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MONITORING LEANING TOWERS BY GEODETIC APPROACHES: EFFECTS OF SUBSIDENCE AND EARTHQUAKE TO THE GHIRLANDINA TOWER

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ABSTRACT

The research focuses on structural monitoring and movements identification applied to cultural heritage safeguard. The final purpose is the integration among different and independent technologies for analyzing and investigating the geometry changing over time of ancient leaning towers. The paper deals with a novel strategy implemented by Authors to compute differential vertical displacements starting from results obtained by repeated high precision leveling network adjustments. These results usually aim at monitoring the subsidence phenomenon, while their use in engineering applications is more or less absent in literature. Moreover, the multidisciplinary approach is also able to analyze gradients of lowering in order to extrapolate the trend of the vertical axis and compute structure's rotations. The approach is applied to the Ghirlandina Tower, Modena (Italy), in order to identify the leaning and the lowering trend. About thirty years of leveling campaigns provide a useful dataset to test the methodology, which is finally validated by the independent observations collected by a pendulum. The approach allows to compute the mean total displacement since 1984 of about 4.7 cm with 30% occurring over the last 6 years. In the same period, the total overhang of the Tower (1.30 m in 2007) increased of about 19.1 mm and 10.4 mm towards south-west. The approach is also able to identify anomalous behavior of the Tower such as the reversal tilting trend due to the scaffolding in the years of restoration and the permanent deformation suffered after the 2012 Emilia Romagna earthquake (failure of 4 mm in 6 months).

KEY WORDS: structural monitoring, leaning towers, high precision leveling, tilting, vertical displacements, Ghirlandina Modena, subsidence effects.

1. INTRODUCTION

The main topic of this research lies in identifying helpful information for structural monitoring in the field of cultural heritage safeguard. It is recognized that the deep knowledge of suffered displacements and their trends are essential to plan the most effective interventions for the safeguard of the structure. The overall goal is of course the conservation and preservation of the integrity of the structure itself. In recent years, the monitoring of civil structures and architectural monuments has assumed considerable importance because the safety of the buildings already characterized by damage and decay as well as the prediction and prevention of these phenomena in buildings that do not have them revealed yet are essential [1] [2]. As a consequence it is necessary

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to design a monitoring system of active movements and rotations to determine the origin, the extent and the laws of evolution of the phenomenon in order to define the most appropriate type of intervention for the future. The most commonly used sensors are accelerometers, deformometers and several other instruments to collect a continuous time series of measurements and to investigate both the static and the dynamic behavior of a structure [3] [4] [5] [6] [7] [8]. The present research focuses on long-term monitoring by means of geodetic techniques. The novelty of the proposed approach lies in processing discontinuous geodetic data, initially collected to check for subsidence effects, in a different way in order to provide suitable results for improving the knowledge of the long-term structural behavior. In particular, Authors refer to a diagnostic monitoring, aimed at verifying the differential movements suffered over time due to the interaction between the structure and the subsoil. The final purpose is to develop and illustrate an original approach for the diagnosis of the changes in the geometry configuration of high-rise towers, based on the innovative way of "reading" and interpreting the adjusted results obtained by periodic high precision leveling. A high precision leveling network is a well-established survey method which is widely used to provide, with uncertainty of ±0.1 mm, vertical displacements. It usually aims at studying the phenomenon of subsidence [9] [10] [11] [12] or to detect ground movements to relate to crustal deformations and geophysical phenomena [13] [14] [15] [16] [17] there are plenty of papers in literature discussing this topic. On the other hand, only few examples analyze the stability of high rise towers and they strictly concentrate on the interaction with the subsoil [18] [19] [20]. There are no examples where precision leveling is used for supporting structural monitoring, no applications nor specific methods developed to focus on the induced effects by the phenomenon of subsidence on the stability of the structures. There is only one attempt in [21] to extrapolate the overall effect of differential components from the buildings point of view. This aspect is even more crucial when cultural heritage is involved and the present paper would be the first contribution that puts the potentiality of exploiting a traditional and cost-effective survey technique into evidence and demonstrates the usefulness in determining the geometry issues that may be critical for the stability of the structure. Basically the proposed methodology provides results which are helpful in the prevention perspective.

2.THE CASE STUDY

The novel approach was tested on the Ghirlandina Tower (Modena, Italy) that is included within the UNESCO World Heritage List since 1997 (Figure 1). Being a monument of great historical and architectural assets, the Tower, together with the nearby Cathedral and the whole Piazza Grande, represents the symbol of Modena and it is one of rare examples where two architectural styles, Romanesque and Gothic, co-exist.

The civic Tower of Modena, called "Ghirlandina" because of the garlands that adorn the top, is a building with narrow section at the base, a side range of up to 10.8 m, a total height of about 89 m, with no foundation and six floors topped by an octagonal drum and a high pyramidal spire (Figure 1). The construction of the Tower , made of brick and fitted with natural stone cladding , was supposedly started in 1099 together with the adjacent Cathedral, designed by the architect Lanfranco and its co-workers, and the completion of the work dates back to 1319 [22]. The assumptions relating to the subsequent stages of construction are multiple and sometimes conflicting, but all recognize that the Tower, as it appears to our eyes today, is primarily the result

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of the following corrections to the verticality of the structure that were made during the various stages of realization and secondly of the phenomena of sink and instability which occurred over time with the effect, so far averted, of undermining the stability of the Tower [23] [24]. This kind of geometry together with the overhang and the inclination lead to the strong need of monitoring the structure in order to achieve protection and conservation. The Tower indeed has been extensively studied over the years to understand the causes of its irregular shape; joint analyses showed that the current geometry is surely due to the different steps of construction that have historically taken place [22] and also to the phenomenon of subsidence in Modena [25] [26] [27].

