

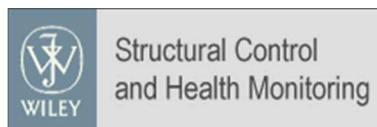
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## GEODETIC MONITORING AND GEOTECHNICAL ANALYSES OF SUBSIDENCE INDUCED SETTLEMENTS OF HISTORIC STRUCTURES

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**GEODETTIC MONITORING AND GEOTECHNICAL ANALYSES OF SUBSIDENCE  
INDUCED SETTLEMENTS OF HISTORIC STRUCTURES**

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**ABSTRACT**

This paper focuses on the integration of geodetic monitoring and geotechnical modeling for the analyses of subsidence induced settlements in historic structures. The aim is the assessment of the behavior over time of the monuments, with particular attention to differential settlements, in order to evaluate the potential risk scenarios in a preventive strategy. The methodology is applied to the UNESCO site of Modena where the Cathedral and the Ghirlandina Tower are characterized by strong visible deformations due to a complex construction history, the peculiar subsoil conditions and the effects of both natural and man induced subsidence. A 3D finite element numerical model has been developed taking into account the soil characteristics gained by laboratory and in situ tests. The model takes into account the influence of previously existing structures, as well as the subsidence phenomena and provides a settlements profile in agreement with the real dataset collected by high precision leveling. The geodetic monitoring, carried out since 1984, allows to optimize and then to validate the numerical model giving the Conservation Authority a useful tool to manage the safety of the heritage.

**KEY WORDS:** high precision leveling, geodetic monitoring, subsidence, structural damage, soil-structure interaction, geotechnical modeling, Unesco site.

**1. INTRODUCTION**

In order to forecast the long term behavior of historic structures, as well as their vulnerability with respect to environmental or seismic actions, there is a need to model the interaction with the supporting soil. In this respect monitoring is an essential component to validate any conceptual model as well as subsequent numerical analyzes.

The case history, here analyzed, proves how monitoring can help in understanding the behavior of historic structures, in capturing the normal physiological trend, in distinguishing deviations from this trend and in highlighting the causes of movements. By only devising a diagnosis of these causes the choice of remedial measures can be fully consistent with the principles of restoration. There should be no need to stress the importance of the concept of integrity, but quite often this is only interpreted as the requirement of preserving the shape and the appearance of the monument. The requirement of integrity is not so simple, because it also implies historic integrity, by

considering the changes the monument experienced with time, as well as material integrity, that means construction techniques, materials and structural scheme. Therefore, preserving integrity requires a multidisciplinary approach as well as to develop the attitude not to rush in deciding the stabilizing measures until the behavior of the monument is properly understood [1].

In this respect, it is proved how the accurate quantification of the vertical displacements, operated through periodic high precision leveling campaigns, can be of great value to improve the knowledge about the behavior of monuments and can help in forecasting future trends.

The novelty of the present work lies in showing how a traditional method for the long-term monitoring of subsidence phenomenon can be successfully exploited for structural monitoring purposes and for the validation of geotechnical predictive models. Few examples in literature deal with these issues. Many papers restrict in fact the use of high precision leveling to the study of geophysical phenomena [2] [3] [4] [5] forgetting the great impact of the induced subsidence in structural analysis, a topic that has been investigated only in few occasions [6] [7] [8] [9] [10] [11]. The methodology, quite often used for analyzing risk and instability scenarios in environmental contexts [12] [13], can be summarized as follows: implementation of a 3D finite element numerical model on the basis of geotechnical characteristics; data collection of significant movements with respect to the investigated phenomenon; optimization and validation of the numerical model by means of the real dataset.

The approach implemented in this research focuses on the effects induced by subsidence (whether due to natural phenomena or to anthropogenic phenomena such as the water pumping from aquifers), which is then seen as a possible source of damage, taking also into account of subsoil peculiarity. In the complex study of settlements, in fact, the influence of the subsidence phenomenon is not absolutely negligible. How important can be the link between the specific local geotechnical problem to the environment (territory) was clearly shown by prof. Arrigo Croce [14] for the safeguard of Milan Cathedral, one of the most impressive medieval architecture in Italy (construction started in 1386). The observed cracks and fissures became so important in 1969 that concrete casing were put in place to safeguard the integrity of the pillars and the whole Cathedral. Focusing the attention in the groundwater conditions existing in the alluvial subsoil, there was a strong evidence that the settlements of the Cathedral had to be considered within the context of the subsidence of a large area, induced by pumping started in 1922 and progressively increased in 1950's. Reduction of water withdrawal was imposed in the following years, and these measures allowed to slow down the settlements of the structure, to remove the casing of the pillars and in 1986 the Cathedral was returned to visitors.

Subsidence effects have also been documented in the case of the Tower of Pisa, highlighting how the pumping operations from the deep aquifers, started since the '70s, produced a failure and a rotation of the Miracles Square to the south-west. In addition, in more recent years new studies have shown as the fluctuations of surface water, due to heavy rainfall, would produce even a small but instant and irreversible rotation of the Pisa Tower towards south, with slow but progressive steepening [15]. These effects have been eliminated by a drainage system put in place recently [16]. Of course more examples could be cited, but those mentioned before are sufficient to emphasize the importance of having an adequate monitoring strategy that allows to successfully investigate the long-term behavior and the correlation between such behavior and the environmental changes induced by anthropogenic causes or natural events.

2. THE CASE STUDY

2.1 The UNESCO site of Modena

The Modena Cathedral (Modena, Italy), a masterpiece of Romanesque architecture and sculpture of northern Italy, is included within the UNESCO World Heritage List since 1997 together with the adjacent Ghirlandina Tower (Figure 1). Its construction was realized between 1099 and 1319, when the construction of the Ghirlandina Tower was completed. Inscriptions on the façade and on the central apse celebrate the sculptor Wiligelmo and the architect Lanfranco, respectively.

The Cathedral, approximately 25 m wide and 66 m long, with a roof height of roughly 24 m, is characterized by a Latin cross plant with three naves, a false transept and a cancel (i.e., the area of the liturgical altar) in elevated position, due to the presence of a crypt containing the relics of Saint Geminianus. Next to the Cathedral is the Ghirlandina Tower, roughly 89 m high, the construction of which proceeded in parallel with that of the Cathedral.

Within the context of the aim of this paper, it is of paramount importance to mention that, before the present Cathedral, three previous ones were built on the necropolis containing the tomb of St. Geminianus, which is the only remaining evidence of the first Cathedral. The second one was erected in the same place and the archeological remains indicate that this church had a length of around 32 m and width of 18 m. Finally, the presence of polylobate pillars, discovered during past excavations, allow to suppose the presence of another Cathedral, presumably built around the 11<sup>th</sup> century [17]. As a consequence of the sequences of construction and demolition of previous Cathedrals, since the soil has “memory” of its previous loading history [9], the Lanfranco and Wiligelmo Cathedral, suffered uneven settlements not only moving from south towards north (as expected due to the interaction with the Tower), but also moving from east towards west.

