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Abstract

The Garisenda Tower and the Asinelli Tower, also widely known as the Two Towers, are the best preserved and famous medieval towers in the city of Bologna (Northern Italy). Standing one close to the other, right in the heart of the city centre, the Two Towers are delicate remains of the old towered city, which counted more than 75 towers in the 12th century.

The foundations of historic towers and the surrounding soil often hide major hazards for the long-term preservation of these heritage structures. The initial fundamental step is indeed a deep understanding of their original conception, including their foundations and subsoil. However, the idea that also such elements are an integral part of the overall structure, and thus subjected to the same conservation rules, is relatively new. The present paper outlines the investigation criteria applied to the soil-foundation systems of the Two Towers of Bologna and describes the authenticity of their characteristics, through the interpretation of new experimental data and the analysis of historical documents. A geotechnical perspective on this type of monuments turns out to be crucial in order to effectively understand the soil-structure interaction mechanisms, which govern their safety conditions over time. This study also aims to better understand the reasons why the Two Towers of Bologna, despite their numerous similarities, have reached completely different structural configurations.

The methodology described to investigate this case study, which required the integration of several aspects, can be usefully applied to any historic tower.

Keywords: Heritage Structures, Preservation, Foundations, Tower stability, Bologna.

1 Introduction

The contribution of Geotechnical Engineering to the preservation of monuments and historic sites has progressively grown over the last 50 years, together with the scientific advancements of the discipline. Geotechnical engineers investigate, more than any others, the characteristics of foundation soils and the causes of related displacements. Therefore, they are the best suited to understand the complex soil-structure interaction issues.

In 1981, the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) formed a technical committee (currently identified as TC301) to specifically work on the topic of preservation of monuments and historic sites (Bilotta et al., 2013). Since then, the approach to the preservation of heritage structures has changed and, recently, the basic principles for the conservation of the foundations of historic buildings have been included in the international Standard ISO13822-2010: "Assessment of existing structures". Annex I of this document introduces the concept of «Authenticity and Integrity of Foundations of Heritage Structures», in which the foundations and the surrounding soil are formally defined as an integral part of the whole historic building, whose authentic elements have to be preserved as much as the above-ground structure. Any intervention on the historic foundations and the supporting ground should respect the same principles applied to the superstructure. Moreover, minimal strengthening interventions and reversible measures should be favoured, whenever possible. A preliminary diagnosis of the main reasons of possible instabilities must always precede the design of such interventions, as design strategies can rely on analytical and numerical models that aim at evaluating their overall safety in static and seismic conditions (Lancellotta and Sabia; 2015; Pisanò et al., 2014; Marchi et al., 2013). The application of such advanced design approaches requires a preliminary in-depth knowledge of the soil-foundation system, of the local groundwater conditions and of the whole load history of the foundations, from the initial construction stage to their current configuration. In fact, soil behaviour can be strongly influenced by its load history; in addition, it depends on its stress state (especially sensitive to groundwater variations) and on the foundation structural features. Furthermore, the slenderness of towers is clearly source of significant second order problems, i.e. possible instability of equilibrium (Marchi et al., 2011): once a tower abandons its vertical position, its inclination can increase over time, inducing a progressive interaction between the subsoil and the superstructure. Whether its leaning state will continue and possibly accelerate over time or not, is one of the main soil-structure interaction problems (Flora et al., 2017). Therefore, a sound geotechnical analysis should try to interpret past displacements in order to predict their possible evolution.

In such a context, the present paper describes step by step the multiple aspects taken into account for the case study of the Two Towers of Bologna, including all the following main issues, constantly analysed in a geotechnical perspective:

- Historical background, with particular emphasis on: ancient techniques for the construction of foundations, main past events affecting the structure (construction phases, demolitions, structural interventions etc..), reported past inclination and settlement evolution over time;
- identification of the geological and hydraulic settings of the area of interest;
- analysis and interpretation of the geotechnical investigations, for the definition of a reliable model of the soil-foundation system;
- geotechnical monitoring of the ground water conditions (using piezometers) and soil settlements (by means of topographic surveys or the installation of dedicated sensors).

This approach could be, in principle, used as a reference conceptual map (Figure 1) to be followed in the initial phases of investigation of any historic tower, providing all the elements that lead to the identification of the best preservation strategy (Gottardi et al., 2015; Lancelotta, 2013, Gottardi and Marchi, 2019).