2.1 The dataset

The dense local leveling network, connected to the regional geodetic network, was established in 1984 in order to control the deformations of the monumental centre nearby the Tower and the Cathedral [28]. It initially consisted of 29 benchmarks while currently it only involves 24 of them because 5 were lost (left Figure 2). After a stop of about 15 years, the Municipality of Modena decided to further investigate the evolution of vertical displacements in such area due to the relevance of the phenomenon and its implications; thus, in 2007 high precision leveling campaigns restarted and they are still in progress. The network is surveyed twice a year by means of a digital level (DNA03 by Leica Geosystems) and an invar staff to minimize the problem of thermal deformations which might affect the quality of the measurements [29]. The network is adjusted by constraining all benchmarks to the reference one, number 12, which is conventionally fixed to an elevation of 10 m. This choice, according to adjusted elevations obtained in 1991, does not trouble the final interpretation of results, especially because a relative analysis is performed and the attention is paid to differences of elevation that are the most interesting concerning the potential dangerous consequences on the stability of the structures. It should be noted that it is always possible to obtain the absolute elevation of each benchmark of the local network through the connection of the reference point to a remarkable benchmark belonging to the regional network for the subsidence monitoring and located in the Apennines nearby Modena, considered not affected by the investigated phenomenon. Such a connection is easily performed by means of a GPS static survey thanks to the constraint to the ItalPoS national permanent network [30].

The data pre-processing lies in controlling the closure of leveling rings before proceeding to the network adjustment. The sketch of measurements is sufficiently redundant to allow a high quality computation, thus obtaining an average accuracy of 0.1÷0.2 mm (95% level of confidence) for final elevation differences. The adjustment computation is performed by STAR*NET-PRO Version 6.0.36, Starplus Software Inc . Results of each network adjustment are then compared to previous survey campaigns, allowing to detect the vertical displacements occurred over time by the various benchmarks of the network as well as to investigate the significance of movements experienced by the structures to which they are rigidly connected. To this end, the right Figure 2 displays the total vertical displacements suffered since 1984 in the historic centre of Modena while Table 1 reports the adjusted elevations computed after each leveling campaign for the benchmarks installed at the base of the Tower. The Tower results to be the building characterized by the greater additional subsidence with respect to the one experienced by the whole city centre (about 47 mm over the period 1984-2013 and 14 mm in 2007-2013 with respect to the reference benchmark).

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3. THE METHODOLOGY

On the basis of results obtained by high precision leveling surveys, a novel approach has been developed in order to obtain, investigate and examine differential movements soliciting the structure and their trend over time, which are the main concern for stability and safety of the structure. First of all, the attention has been paid to the correlation of high precision leveling data. On investigating the adjusted elevations, the implemented methodology uses some structural and geotechnical hypothesis: the structure is considered as a rigid body, an infinitely stiff structure [31] [32], with the foundation behaving as a flat surface due to the highly deformable substrate (criterion for the benchmarks constraint) as demonstrated by geotechnical investigations carried out nearby and under the structure [33]. The benchmarks installed at the base of the Tower, despite the fact they do not actually belong to the same plane, move stiffly all together. For each leveling results dataset, although it is not possible to identify a plane exactly passing through these points, it is possible to compute the best-fitting plane that minimizes the distance from each benchmarks and then to determine the stiff movements and rotations accordingly. The study of the rigid behavior of the Tower over time can be derived directly from the study of the behavior of such a plane by assuming the best-fitting plane as the rigid foundation. The procedure has been implemented in an algorithm developed in MATLAB (v. 7.0) whose general workflow is shown in Figure 3. The procedure is based on the calculation of vertical displacements and gradients between benchmarks belonging to the same structure by means of elevation differences at each epoch. The computation of the best-fitting plane for each epoch (best-fit of the elevations) is then essential to allow the following identification of the geometric barycentre of each plane and its trend over time. This is to identify and isolate the vertical component of displacement. By this way the translational component is achieved whereas the rotational one is isolated through the identification of the normal to the plane for each epoch.

The identification of the gradients of vertical displacements and the visualization of the inclination of best-fitting planes allow mainly qualitative analysis; in order to quantify the changes in the geometry such as rotations and the overhang trend, the normal to plans needs to be considered by projecting it along the axes of the defined reference system. The sign of these components allows to confirm the qualitative assumptions derived from the best-fitting plane attitude while their values to uniquely quantify it.

To critically analyze the proposed approach and provide some kind of confirmation, results have been compared to data collected by a completely different and independent technology. The comparison aims to validate the potentiality of studying the slow and rigid motions of a structure with a not expensive technique either in terms of time or money and of identifying differential movements in order to evaluate whether they might be responsible for any future instability.

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4. RESULTS AND VALIDATION

The first analysis based on the adjusted elevations is the calculation of the movements and the resulting differential components at the base of the Tower. The vertical displacements and gradients over the long term, since 1984 to date, and in the most recent period, since 2007 to date, are represented in Figure 4 where significant differential components are highlighted in south and west direction in accordance with the strongest displacement occurred to benchmark 18. These data therefore suggest an increasing trend of gradual slope of the Tower in the south-west side. Next step lies in the computation of the best-fitting plane for each leveling campaign and the visual qualitative examination of the evolution in time of such a plane. It is essential to define a suitable reference system; the choice consists of a right-handed triad characterized by the origin positioned at the benchmark 17, the *x*-axis along the line joining benchmark 17 to benchmark 18 (parallel to the Tower's west side) with positive direction towards south, the *y*-axis along the line joining benchmark 17 to benchmark C/1 (parallel to the Tower's north side) pointing towards east and finally the *z*-axis being orthogonal to the *xy*-plane with the positive direction upward.

The definition of the reference system is not of secondary importance, but it is functioning to correctly interpret the rotations at the base of the Tower as well as to proper identify the trend of the overhang experienced by the structure.

To analyze from a quantitative point of view the changes suffered by the Tower since 1984, it is useful to decompose the movements in order to separate the vertical displacement and the rotations.

The improvement of local subsidence experienced by the Tower can be investigated by considering the vertical displacement suffered by the barycentre of the best-fitting plane at each epoch. Figure 5 plots the trend of the elevation changes of the barycentre over the last thirty years and also reports a table containing the lowering velocity, which allows to analyze any signs of acceleration or deceleration of the phenomenon. The table refers to long-term analyses and highlights a slight acceleration of the phenomenon since 2007 which strengthens over the last two years of observations. The vertical rate, indeed, ranges from about 1 mm/y, providing a displacement of 2.0 cm over the period 1991-2007, to 2.3 mm/y, providing a displacement of 1.4 cm over the period 2007-2013. This is easily noticeable by a careful analysis of the plot in Figure 5 where the slope of the line is significantly higher since 2007 (the plot time scale has been previously homogenized in order to provide a reliable and immediate comprehension of the rate changes).