The complex history of construction, including the pre-existence of other Cathedrals that influenced the stress-history dependent soil response, lead to extensive studies over the years to understand the causes of its differential settlements and damages; in particular, joint analyzes showed that the current geometry is surely due to the different steps of construction that have historically taken place [18] and also to the phenomenon of subsidence in Modena [19] [20] [21], and claimed for the need of monitoring the structure in order to achieve protection and conservation.

2.2 The subsidence in Modena

The phenomenon of subsidence in the plain as well as in the historic center of Modena has had a considerable effect in the past [22] [23]. Several studies suggest a natural subsidence rate of the order of about 2.5 mm /year. These studies are based on topographic leveling campaigns carried out by the Italian Military Geographical Institute (IGM) between 1887-1889 and 1949-1950, a period of time in which it can be supposed that the Modena area has remained alien to subsidence induced by anthropogenic causes. Subsequently, since 1981 the Municipality of Modena promoted a comprehensive study of the induced subsidence, that resulted in the creation of a local dense network of geodetic leveling [24] and in the execution of geotechnical investigations [19] [20] [25] [26], with particular attention to the extent of the piezometric levels of both the surface groundwater and the groundwater related to the deeper aquifers. These studies have shown that the deep aquifer level, which originally exceeded the ground level, is subsiding over time because of the strong water withdrawals, resulting in the late ‘70s to around 10 m below ground level at the most industrialized areas. The increase of subsidence induced by this withdrawal reached peaks ranging

from 60 cm in the historic center of Modena to about 80 cm at the northern part of it (see left Figure2).

In the following years, thanks to the initiatives of the Municipality of Modena to reduce water withdrawals, the piezometric level of the aquifers located between 22 and 34 m as well as the ones between 54 and 63 m depth, that in the years 1975-1976 stood at 10 m from the ground level, rose to 3-4 meters in the late '80s. Today, recent measurements performed in the historic center place again this level to about +0.5 m from the ground level.

The geodetic leveling network, promoted by the Municipality, consists of about 280 benchmarks with the historic center covered by a density double with respect to the rest of the territory; the network is connected to the national infrastructure. A local small densification was established in 1984 and surveyed until 1991 in order to control the deformations in areas of particular interest, such as the monumental center nearby the Tower and the Cathedral. It initially consisted of 29 benchmarks while currently it only involves 24 of them because 5 were lost (see right Figure 2). After a stop of about 15 years, the Municipality of Modena decided to further investigate the evolution of vertical displacements in the historic center due to the relevance of the phenomenon and its implications for the cultural heritage involved; thus, in 2007 high precision leveling campaigns restarted focusing on this local densification and they are still in progress [27] [28] [11].

### 3. METHODS

#### 3.1 Modeling the settlement pattern

In order to analyze the soil-structure interaction, as well as the mutual interaction between the Cathedral and the nearby Tower, 3D Finite Element Model (FEM) has been developed using the commercial code Plaxis 3D<sup>®</sup>. An appropriate dimension of the spatial domain (146 m x 133 m) was defined to avoid boundary effects, and 15-node wedge elements were employed. These elements are generated from the 6-node triangles in horizontal direction and 8-node quadrilaterals in vertical direction. The average size of horizontal elements of mesh is about 13.5 m and it is refined in proximity of the two structures. The depth of the model is established equal to 80 m, in order to be representative of the soil volume that influences the behavior of the structures. This is also the depth of borehole performed to detect the soil profile. To this aim, a rather comprehensive site investigation was planned in September 2007 and December 2008 as described in details by [29] [30] [10]. The soil profile, summarized in the left portion of Figure 3, is quite complex, being a sequence of recently deposited alluvial horizons. The first horizon is made of medium to high-plasticity inorganic clays with a number of millimeter-thick laminae of sand and peat. The upper portion of this horizon, which has a thickness of 5–7 m, is known as the Modena unit and is linked to flooding events (of post-Roman era) produced by minor streams. The subsequent underlying horizons, ranging in depth from 22 to 54 m, represent the result of a complete transgressive-regressive cycle: the fine-grained sediments, belonging to the horizon known as Niviano Unit, were deposited during the penultimate interglacial cycle, and the superimposed coarse-grained materials, belonging to the Vignola Unit, are linked to transport activities of the Secchia River [31]. A second horizon of coarse-grained materials is encountered at depths ranging from 54 to 63 m, and thereafter a fine-grained materials horizon is found down to a depth of 78 m, here again characterized by a diffuse presence of laminae of sand.

To properly capture the change with depth of soil properties, the soil profile was represented as a sequence of 11 layers (right Figure 3).



An elastoplastic hardening soil model was assumed for clay layers, while a simple linear elastic model was employed for sand layers. The soil parameters (referred in Table 1) are defined on the basis of a comprehensive investigation. This includes oedometer, tests to evaluate the stress history, tri-axial and resonant column tests and cross-hole tests which are of particular value to characterize the coarse-grained material [29].

To validate the model, an important aspect was represented by the settlements suffered by the Ghirlandina Tower, inferred through a proper interpretation of borings performed to have a deeper knowledge of what the Tower foundation is like [29]. In 2007 some inclined borings were planned around the Tower which allowed to reach the following conclusions: (a) the brickwork made foundation has a thickness of 3 m and was conceived as a spread foundation without supporting piles; (b) the doorstep of the ancient door is found at depth of 1.48 m from the actual ground level; (c) one of boring allows to intercept the *basolato* of the Roman road (via Emilia) near the edge (at depth of 5.45 m) and just below the foundation (at depth of 6.75 m). By comparing the difference ( $6.75 - 1.48 = 5.27$  m) with that ( $4.90 - 1.36 = 3.54$  m) found during the investigation made in 1898-1901, it can be argued that the Tower settlement was about 1.73 m ( $5.27 - 3.54$ ) at the North side and, by considering the tilt, the average settlement was about 1.85 m. This value represents a lower bound of the settlement experienced by the Tower, because it can be certainly speculated that the depth of the *basolato* near the side of the foundation cannot be considered as representative of a free-field condition. Similar arguments, linked to the depth of the *basolato* when referred to free field conditions, would suggest an upper bound value of the average settlement equal to 2.07 m. The model was defined and validated by reproducing these values.

**3.2 Monitoring of settlement evolution**

The leveling network was 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 [28]. The network was adjusted by constraining all benchmarks to the reference one, numbered as 12, which is conventionally fixed to an elevation of 10 m. This choice, according to adjusted elevations obtained in 1991, does not influence the interpretation of results, 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 [11]. The purpose of this local network, indeed, is to highlight differential effects for the structural safeguard, leaving the investigation of the absolute subsidence effect of the whole town to the regional network. 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 GNSS (Global Navigation Satellite System) static survey thanks to the constraint to the ItaiPoS (ITALian POsitioning Service) national GNSS permanent network [32].

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  $0.1 \div 0.2$  mm (95% level of confidence) for final elevation differences. The adjustment computation was performed by STAR\*NET-PRO Version 6.0.36, Starplus Software Inc . Results of each network adjustment were 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.