2 Historical background

Among the most important historical data that must be carefully taken into account in the study of the soil-foundation system of a historic tower, the most significant are as follows:

- main events in the construction process and structural modifications during their lifespan: these could affect the load history of the soil and thus the soil-structure interaction mechanism;
- configuration changes recorded in the lifespan of the towers (in terms of inclination or settlement evolution over time): useful for the calibration of predictive models and, then, for the design of conservation interventions.
- ancient techniques for the construction of foundations: such information could be used to integrate the lack of data from field investigations on the foundation structures (e.g. installation and length of piles, materials, etc..). In fact, considering the punctual character of geotechnical field investigations, it can be easily deduced that they cannot cover the whole volume of the foundations, mainly hidden below the ground surface, creating possible lacks in data collection. Moreover, the knowledge of construction techniques (including phases) is relevant to model the subsoil behaviour during the tower construction and after its completion, providing knowledge of load succession during the different construction phases of the structures.

These elements can be carefully extrapolated from historic sources, technical reports or other bibliographic sources. The described approach (shown in the central columns of Figure 1, ‘’Historical background’’) was applied to the Asinelli and Garisenda Towers as described in the following Sections.

2.1: Main events and structural modifications during tower lifespan

With their feet firmly resting on the ground and their walls soaring towards the sky, the Two Towers of Bologna (Figure 2A, image A) are stunning remains of the medieval splendour of the town. These monuments, together with the numerous civic towers and tower houses built during the Middle Ages, are an invaluable part of the Italian heritage, peculiar of Northern and Central Italy.

Among the many attributions given to Bologna, the most common is "La Turrita" (the Towered One). In the 12^{th} and 13^{th} centuries the skyline of Bologna was marked by an impressive number of towers (about 75) within its walls (Figure 2A, image B). At present, we can see the remains of twenty-two towers/tower-houses, few still intact - like Asinelli and Garisenda -, whilst most of them were shortened, demolished (Figure 2A, images C and D) or included within the walls of more recent buildings (Fanti, 1989). The Asinelli and Garisenda Towers were named after the aristocratic families that are believed to have been responsible for their construction. Initially, the Two Towers were symbols of social prestige, then they became defensive military bulwarks and subsequently, during the 14^{th} century, Asinelli became a prison for clerics sentenced to death, while Garisenda started to be used for religious functions (Roversi, 1989).

A detailed timeline of the Two Towers, showing their main structural events, is shown in Figure 2B. The current configuration of the Two Towers is quite different from the original one (frame 2, Fig. 2B). At present, the Garisenda Tower is 48.16 m high above ground level, 7.4 m wide at the base, with an inclination of its straight axis of 3.914° toward east and 0.6651° toward south (SOING, 2018).

At the end of its construction, the tower was 60 m high, but in 1353, due to its dangerous leaning, the city government decided to partially demolish the tower, which was cut off to the actual height (frame 4, Fig.2B).

Asinelli is 97.20 m high above ground level and 8.7 m wide at the base (the width of the masonry porch at the base is 14.5 m). Historians claim that originally the tower measured 60 m in height, like Garisenda (frame 2, Fig.2B), but in an unidentified year between the 12th and the 13th centuries the Bologna Municipality raised the tower to its current height (frame 3, Fig. 2B), possibly for defensive reasons and communication functions. This hypothesis is also supported by structural evidence. In fact, from the height of 60 meters upwards, the thickness of the external walls is reduced and the central axis of the tower shows a different inclination compared to the lower part. At present, the average inclination of its axis (i.e. average of the inclinations of the three blocks composing its above-ground structure) is 1.5° westwards (Capra et al., 2011).