Regarding the identification of rotations and the increment of the Tower overhang, the computation is based on the normal to each best-fitting plane, which is on purpose extrapolated. The normal is then decomposed by projecting with respect to the axes of the reference system. This allows immediate analysis of the tilt over time with separation into the two main directions, north-south and east-west. This also is essential to calculate the overhang of the Tower by knowing its total height and the slope angle of the axis variation. Figure 6 and 7 reports the tilting trend for both directions; it immediately appears as the Tower is subject to constant although small increments of tilting, thus overhang as well, clearly displayed also in Figure 8. The axis of the Tower, although it is not straight as mentioned above, is here modeled by a linear behavior according to the initial hypothesis that supposes the structure to be an infinitely rigid body. In addition it should be noted that this study aims to identify the rigid motions of the structure due to the interaction with the ground, while for a monitoring of its deformations it is necessary to provide long-term measures along the entire height of the structure and not only at the base. In addition to the tilting analysis, the rotation at the base of the Tower can also be investigated. The normal, indeed, is also projected with respect to *xy*-plane thus a third component is also taken into consideration. Figure 9 shows that the base of the Tower is progressively and gradually rotating anticlockwise. Such a consideration could be of some interest if coupled with any further measurements along the elevation of the Tower in order to check for torsion.

In order to test the methodology and provide some kind of confirmation, an independent technology is adopted. The multi-sensors approach is indeed the most suitable way to check for the reliability

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of solutions; this is even more important in monitoring applications where the possibility to trust and have confidence in results is a must [34]. Regarding the computation of rotations and the trend of the Tower tilting, the continuous observations of a pendulum are used to validate the results. The pendulum was especially set up in 2003 for monitoring the tilting and the consequent increase of the total overhang of the Tower. It is actually able to sense directly the tilting of the structure where it is installed on and does not need much processing, thus resulting in an extremely reliable terms of reference for the validation process. Figure 10 shows a picture of the dual axis pendulum and its location within the Tower. The pendulum is 23 m long and senses the tilt changes with respect to the first epoch. The time series is represented in Figure 10 and shows the tilting by means of the displacements experienced by the Tower at the pendulum level. The analysis of spatial values, indeed, are easier to be understood and interpreted than the angular values. By examining the pendulum time series, the Tower tilts providing a total overhang ranging from 1 mm to 2 mm towards west and north respectively since 2007 to 2011 related to the length of the pendulum . Please be aware that the pendulum-based solutions are perfectly comparable together with the leveling-based solutions because they are referred to the same Tower-dependent reference system and moreover the analyzed time span is also the same (2007-2011). Due to the earthquake occurred in Modena in 2012, the last two years of the pendulum observations are not reliable for being used as terms of reference in the validation process. Due to continuous malfunctioning, indeed, the most recent part of the time series is affected by data gaps and interruptions.

The rotations computed by the methodology and shown in Figure 6 and 7 are transformed into spatial displacements taking into account the total length of the pendulum (23 m) in order to provide comparable values for the validation process. The calculation is expressed below and allows to identify the change of the overhang occurred since 2007 to 2011 on the basis of the proposed methodology, ranging from about 1 mm to 2 mm towards west and north respectively.

$$\Delta s_{EW} = \tan\Delta\vartheta_{yz}\cdot pl = \tan\left(0.5065^{\deg} - 0.5039^{\deg}\right)\cdot 23m = 1.0mm$$
$$\Delta s_{SN} = \tan\Delta\vartheta_{xz}\cdot pl = \tan\left(0.8457^{\deg} - 0.8397^{\deg}\right)\cdot 23m = 2.4mm$$

with:

Δs_{EW} and Δs_{SN} being the overhang changes towards the east-west (y-axis) and south-north (x-axis) directions respectively;

$\Delta\theta_{yz}$ and $\Delta\theta_{xz}$ being the tilting variations in the yz-plane and xz-plane respectively;

pl being the length of the pendulum.

Such values are coherent and completely agree with the pendulum observations, thus providing a very nice validation for the proposed methodology concerning the identification of reliable rotations to be helpful for any further structural health analysis.

5. DISCUSSION

The implemented approach allows to detect the rigid motions suffered from the investigated structure, being a leaning tower, under specific and realistic hypothesis. Both the vertical displacements and rotations are computed achieving the goal to numerically quantify the trend of tilting as well as the total overhang at each epoch. Moreover the local effect of additional

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subsidence due to the interaction between the structure and the ground is also quantified. By deeply analyzing the final results, some further considerations can be drawn concerning the trend of geometry changes experienced by the Tower. Particularly, some anomalous situations are identified and allow interesting comments about the response of the structure to external conditions.

First of all, a significant reversal trend appears in Figure 6 and 9 since 2008. Before that epoch, the tilt progressively grows with the Tower rotating towards south-west. Since 2008 the tilt changes and the Tower starts rotating towards north-west, reducing its total overhang accordingly. The reversal trend continues until 2011 when the past behavior is reactivated. The strange phenomenon appears to be anomalous if compared to the past documented story of the Tower which rotated towards south-west since 1984. A deed knowledge of the recent story of the Tower provides a reasonable explanation: an important intervention of artistic and structural restoration of the Tower started in 2008 and brought back the Tower to its ancient beauty in 2011. During restoration a big and heavy scaffolding was installed all around the Tower; it strongly influenced the behavior of the Tower by stiffening it and protecting by the wind. As soon as the scaffolding is removed in 2011 the reversal trend stops and the Tower starts again acting as before.

A second question should rise by looking at the strong vertical displacements sensed in 2012 when the Tower suffers a failure of about 4 mm in just 6 months. In this case the Tower is responding and adapting to the behavior of the soil which was strongly solicited during the big earthquake that occurred in Modena in May 2012. The earthquake, indeed, was characterized by a main vertical component [35] [36] and the soil has gradually released the compression, accumulated in the form of interstitial pressure [37]. As a consequence, the Tower has expressed with a certain time latency the permanent residual component of vertical displacement which was highlighted only by this analysis. It is possible to affirm now that this is a permanent modification of the Tower asset because a certain time is undergone and the vertical trend of lowering is continuing with the rate had before the earthquake. This is a key point for the importance and the usefulness of the methodology because the deformation was not detected by any other installed system. The Tower was monitored just by the long-term monitoring system characterized by the pendulum, extensometers and piezometers with logging rate of 15 minutes. At the earthquake epoch no sensors for a dynamic monitoring were implemented. As a consequence, there was no way with the existing sensors to determine whether the Tower experienced a permanent deformation or not until the present methodology put the residual vertical failure suffered by the structure into evidence. After the confirmation given by the following survey campaigns, where no raising was detected, the Municipality, in accordance with the Scientific Committee, installed a number of accelerometers for a dynamic monitoring [37]. In some way, it can be noticed that the proposed methodology highlighted the potential need of a dynamic monitoring system and supported the decisional process to implement it. This is also a positive strategy, in terms of a cost-effective management of cultural heritage in a period with scarce economic resources, to plan the upgrade of sensors on the basis of an evident and quantified need.