## 4. RESULTS

### 4.1 Soil-structure interaction and settlements: FEM analyzes

In order to properly forecast the profile of settlements of the Cathedral and the Tower, and to study the subsidence effects as well, it is of paramount importance to take into account the previously mentioned aspects related to construction of the Cathedral. The process of building and dismantling previous Cathedrals induced on the supporting soil a loading and unloading process (known as over-consolidation process in Soil Mechanics) in the west zone, so that part of the Lanfranco Cathedral was built on less compressible soils, while the apses were built on a virgin, more compressible soil. This explains in particular the rotation of the apses of the Cathedral toward east and not only towards north, as result of the interaction with the Ghirlandina Tower. This stress history is by far the most relevant aspect, therefore the numerical model was able to reproduce the pattern of differential settlements (see Figure 4), even if the applied loads were introduced by only considering the foundations structures, without accounting for the superstructure (i.e. walls and vaults). The foundations depth was assumed to be 3.70 m from ground level for the apsidal zone of the Cathedral and the Tower, and 2.50 m for the nave and the façade. Figure 4 shows the performance of the numerical model in evaluating the settlements of the historical complex on the basis of the construction history only.

The numerical model was also used to analyze the effects of subsidence induced by lowering the main aquifers (confined between 22 and 33 m and from 54 to 60m depth) by 10 m during '70's [24]. Figure 5 shows the results in terms of settlements profile and isochrones of excess pore pressure at different consolidation time. This figure highlights that the main contribution to the induced settlements is due to the shallow clay deposit, especially the first clay layer ranging from ground surface up to 21.4 m. More in details, Figure 6 shows the settlement profiles induced by the subsidence phenomenon on the Cathedral and Tower. In particular, this figure reports results of both the simulations: the first considering the construction history and the second accounting for the local subsidence. The aim is to highlight that the subsidence effects have a major influence especially on the differential settlements of structures. These aspects are more evident in Figure 7, where tilt of Ghirlandina Tower on the plane orthogonal to the nave of Cathedral (plane X-Z) and the parallel one (plane Y-Z) are shown. The three lines corresponds to the slope of Tower for three different value of piezometric lowering: 10, 12 and 15 m.

### 4.2 Trend of settlements

The comparison between elevation data resulting from subsequent leveling campaigns allows to identify the trend of vertical displacements suffered over time by the benchmarks of the network, and then by the structures to which they are rigidly connected, and also to investigate the related differential components and to evaluate their significance. In particular, Figure 8 displays the total vertical displacements measured since 1984 in the historic center of Modena, while Table 2 reports the elevation data detected after each leveling campaign for the main benchmarks installed at the base of the Cathedral, of the Tower and of the nearby buildings of Piazza Grande square. As can be inferred from these data, the apses of the Cathedral and the Tower result to be the portions



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3 characterized by the greater additional subsidence with respect to the one experienced by the whole  
4 city center (mean values are 48 mm for the Tower and 18 mm for the apse of the Cathedral over 32  
5 years) [11].

6  
7 A careful analysis of the trend shown in Figure 8 also highlights that several benchmarks report an  
8 apparent uplift starting from November 2011 and throughout 2012, particularly marked for  
9 benchmark n.3. The apparent anomaly is explained by remembering that the results are not absolute  
10 elevations but they are referred to the reference benchmark n.12 which is conventionally considered  
11 as a stable point, even if it is not. For this purpose, further leveling campaigns were carried out  
12 since 2011 in order to connect the reference benchmark to a remarkable point located at the extreme  
13 boundary of the historic center and making part of the regional network for subsidence control with  
14 the aim to check the motion of the network (top Figure 9). The lower part of Figure 9 shows the  
15 vertical displacement trend of the reference point and some other benchmarks of the network over  
16 the time interval 2011-2013. As already mentioned, it should be noted, indeed, that sometimes the  
17 reference point suffers a displacement higher than other points of the network. Therefore, the  
18 apparent raising of benchmarks noted in Figure 8 is not a real one but corresponds to a settlement  
19 lower of that suffered by the reference benchmark itself. It must also be noticed that, due to the  
20 longer distances involved (up to 1km for each connection) the final accuracy obtained by the  
21 computation is about 0.3 mm (95% level of confidence).  
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28 **5. DISCUSSION**

29 The geotechnical model, developed on the basis of soil profile and geotechnical parameters defined  
30 throughout laboratory and in situ tests, can help to enhance the knowledge of the soil-structure  
31 interaction and to forecast differential settlements and damage scenarios due to subsidence,  
32 provided it can be properly validated by means of measured behavior of the structures.

33 In this respect, a first relevant validation is given by the settlements suffered by Ghirlandina Tower,  
34 as discussed in section 3.1. As a second step, the model was used to provide the settlement pattern  
35 suffered by the Cathedral, by considering previous loading histories and the interaction with the  
36 Tower, as well as the contribution of subsidence. The geodetic approach, providing high precision  
37 leveling dataset, was then used to validate the settlements profile provided by the numerical model.  
38 For this reason, it is of great interest to compare the numerical simulations shown in Figure 4 with  
39 dataset from high precision levelling performed from 1984 to 2016, as shown in Figures 8 and 10,  
40 revealing a rather good agreement, especially in terms of differential settlements.  
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43

44 Therefore, while the high precision levelling allows to monitor constantly and carefully the two  
45 structures, the numerical model can be used to forecast the expected behavior of structures. In this  
46 way, the integration between geodetic and geotechnical approaches reveal to be of great value to  
47 Authorities to perform damage scenarios and to define thresholds values of settlements. A more  
48 insight into the obtained results proves the following relevant aspects: the Tower suffers settlements  
49 larger than Piazza Grande square and the Cathedral as well shows significant differential  
50 settlements between South and North apses (Figure 10). In particular, by considering the time  
51 interval 1985-2016, the average rate of settlement of the Ghirlandina Tower is about 1.50 mm/year,  
52 but in more recent years (interval 2013-2016) a reduced rate of about 1.19 mm/year is being  
53 observed. These values are well below those reached during the interval 1970-1980, when the  
54 subsidence induced by withdrawal reached its peak, and prove the effectiveness of the initiatives of  
55 the Municipality of Modena to reduce water withdrawals, the difference being even more  
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pronounced in terms of rate of tilting of the Tower, as can be appreciated by comparing Figure 11 and Figure 7.

These conclusions prove how important can be to constantly and carefully monitor the two structures in order to train and verify not only our predictive models (numerical or simply conceptual), but also the effectiveness of protective measures. The hydraulic boundary conditions also need to be carefully monitored through piezometric level measurements, because of their negative effect on the stability of both the historical buildings and particularly for the Ghirlandina Tower.

## 6. CONCLUSIONS

Preserving the integrity of cultural heritage requires a multidisciplinary approach as well as to develop the attitude not to rush in deciding the stabilizing measures until the behavior of the monument is properly understood [1].