The precise period of construction of the towers is not known. Thermal-luminescence tests on masonry bricks (Bergonzoni, 1991) suggest that Garisenda was built only few years before Asinelli, at the end of the 11th century. This is consistent with the better structural characteristics of the Asinelli Tower: larger foundations and thicker masonry walls. These precautions could have been adopted to avoid the differential settlements shown by Garisenda. More recently, radiocarbon dating tests were performed by the authors on some lime mortar samples, one fragment of charcoal and a wooden one, all extracted from the foundation blocks of the towers (see details about the position of the inclined borings on the foundation blocks in Section 5.1). The main goal of these sets of tests was to confirm, using a different experimental technique, the construction time deduced from the thermal-luminescence investigations and, in addition, to acquire more information on the time interval between the construction of Garisenda and that of Asinelli. This time-lapse might indeed have played a significant role in the evolution of the foundation settlements over time. In fact, the longer the time interval between the conclusion of the works on the first tower and the beginning of construction of the second one, the longer the time available for the soil to dissipate pore water pressure developed during the initial construction phases of the first tower. As a consequence, at the beginning of the construction of the second tower, the subsoil could had taken advantage from a greater advancement of the consolidation process. The radiocarbon dating technique is based on the principle that during the construction of the foundation blocks (i.e. hardening of the mortar) the carbon dioxide is absorbed by the mortar from the atmosphere and, then, it is subjected to standard ^{14}C decay. Moreover, the measurement of its presence in the mortar matrix can be correlated to the construction time of the historic tower. Such analyses provided a possible time interval, which turned out to be 1185-1268 AD, for the sample of mortar extracted from the Asinelli foundations, while a charcoal fragment found in the mortar of the Garisenda foundations was dated back to 783-841 AD. Moreover, the wooden fragment in the Asinelli foundations turned out to belong to the time-interval 1029-1155 AD. The older age of the wooden fragment, in comparison to that of the Asinelli mortar, is consistent with the fact that the outcome of the test on the wood depends on the original position of the tested fragment within the trunk: the more external the ring, the older the age. Moreover, it has to be stressed that should the wood sample belong to the external sapwood, radiocarbon dating identifies the time when the tree stopped growing and exchanging carbon with the biosphere (death of the plant), and not the moment when it was included in the foundation block (known as the ‘’old wood problem’’). These aspects could explain the younger age found for the Asinelli mortar with respect to the wooden fragment. For the same reason, the time interval between the construction of Asinelli and Garisenda deduced from these tests is longer than the real one. Although the novel application of the radiocarbon technique to the dating of foundation blocks seems to be promising, it provides results in a range which is quite large if compared to the required precision. Future advancements in the technological development of this technique could provide more accurate results in the upcoming future. It is worth noticing that also termo-luminescence tests on bricks are characterized by a number of uncertainties. In this case, dating refers to brick heating in kilns and not to the time of their use. Moreover, during the tower life span, many structural interventions could have caused the replacement of parts of the bricks in the masonry walls. All things considered, the results of these two different dating techniques are the only available data at the moment.

The masonry structure of Asinelli is divided into three blocks, showing different inclinations of their central axis. This evidence suggests that a small, but still significant, differential settlement developed during the different construction phases of the tower. The risk connected to an inhomogeneous load distribution on the foundation soil was well-known also in the past and the practice of straightening the vertical axis during the construction was a recurrent strategy. Indeed, the same shrewdness was used during the construction of the most emblematic and famous among the leaning towers, the Pisa Tower (Viggiani, 2019; Burland et al., 2009). The first block of Asinelli starts from ground level and arrives at 35 m in height. The second one goes from 35 m to 60 m. They are characterized by an inclination of 1.64° and 1.69°, respectively. The third block, presumably constructed afterwards, as already mentioned in the text, goes from 60 m up to the top of the tower with a current inclination of 1.18° (Capra et al., 2011). The second block of the structure is not perfectly aligned with the block below. In fact, the battlements built in the 15th century (frame 7, Fig. 2B) stick out by 30 cm westwards and by 50 cm eastwards. Although relatively moderate, this asymmetry generated an eccentricity of the vertical load applied in the centre of gravity of the structure, which may have caused the global inclination of the tower westwards. The presence of an initial tilt of the tower, due to construction imperfections, is almost unavoidable from a practical point of view, and it is a peculiarity of many ancient towers. This produces an initial overturning moment (as a consequence of the initial rotation angle of the tower) which may move the tower inexorably from its initial stable equilibrium conditions (Marchi et al., 2011).