Both these considerations allows to underline the success of the methodology to pick movements and understand the responses of the structure to the changes of external conditions, being them natural such as the interaction with the ground and the earthquake or anthropogenic such as the activities carried out on the monument.

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Concerning the vertical displacement component, results of the last six years show that the Tower lowering appears to weakly accelerate (Figure 5). Caution is required in affirming that there is an acceleration of the phenomenon; an apparent increasing trend is for sure evident but it will be checked with a longer time series, particularly when the equal time scale length is available. What certainly cannot be neglected is that the Tower undergoes local effects in addition to the general subsidence phenomenon that already affects the whole area. The trend of the barycentre vertical displacement, indeed, clearly shows a local effect which is only proper of the Tower, of about 0.8 cm over the period 2007-2011, strengthened during last two years by an additional component of 0.6 cm. Do not forget that these considerations come from analyses based on adjusted elevations related to a local benchmark especially processed to identify the differential components and rigid motions on the involved structures.

To complete the discussion, the total overhang of the Tower can be obtained by adding the increase computed by the proposed methodology since 2007 to the initial overhang observed in 2007. At that time, indeed, a terrestrial laser scanner survey was performed in order to provide the 3D model of the Tower [38]. Some investigations about the geometry of the structure were carried out and allowed to identify the total height of the Tower, being 88.82m from the base to the centre of the cross at the top, and the total overhang depending on the axis pattern (Figure 11). The overhang in 2007 was about 1m towards west and 70 cm towards south. Moreover, since 2007 to 2011 the Tower experienced an additional contribution to the total overhang of about 4 mm and 9 mm towards west and north respectively, as computed below by referring the tilting increment to the total height of the Tower:

$$\Delta s_{EW} = \tan \Delta \vartheta_{yz} \cdot pl = \tan\left(0.5065^{\deg} - 0.5039^{\deg}\right) \cdot 88.82m = 4.0mm$$
$$\Delta s_{SN} = \tan \Delta \vartheta_{xz} \cdot pl = \tan\left(0.8457^{\deg} - 0.8397^{\deg}\right) \cdot 88.82m = 9.3mm$$

To conclude, the general trend of rigid motions suffered by the Tower since 1984 are outlined in Figure 11 and comprehensively lies in south-west tilting and in anticlockwise rotation at the base, according to the investigations and computations provided by the proposed methodology and validated by means of the independent technology.

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6. CONCLUSIONS

Although the adjusted elevations obtained by periodic high precision leveling are originally intended to monitor the subsidence phenomenon within the historic centre of Modena, the proposed methodology highlights how they can be successfully involved in structural monitoring applications. The implemented approach aims to add information about the stability on an ancient structure, particularly a Tower, with the purpose to safeguard its integrity. In order to highlight all conditions and solicitations which affects the structure, a multidisciplinary approach based on the integration of multiple techniques is essential. The present research starts from a very consolidated technique, the well known high precision leveling, whose results are then analyzed and processed in a novel way giving strong attention to the structural point of view. The usefulness of the approach lies in starting from a dataset which is commonly available to most Municipalities and Local Authorities, which regularly pay attention to control the phenomenon of subsidence. To provide the validation, the leveling-based results are compared to observations of a pendulum in continuous operation inside the Tower since about 10 years, being precisely dedicated to monitor the vertical axis of the Tower and its changing over time.

Once raw data are collected, a deep analysis needs to be carried out in order to detect rigid motions and achieve the above mentioned goals; the proposed methodology illustrate how vertical displacements, tilting and rotation at the base can be extracted simply starting from adjusted elevations. The basic steps lies in the definition of suitable geotechnical hypothesis depending on the main features of the structure, then both qualitative and quantitative investigations are performed to compute rigid motions. These solutions are validated by the comparison with independent technique, such as continuous pendulum observations for the tilt component. The comparison gives the opportunity to validate the methodology, confirms the success of the approach and the usefulness of the strategy for identifying rotations of the Tower axis and consequently changes in the tilting rate of the structure.

The proposed approach is tested on a thirty-years dataset of the Unesco site of Modena. The results obtained thanks to the implemented analysis proved to be interesting and helpful for improving the knowledge of the geometry of the Tower and its behavior. Concerning the Ghirlandina Tower, results about the last six years are particularly interesting because the vertical displacement component appears to weakly accelerate: the mean total displacement since 1984 is about 4.7 cm with its 30% occurring over the last 6 years. Moreover, the rotational component shows a significant reversal trend over the period 2008-2011 with respect to the past then inverted again since 2011 to date. Reasonable explanations are given for both behaviors allowing to understand how complex is the response of a structure to external condition changes (earthquakes, interaction with the soil, human interferences and so on) and how much important is to monitor and provide a longer time series in order to improve the knowledge. The tilting of last 6 years provides the increase of the total overhang of the Tower which is estimated to be about +19.1 mm and +10.4 mm towards south-west at the top. Please take into consideration that these values are based on the hypothesis that the Tower axis is regular, which is not in the real geometry; thus, the exact amount of the overhang increase might be slightly different and it should be verified, for instance, by a repetition of the laser scanning survey. In conclusion, the obtained results allow to comment that the Tower slightly experienced rigid motions over the last thirty years which suggests the importance to continue with the long-term monitoring in order to check for the stability. The approach gives the opportunity to provide useful information to study the vulnerability of a structure as well as its response mechanism by processing in a novel way the dataset obtained by a commonly used technique. High precision leveling provides reliable solutions which reveals to be extremely efficient and effective for the computation of high accuracy rigid motions. The success of the methodology strengthens to improve the algorithm for different kind of structures, such as the Cathedral for which in the next future a deep study is required to define structural and geotechnical hypothesis. This would be really useful to better investigate the Tower-Cathedral interaction for the safeguard of the whole Unesco site.