Therefore, observation of the long-term behavior of monuments, through a careful monitoring is certainly a prerequisite. Long term measurements of settlement and tilting help to capture what can be considered a “physiological behavior” of the structure and to detect possible deviation from this trend, by identifying causes of potential damage of instability mechanisms. In addition, dynamic measurements to identify the actual behavior of the structure and the influence of soil-structure interaction are of great value to forecast its response in presence of seismic events [10].

However, a deep knowledge of the construction history is also essential to develop any reliable model to be used to forecast future trends. In the present case, as a consequence of the sequences of construction and demolition of previous Cathedrals [18], the Lanfranco and Wiligelmo Cathedral, suffered uneven settlements not only moving from south towards north (as expected due to the interaction with the Tower), but also moving from east towards west. In more recent times, the effects of induced subsidence proved to be relevant as far as the pattern of settlements and their rate over time is concerned.

All the previous aspects were detected thanks to a multidisciplinary approach, and in particular the monitoring program proved to be of paramount importance to verify not only our predictive models (numerical or simply conceptual), but also to perform a careful analysis of the crack patterns and geometric anomalies [33] [34], as well as the effectiveness of protective measures.

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Layer	Lithology	Depth [m]	Thickness [m]	$\sigma'_{vo}$ [kPa]	OCR	$C_c$	$C_r$	$E_{oed}$ [MPa]	$\phi'$ [°]	K [m/s]
1	Clay	0.00 ÷ 6.00	6.00	37.50	1.94	0.27	0.08	1.500	32	$3.90 \cdot 10^{-9}$
2	Clay	6.00 ÷ 9.00	3.00	72.10	1.00	0.37	0.08	1.200	32	$5.08 \cdot 10^{-9}$
3	Clay	9.00 ÷ 11.50	2.50	92.83	2.09	0.42	0.08	1.100	32	$5.48 \cdot 10^{-9}$
4	Clay	11.50 ÷ 14.00	2.50	111.68	1.00	0.57	0.08	0.880	32	$7.43 \cdot 10^{-9}$
5	Clay	14.00 ÷ 15.00	1.00	124.88	1.00	0.40	0.08	1.150	32	$5.22 \cdot 10^{-9}$
6	Clay	15.00 ÷ 17.00	2.00	136.19	2.10	0.40	0.08	1.150	32	$5.22 \cdot 10^{-9}$
7	Clay	17.00 ÷ 21.40	4.40	160.31	2.37	0.40	0.08	1.150	32	$5.22 \cdot 10^{-9}$
8	Sand	21.40 ÷ 34.80	13.40	233.85	-	-	-	147.8	32	$1.00 \cdot 10^{-5}$
9	Clay	34.80 ÷ 54.00	19.20	372.40	1.18	0.29	0.02	1.440	32	$4.16 \cdot 10^{-9}$
10	Sand	54.00 ÷ 63.20	9.20	493.10	-	-	-	147.8	32	$1.00 \cdot 10^{-5}$
11	Clay	63.20 ÷ 80.00	16.80	603.60	1.18	0.29	0.02	1.440	32	$4.16 \cdot 10^{-9}$

**Table 1.** Parameters of the numerical model ( $\sigma'_{vo}$ : effective vertical stress; OCR: over consolidation ratio;  $C_c$ : compression index;  $C_r$ : recompression index;  $E_{oed}$ : constrained modulus;  $\phi'$ : angle of shearing resistance; K: hydraulic conductivity).

#	Dec/84 [m]	Dec/85 [m]	Sep/86 [m]	Feb/88 [m]	May/89 [m]	Aug/90 [m]	Dec/91 [m]	Dec/07 [m]	Apr/08 [m]	Nov/08 [m]
3	8.9831	8.9804	8.9797	8.9774	8.9772	8.9754	8.9704	8.9589	8.9578	8.9576
8	9.9413	9.9407	9.9412	9.9402	9.9393	9.9385	9.9369	9.9335	9.9330	9.9329
12	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000
14	9.8168	9.8162	9.8164	9.8145	9.8149	9.8146	9.8108	9.8053	9.8052	9.8050
15	9.8365	9.8356	9.8353	9.8334	9.8335	9.8330	9.8291	9.8215	9.8213	9.8212
16	9.3986	9.3967	-	9.3930	9.3927	9.3917	9.3868	9.3662	9.3644	9.3638
17	9.1508	9.1472	9.1461	9.1437	9.1435	9.1426	9.1376	9.1178	9.1153	9.1143
18	9.4186	9.4149	9.4137	-	9.4115	9.4102	9.4048	9.3839	9.3814	9.3812
C/I	9.3774	9.3740	9.3734	9.3715	9.3711	9.3707	9.3657	9.3464	9.3441	9.3432
19	9.1076	9.1069	9.1060	9.1051	9.1050	9.1054	9.1019	9.0890	9.0882	9.0878
20	9.3230	-	-	-	9.3196	9.3202	9.3162	9.3067	9.3062	-
25	9.9880	9.9872	9.9877	9.9862	9.9866	9.9864	9.9832	9.9792	9.9790	9.9790
26	-	9.9430	9.9431	9.9419	9.9418	9.9417	9.9387	9.9333	9.9329	9.9328
#	Sep/10 [m]	Dec/10 [m]	Apr/11 [m]	Nov/11 [m]	May/12 [m]	Nov/12 [m]	Apr/13 [m]	Nov/13 [m]	May/16 [m]	$\Delta$ '84/'16 [mm]
3	8.9555	8.9548	8.9549	8.9574	8.9578	8.9577	8.9546	8.9537	8.9528	-30.3
8	9.9331	9.9332	9.9329	9.9329	9.9327	9.9326	9.9324	9.9329	9.9327	-8.6
12	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	0.00
14	9.8048	9.8034	9.8040	9.8034	9.8041	9.8036	9.8036	9.8031	9.8027	-14.1
15	9.8200	9.8186	9.8191	9.8186	9.8193	9.8193	9.8188	9.8183	9.8178	-18.7
16	9.3601	9.3586	9.3587	9.3583	9.3586	9.3540	9.3530	9.3522	9.3513	-47.3
17	9.1104	9.1090	9.1088	9.1086	9.1087	9.1062	9.1049	9.1041	9.1027	-48.1
18	9.3774	9.3757	9.3758	9.3754	9.3751	9.3698	9.3689	9.3680	9.3668	-51.8
C/I	9.3391	9.3379	9.3378	9.3378	9.3382	9.3361	9.3349	9.3342	9.3329	-44.5
19	9.0855	-	9.0843	-	-	-	-	-	9.0825	-25.1
20	9.3041	9.3025	9.3028	9.3024	9.3036	9.3037	9.3030	9.3022	9.3016	-21.4
25	9.9782	9.9769	9.9773	9.9768	9.9774	9.9771	9.9767	9.9765	9.9764	-11.6
26	9.9318	9.9304	9.9308	9.9303	9.9307	9.9305	9.9299	9.9296	9.9293	-13.7

**Table 2.** Periodic high precision leveling since 1984: adjusted elevations [m] referred to benchmark 12 (conventionally fixed to 10 m) and total vertical displacements occurred over 32 years [mm].





