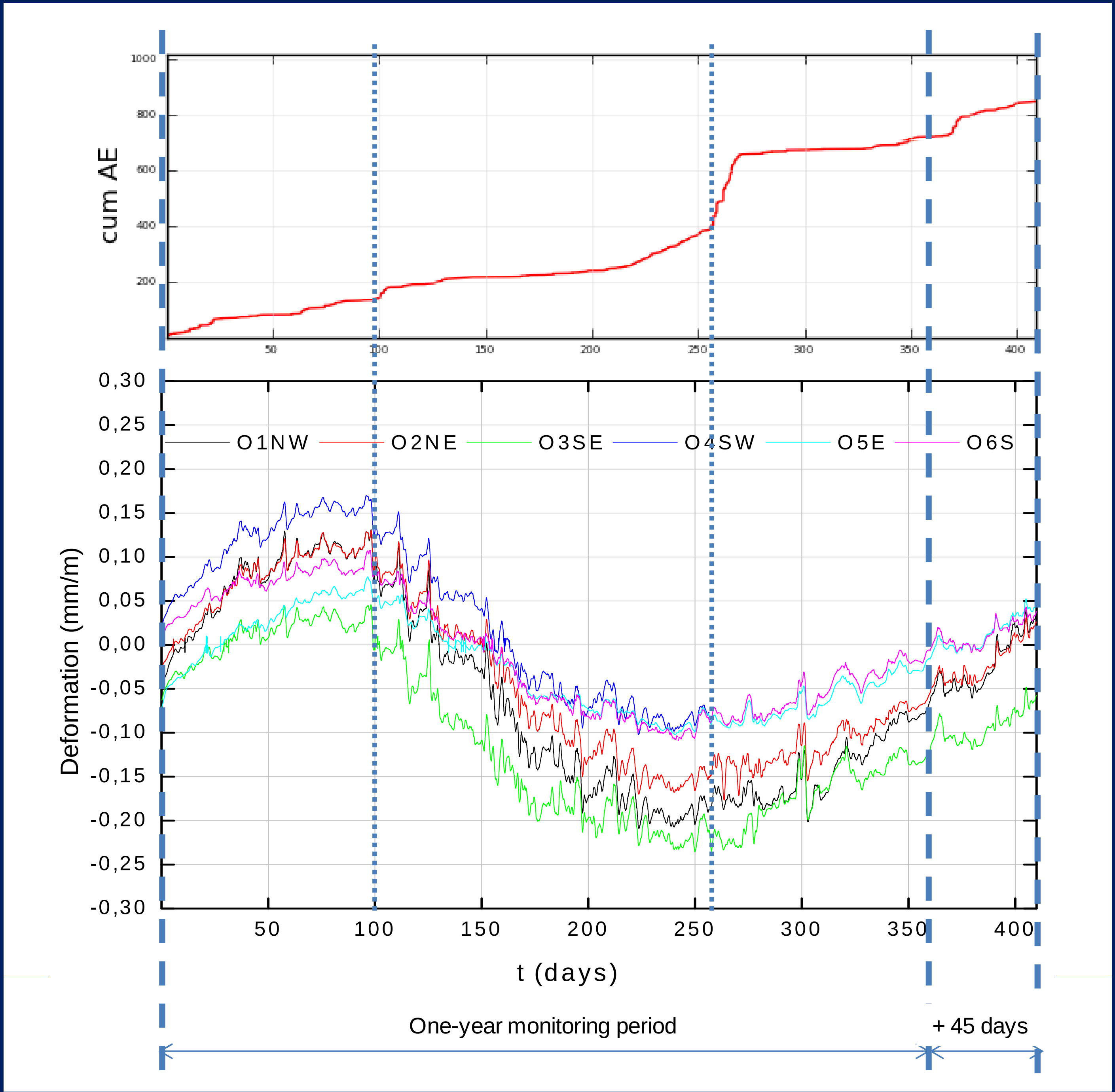
Cumulative function of AE signals

Daily rate of AE signals (AE/day)

Period from May 31st, 2019 to July 15th, 2020, date of the last survey



Comparison between the cumulative function of AE signals and the strain trends detected by the optical cables



The comparison between the two diagrams shows that around the 100th day from the start of monitoring there is a significant increase in AE activity, also highlighted by a change in the strains growth.

It can then be noted that starting from the 100th day there is a sort of inversion in the strain trend obtained through the optical cables.

From a situation of growth towards ever increasing positive values, and therefore attributable to extension phenomena, we move on to a behavior that leads to ever lower values of strains up to negative values, generated by contraction phenomena.

When the minimum of the contraction occurs, around the 250th day, a rapid increase in the AE cumulative function is determined in correspondence with it.

<u>The variations in the strain trends are clearly due to seasonal thermal excursions.</u>

Conclusions

In this contribution –in the framework of non-destructive testing methods, and especially of the Acoustic Emission (AE) technique applied as in situ monitoring systems– are briefly presented the results already obtained from the monitoring of the “Asinelli” Tower, and the preliminary outcomes on the monitoring of the "Garisenda" Tower.

The two Towers, recognized as the "*twin towers*" of Bologna, represent a remarkable symbol of the City and of the Italian Architectural Heritage.

Conclusions

The data collected during the monitoring period of the Asinelli Tower were analyzed to evaluate the damage progress in a certain region of the masonry structure and correlate it with other considered phenomena, such as the influence of vehicle traffic, seismic activity, and wind action.

During the monitoring period a correlation between peaks of AE activity in the tower and regional seismicity was found. The Tower, in fact, seems to be particularly sensitive to the action of nearby earthquakes, behaving as a sensitive earthquake receptor.

Conclusions

For the Garisenda Tower, in order to arrive at a comprehensive and objective evaluation of the structural conditions, the results obtained by the AE technique are supplemented by means of other techniques.

In this Tower, other than an AE device provided of 8 piezoelectric sensors, six optical cables were also installed to measure in real time, the vertical displacements of the tower basement.

Moreover, a seismometer was fixed at a height of about 150 cm from the floor basement. This device is capable of acquiring motion speeds greater than or equal to 0.127 mm/s.

Conclusions

During the monitoring period no high Richter scale magnitude earthquakes hit the region around the City of Bologna, is therefore demonstrated also by the AE monitoring that the Tower damage is not correlated to the regional current seismicity.

Considering the strain trends obtained during all the monitoring period detected by the optical cables, it can be said that they are clearly generated by seasonal thermal excursions.

It seems therefore that the damage evolution in the basement of the Tower is due to the strain inversions which, producing expansion and contraction phenomena of the selenite masonry, would also generate the formation of micro-cracks.

Additional interesting evaluations will be carried out in the further monitoring steps.