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#	Dec/84	Dec/85	Sep/86	Feb/88	May/89	Aug/90	Dec/91	Dec/07	Apr/08	Nov/08	Sep/10	Dec/10	Apr/11	Nov/11	May/12	Nov/12	Apr/13	Nov/13
16	9.3986	9.3967	-	9.3930	9.3927	9.3917	9.3868	9.3662	9.3644	9.3638	9.3601	9.3586	9.3587	9.3583	9.3586	9.3540	9.3530	9.3522
17	9.1508	9.1472	9.1461	9.1437	9.1435	9.1426	9.1376	9.1178	9.1153	9.1143	9.1104	9.1090	9.1088	9.1086	9.1087	9.1062	9.1049	9.1041
18	9.4186	9.4149	9.4137	-	9.4115	9.4102	9.4048	9.3839	9.3814	9.3812	9.3774	9.3757	9.3758	9.3754	9.3751	9.3698	9.3689	9.3680
C/1	9.3774	9.3740	9.3734	9.3715	9.3711	9.3707	9.3657	9.3464	9.3441	9.3432	9.3391	9.3379	9.3378	9.3378	9.3382	9.3361	9.3349	9.3342

Table 1. Periodic high precision leveling since 1984: adjusted elevation [m] referred to benchmark 12 (conventionally fixed to 10m).

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The Ghirlandina Tower and the nearby Cathedral, Modena (Italy), included within the UNESCO World Heritage List since 1997 (left); detail of the top of the Tower (middle); location map (right).
105x47mm (300 x 300 DPI)

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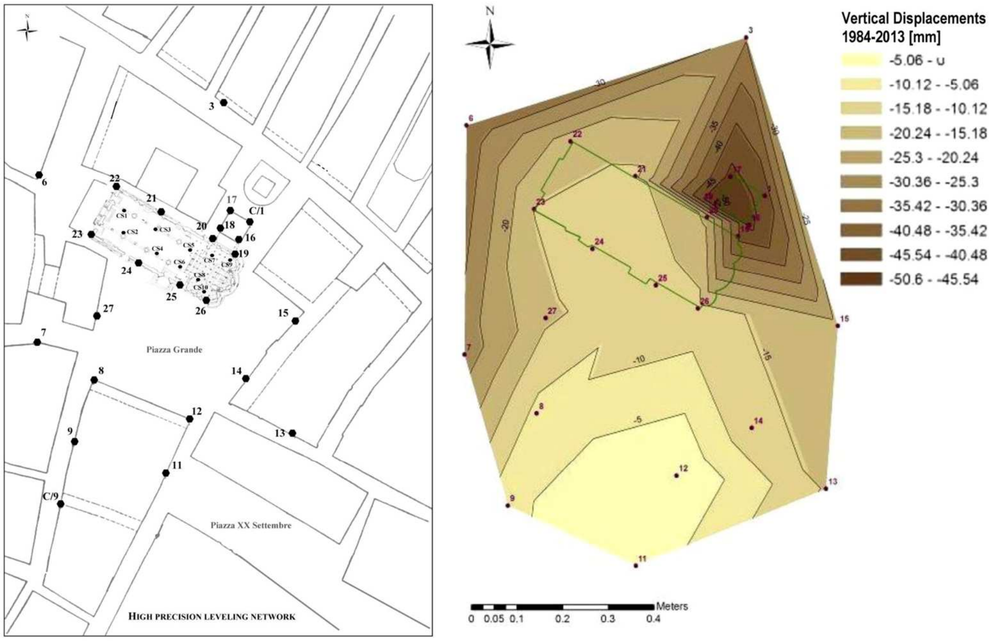
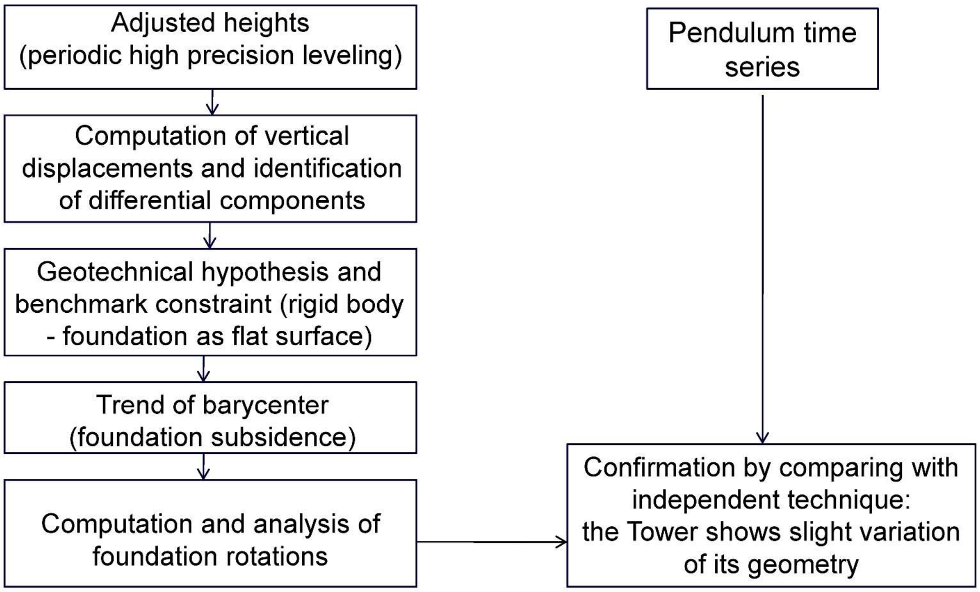


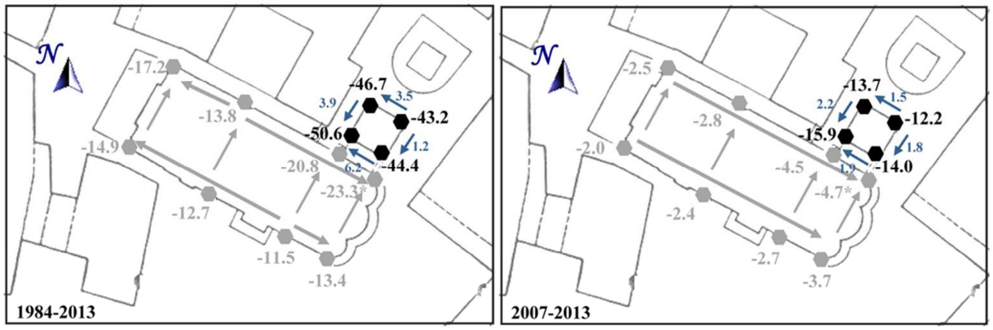
The dense local high precision leveling network in the historic centre of Modena (left) and the 3D representation with contours of total vertical displacements over the period 1984-2013.
165x109mm (300 x 300 DPI)