Figure 1. The Cathedral of Modena and the nearby Civic Tower, Modena (Italy), included within the UNESCO World Heritage List since 1997. Detail of the west façade of the Cathedral (left), the monuments during leveling measurements (middle); location map (right).

270x124mm (96 x 96 DPI)

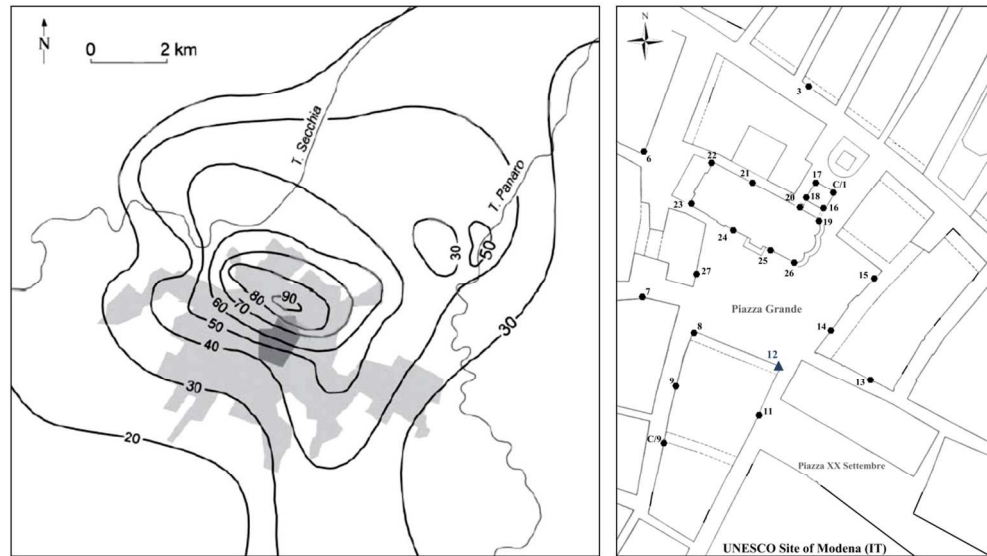


Figure 2. Left: the phenomenon of subsidence in the town of Modena over the period 1950-1980 under the strong anthropogenic exploitation for water pumping; contours are reported in [cm] (courtesy of internal archive of Modena Municipality). Right: the dense local high precision leveling network in the historic center of Modena.

145x83mm (300 x 300 DPI)

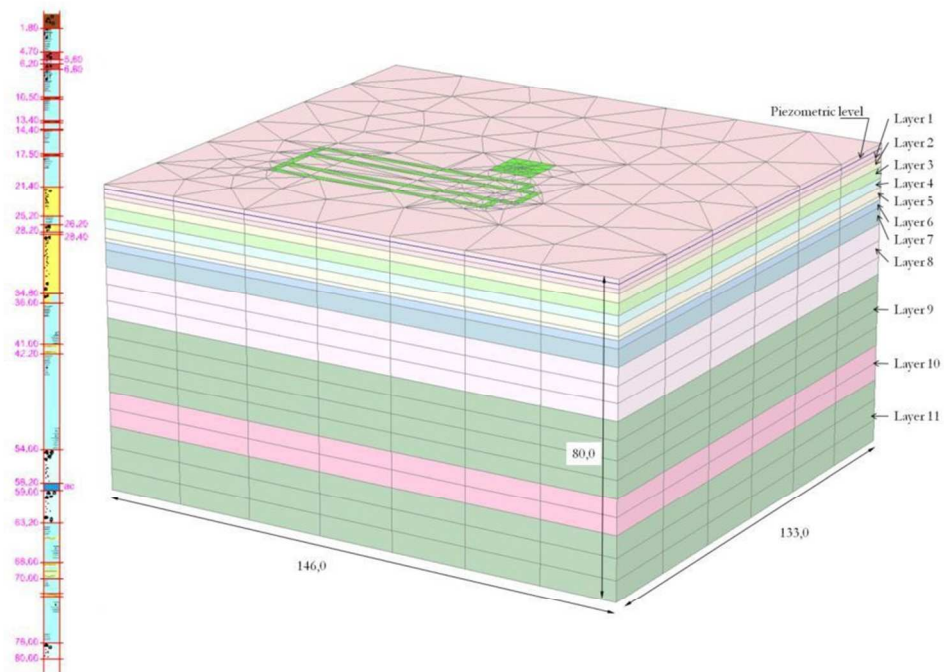


Figure 3. Left: soil profile of Piazza Grande square (after [9]); right: FEM model of the soil and the Cathedral - Ghirlandina Tower. All units in [m].

270x193mm (96 x 96 DPI)

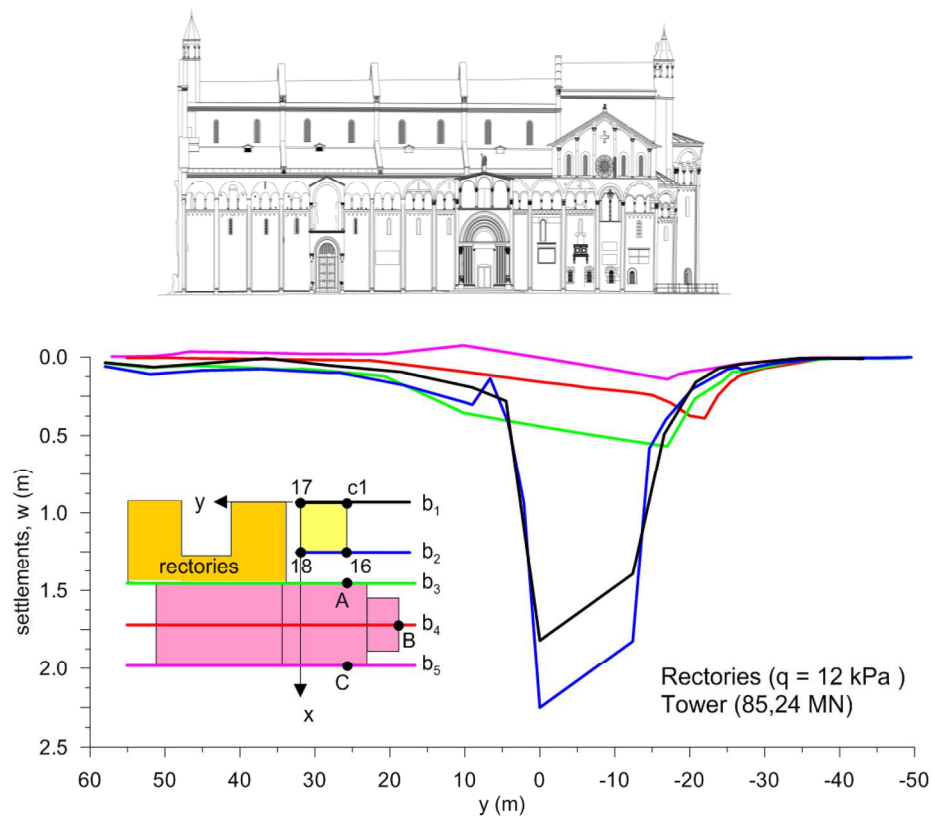


Figure 4. Settlements of the Cathedral and the Ghirlandina Tower simulated with numerical model.

192x166mm (300 x 300 DPI)

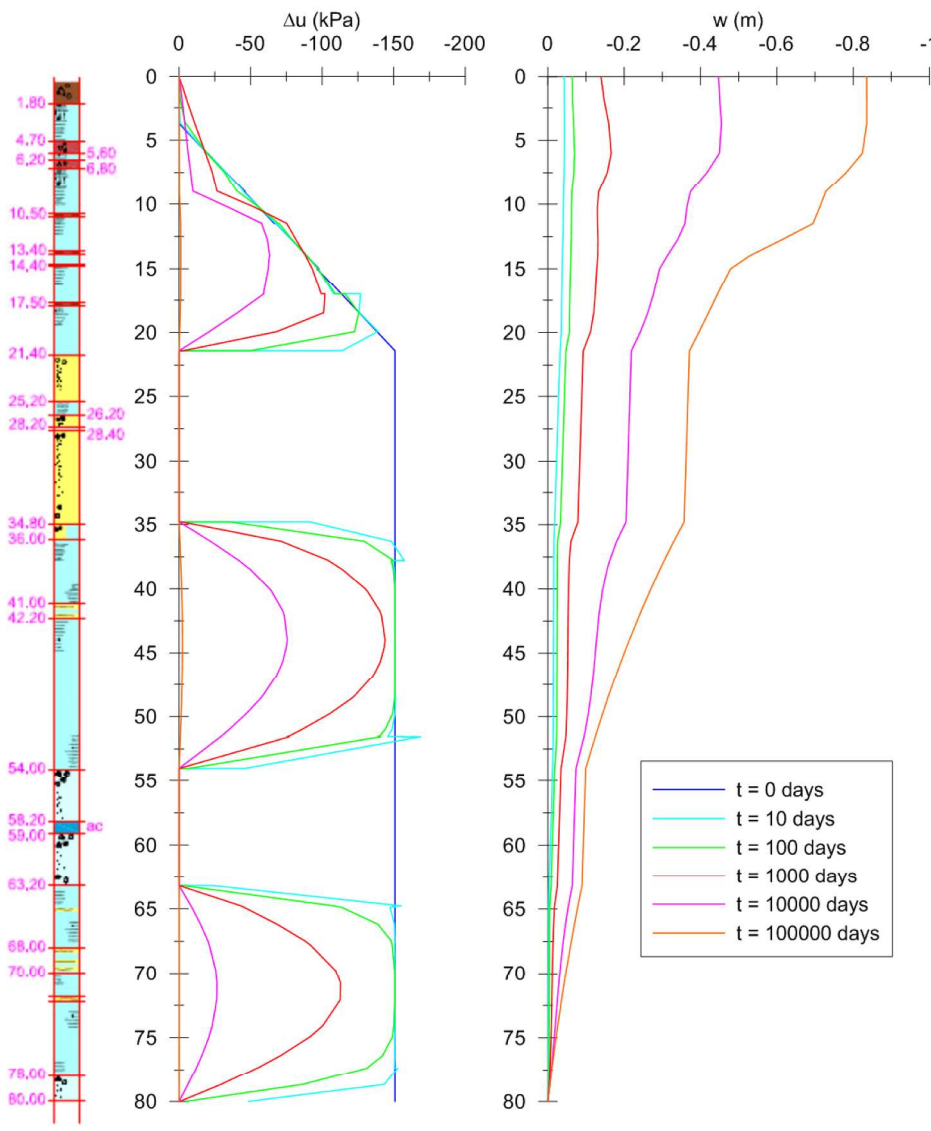


Figure 5. Subsidence induced by a piezometric lowering of 10 m.

263x312mm (300 x 300 DPI)

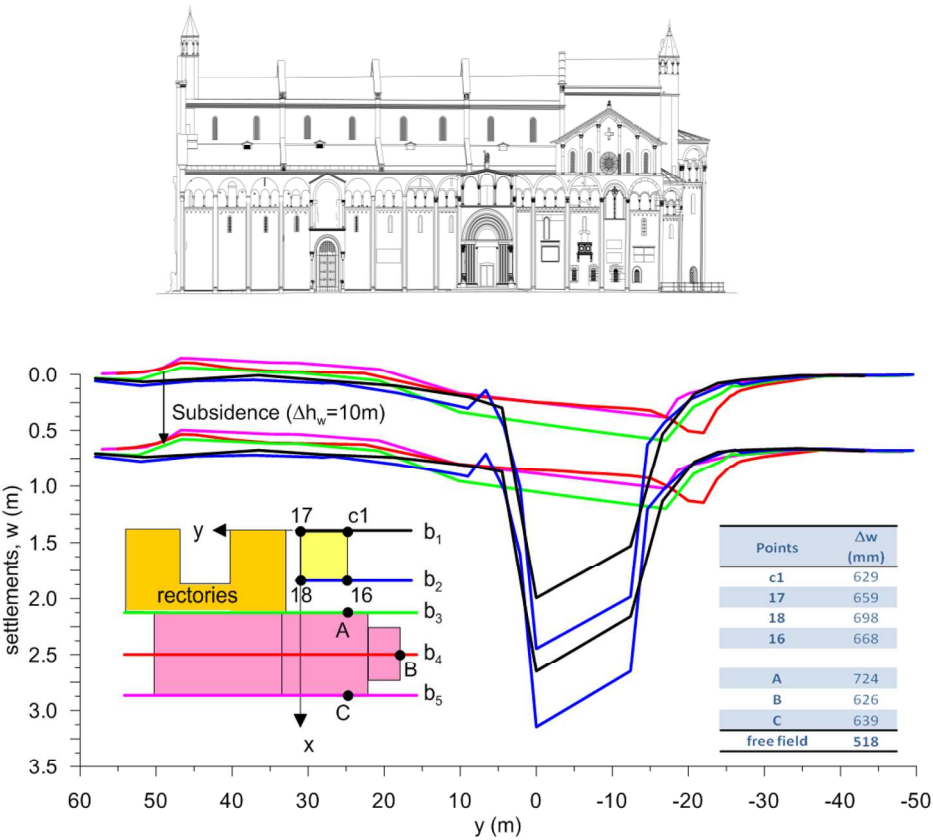


Figure 6. Settlements of the Cathedral and the Ghirlandina Tower induced by the subsidence simulated by numerical model.