Review



The methodology: general workflow of the data processing strategy.
1395x860mm (96 x 96 DPI)

er Review



Vertical displacements and gradients over the period 1984-2013 and 2007-2013 for the benchmarks installed at the base of the Tower. All values in [mm].
94x32mm (300 x 300 DPI)

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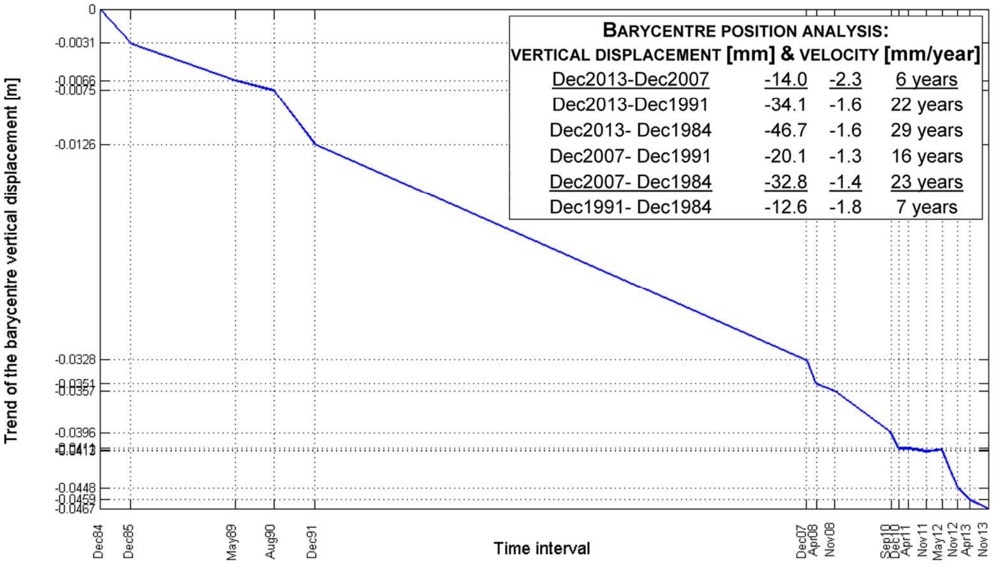

BARYCENTRE POSITION ANALYSIS:
VERTICAL DISPLACEMENT [mm] & VELOCITY [mm/year]

Dec2013-Dec2007	-14.0	-2.3	6 years
Dec2013-Dec1991	-34.1	-1.6	22 years
Dec2013- Dec1984	-46.7	-1.6	29 years
Dec2007- Dec1991	-20.1	-1.3	16 years
Dec2007- Dec1984	-32.8	-1.4	23 years
Dec1991- Dec1984	-12.6	-1.8	7 years

Trend of vertical displacement suffered by the Tower over about 30 years based on the computation of the best-fitting plane barycentre at each epoch. The table specifies numerical values and highlights the velocity of the local effect.
138x78mm (300 x 300 DPI)

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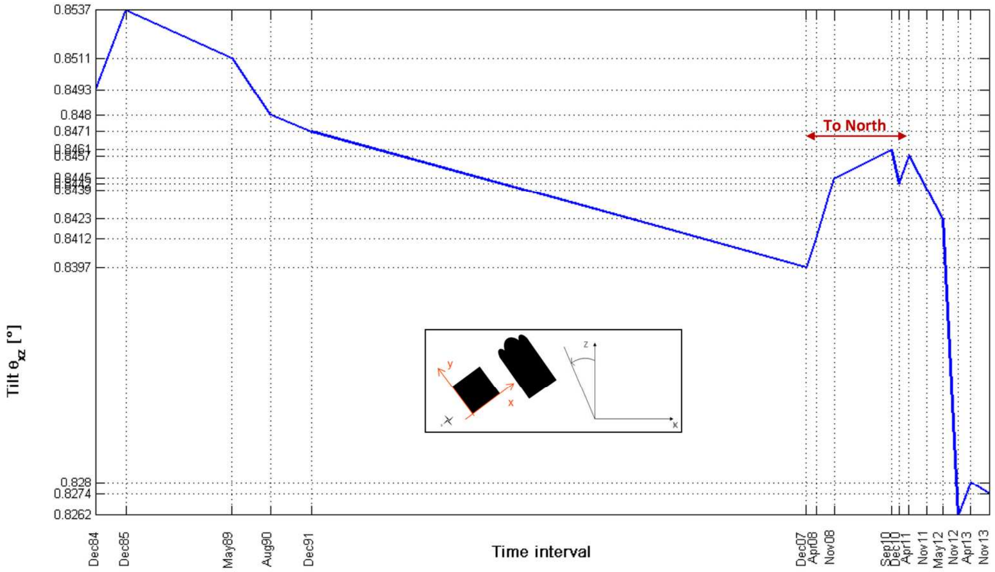

Trend of the Tower tilt over the period 1984-2013 obtained by computing the normal to each best-fitting plane. The decomposition with respect to the xz-plane allows to separate the tilt towards north-south.
145x84mm (300 x 300 DPI)