189x166mm (300 x 300 DPI)



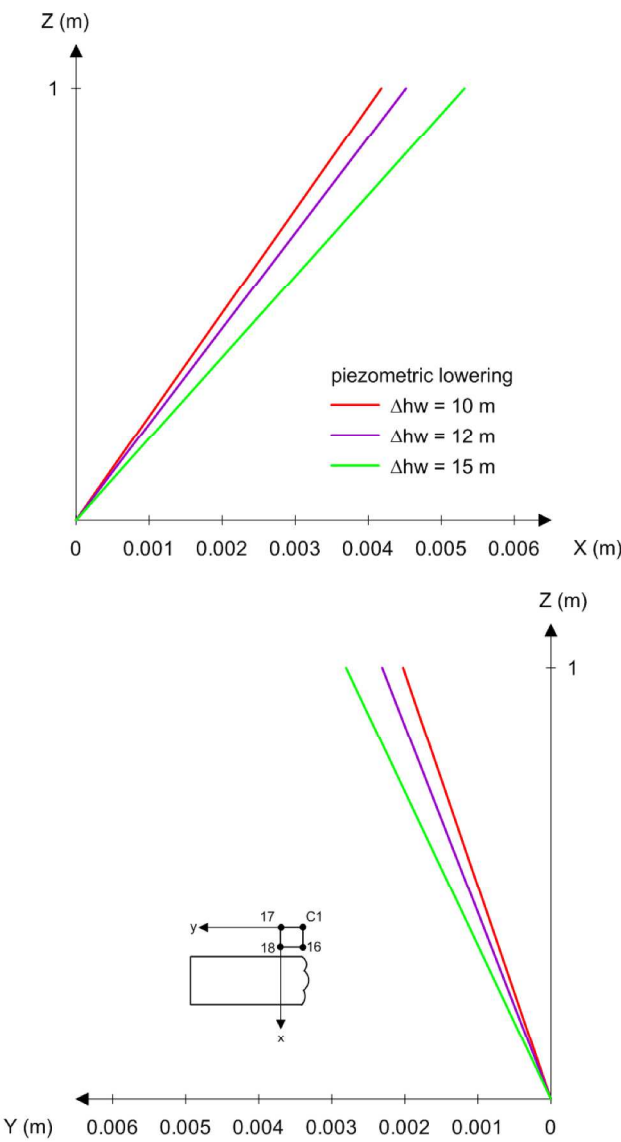


Figure 7. Tilt of the Tower induced by the subsidence obtained by numerical simulation.

233x419mm (300 x 300 DPI)

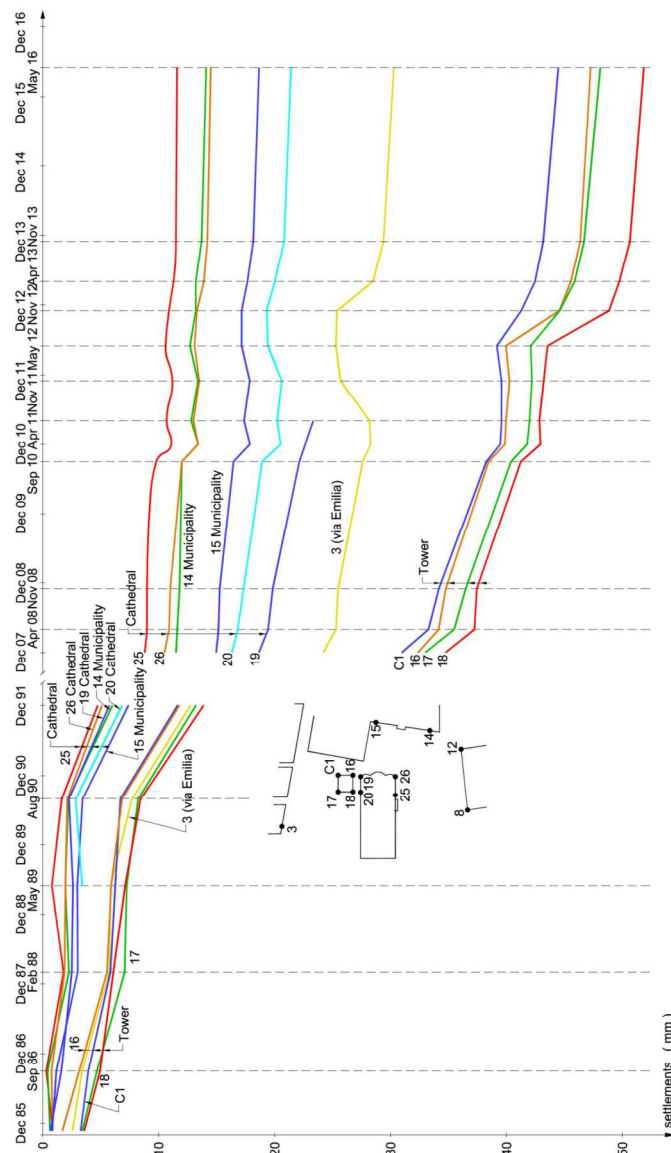


Figure 8. Trend of vertical displacement of the main benchmarks located nearby the Cathedral over the periods 1984-1991 and 1991-2016.

311x483mm (300 x 300 DPI)

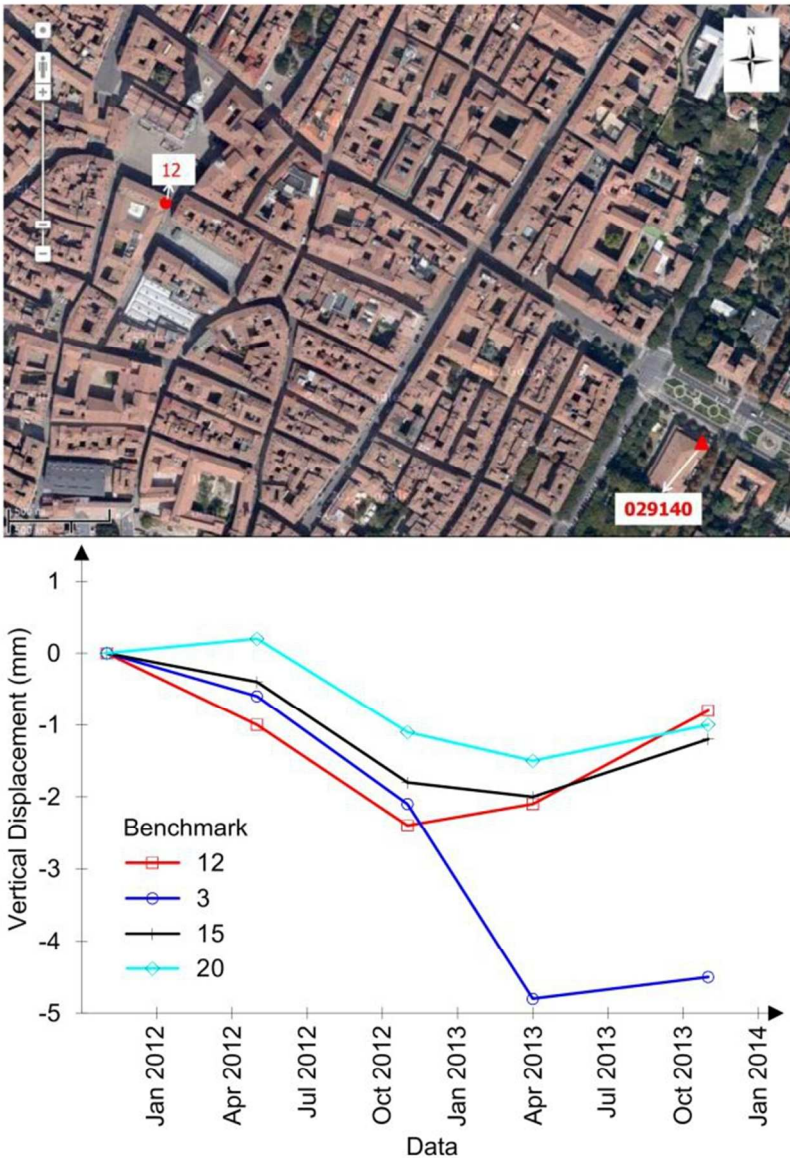


Figure 9. On top, the location of the local reference benchmark #12 and of the regional remarkable benchmark #029140. Bottom, the trend of vertical displacement over the period 2011-2013 for some key benchmarks computed with respect to the reference regional benchmark #029140 installed on the theatre outside the local network. Benchmarks: #12 is the reference point for the local network of Piazza Grande; #3 is the northern benchmark of the local network; #20 is installed on the Cathedral; #15 is installed on the Municipality palace.

190x270mm (96 x 96 DPI)

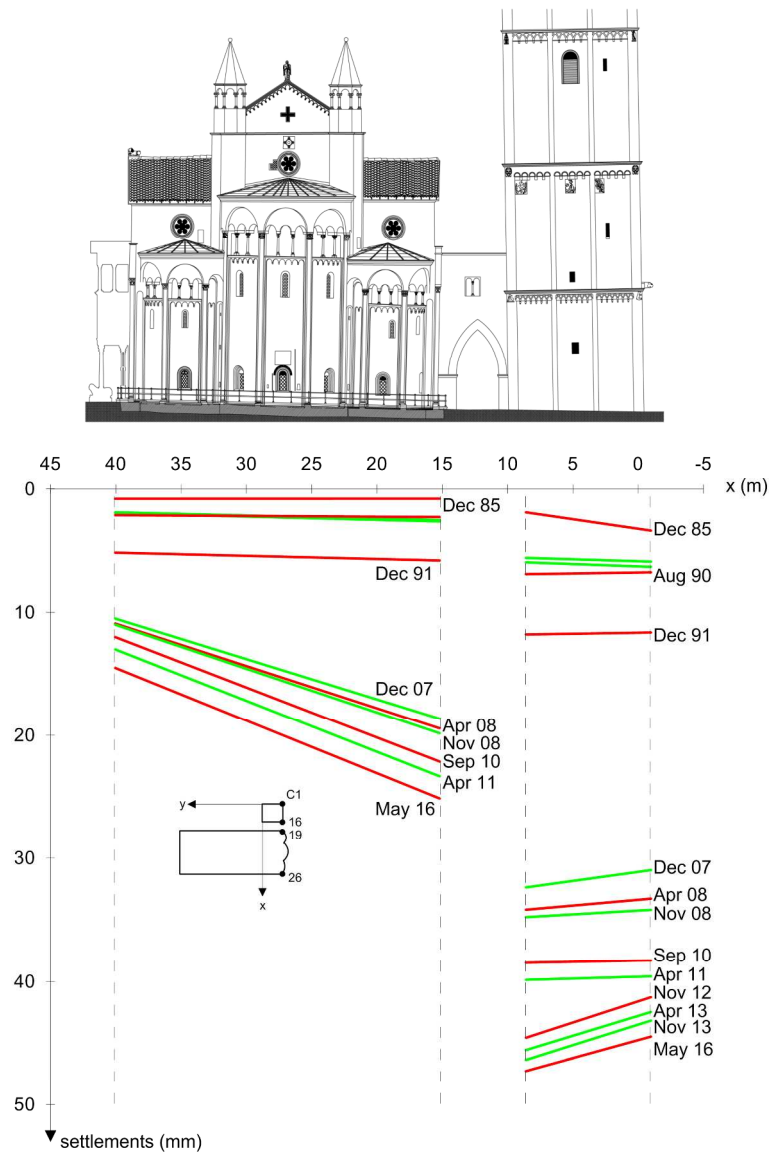


Figure 10. Time evolution of settlements of some points of the Ghirlandina Tower and the Cathedral obtained by high precision leveling over the period 1984-2016 (North - South view).

318x467mm (300 x 300 DPI)

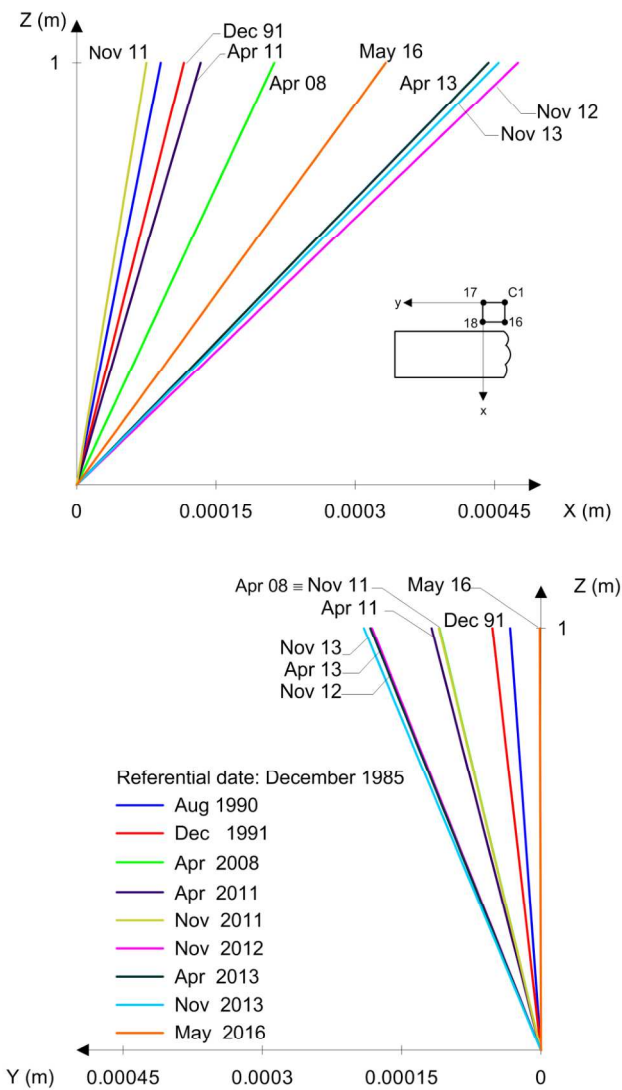


Figure 11. Time evolution of the Tower tilt obtained by high precision leveling over the period 1984-2016.

244x409mm (300 x 300 DPI)