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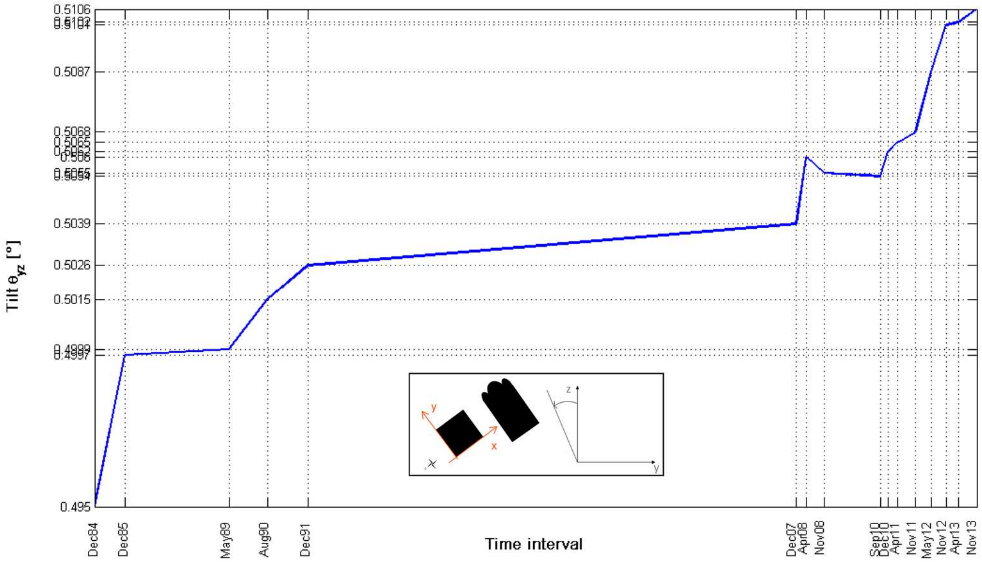

Trend of the Tower tilt over the period 1984-2013 obtained by computing the normal to each best-fitting plane. The decomposition with respect to the yz-plane allows to separate the tilt towards east-west.
143x82mm (300 x 300 DPI)

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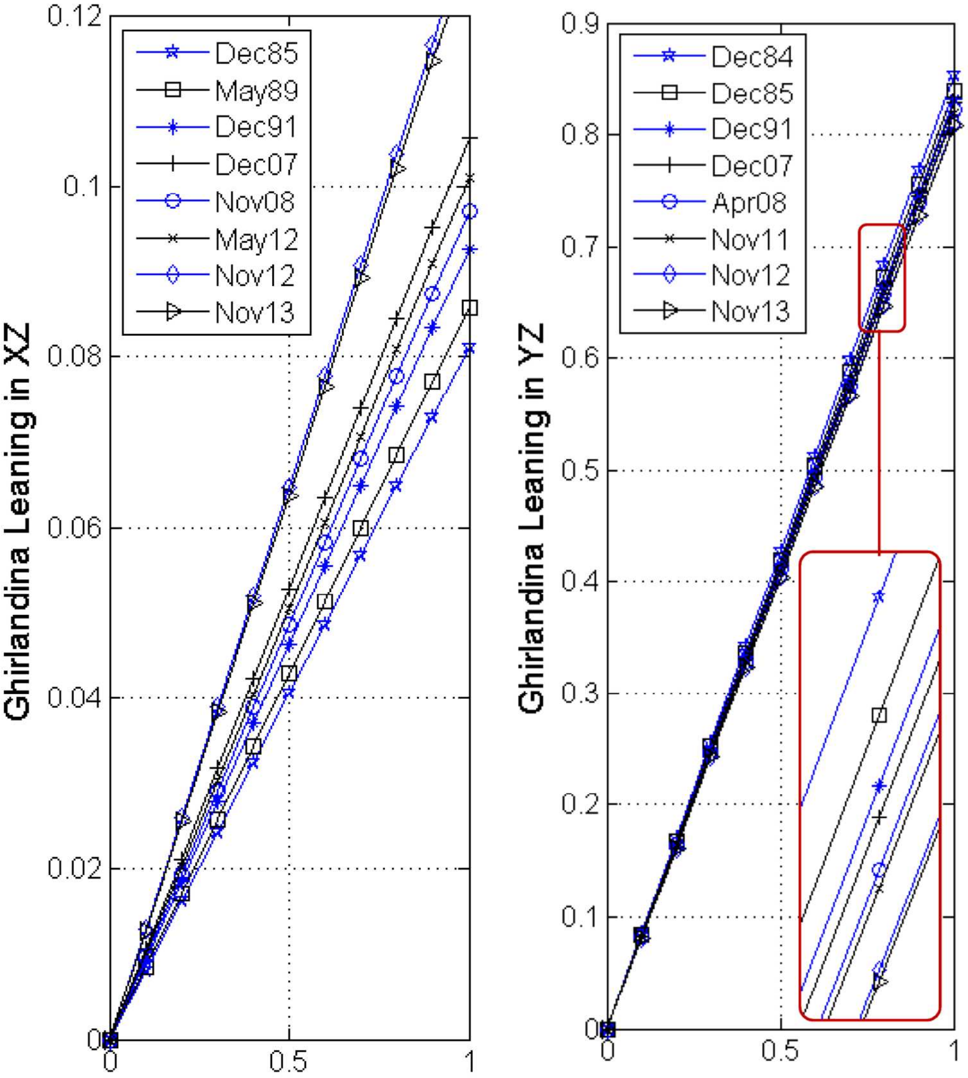
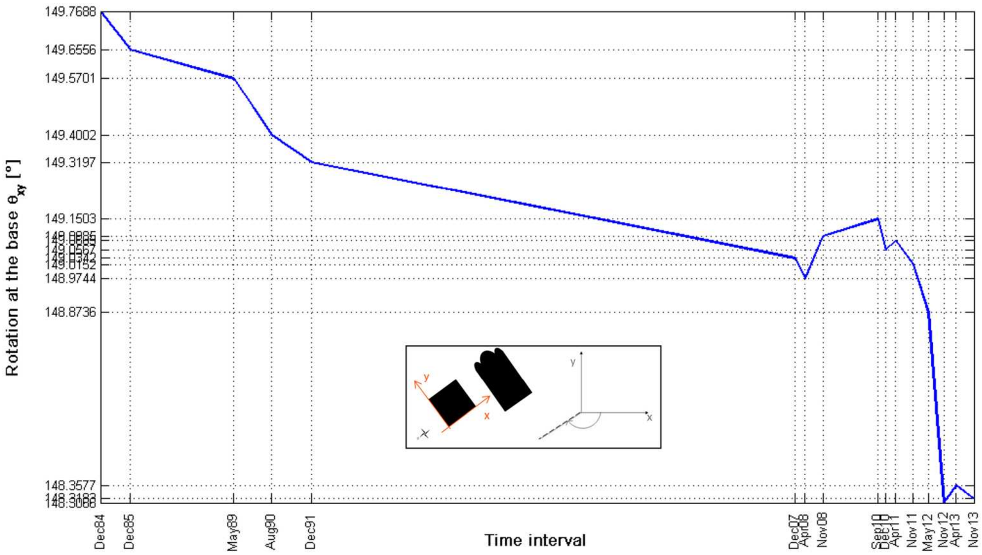
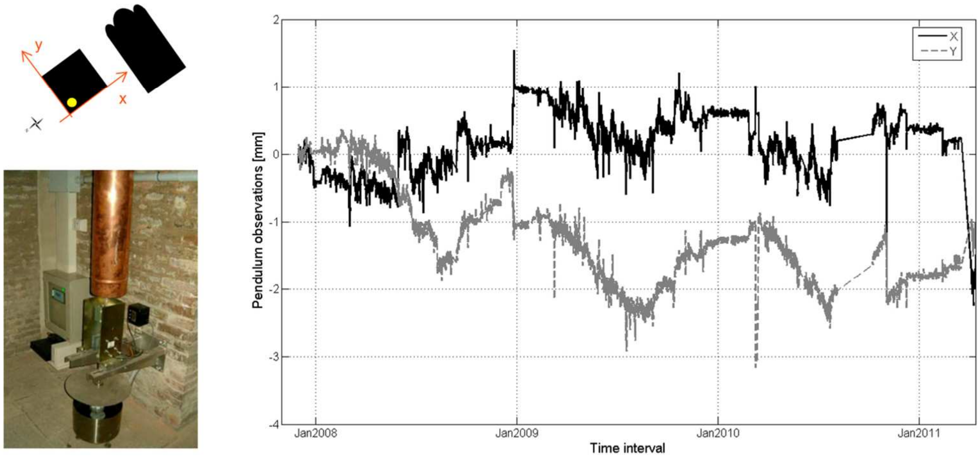


Trend in leaning of the Ghirandina Tower obtained by displaying the tilting variation over the period 1984-2013 (for readability reasons the tilt of displayed lines is amplified).
181x200mm (300 x 300 DPI)



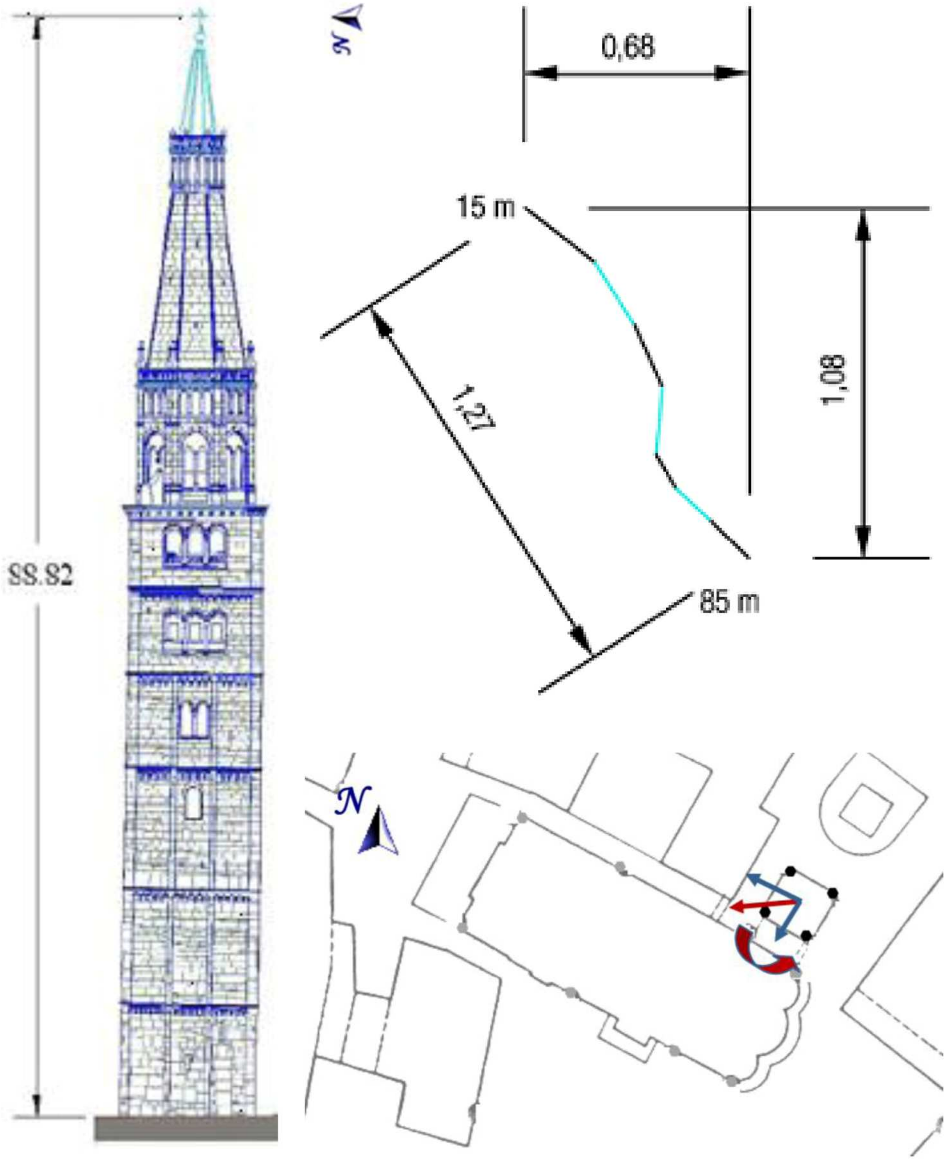
Trend of the horizontal rotation at the base of the Tower over the period 1984-2013 obtained by computing the normal to each best-fitting plane and projecting it to the xy-plane.
142x81mm (300 x 300 DPI)

er Review



The observation reference system, picture and location of the dual-axis pendulum which is installed inside the Tower since 2003 (left); the pendulum time series representing the overhang trend in the same time span investigated by the proposed methodology (right).
118x56mm (300 x 300 DPI)

eer Review



The tilt of the Tower axis detected in 2007 by Terrestrial Laser Scanner (TLS) survey (left and top right); the final results of rigid motions suffered by the Tower as obtained by the proposed methodology (down left). All units in [m].
159x198mm (300 x 300 DPI)