On the other hand, it can be observed that the axis of what has survived of the Garisenda Tower is quite surprisingly linear: it is tilted but straight, not made of blocks with a different mutual axis inclination, like the Asinelli Tower, the Pisa Tower and the majority of the historic leaning towers. A possible explanation can be found in the speed of construction. Workers may have built the still existing part of the tower in one single step, in a relatively short time, with partial undrained conditions in the subsoil during the construction of the tower. Such condition, is justified by the presence of fine grained soils, with a coefficient of primary consolidation (c_v) $1.4*10^{-6}$ m^2/s obtained from an average coefficient of compressibility - m_v estimated from oedometer tests performed on undisturbed samples collected in the first 25m of the deposit, and a permeability coefficient 10^{-9} m/s, typical of a silty-clay deposit, together with a minimum construction time which was estimated to be about 3.25 years for a 60 m high medieval tower. is justified assuming. This hypothesis estimations confirm that the most relevant part of the settlement could have showed up only after the completion of the tower. The hypothesis that Garisenda was built in a relatively short time is supported by an evident lack of accuracy in the manufacture of the rubble masonry walls, especially in comparison with the better quality of the Asinelli Tower (Fanti, 1989). Historians claim that Garisenda's differential settlement was of remarkable entity immediately after its construction, to the extent that, at the time, rumours spread that the leaning was part of the design conception of the Tower itself (Bergonzoni, 1989). The first related written source is found in the allegorical poem "Divina Commedia" (Inferno, canto XXXI), composed by Dante

Alighieri between 1304-1321, in which the Garisenda leaning tower was compared to giant Anteo who bent down in order to facilitate the passage of Dante and Virgilio during the descent into the infernal circles.

From a historical point of view, after the demolition of the top part of Garisenda, in 1350, no significant structural interventions were carried out on the Two Towers. The subsequent period is characterized by the construction of a number of minor buildings, adjacent to the tower walls, as shown from the fifth to the ninth frames in Figure 2B. Of particular relevance, there is: the construction of a wooden corridor connecting the Towers (frame 5, Fig.2B), a crenellated crown around the Asinelli walls (frame 6, Fig.2B), a crenellated terrace at the basement of Asinelli (frame 8, Fig.2B) and a chapel at the base of Garisenda (frame 9, Fig.2B).

The Two Towers have been threatened many times during their lives by fires, lightnings, seismic events, wars and last but not least, by the need of renovation at the end of the 19th century and in the early 20th century. In 1980 the selenite basement of the Garisenda Tower was overlaid by a new one, with no care for resemblance with the original. Noticeable was the devastating fire that broke out in 1398 and destroyed all the wooden elements of Asinelli (the internal staircase, the bell chamber, the wooden corridor between the towers). Afterwards, an intense restoration campaign was carried out, during which a masonry shelf was built on top of Asinelli to serve as bracing of the perimeter walls. In addition, a brick vault was constructed at 30 m above ground level. It was used to interrupt the chimney in case of fire in the tower (Giordano, 2000).

Nowadays, the Two Towers of Bologna boast two quite remarkable records in the worldwide population of medieval masonry towers: the Asinelli Tower is the highest original medieval tower existing in Italy. The San Marco Bell Tower in Venice, in fact, was built in 1150 with a height of 98.6 m above ground level, but suddenly collapsed in

1902; it was subsequently reconstructed "as it was, where it was". On the other hand, the Garisenda Tower contends with the Pisa Tower the record of the most leaning medieval tower in Italy. After the stabilization measures carried out from the second half of 1993 to 2002, the Pisa Tower recovered part of its tilt, approximately 1800 arcsec, from its initial 5.5° of inclination, opening the competition between these two old 'madams' (Burland, 2004).

2.2***: Settlements and inclinations***

From the beginning of the 20th century, when scientists started to be interested in the conservation of the Two Towers, some significant investigations on their settlements and on the evolution of their inclination over time were carried out.

All the available direct and indirect measurements of the inclination of both towers have been collected and described in Table 1. Note that, wherever possible, the inclinations of the single blocks of the Asinelli Tower are reported in detail. Data are expressed in terms of average inclination of the axes (α), while available historic measurements of eccentricity (e) are provided in the last column of Table 1 (a sketch with definitions of α and e is shown in Figure 3). In the same figure, data are plotted as a function of time, starting from the construction of the Garisenda Tower, and their reliability is described in the legend. Garisenda's inclination, plotted in Figure 3 for the 1353 record, was deduced using a graphical construction, conceived within this study. The authors observed the holes left in the masonry by the wood logs of the wooden corridor built in 1353 (frame 5, Fig. 2B). Assuming that the corridor had been built horizontally, the current inclination of the holes left in the masonry provide the increase of inclination of the tower developed from 1353 to date. In this way, an inclination of 2.6° in 1353 was deduced. Unfortunately, the same methodology could not be replicated for the Asinelli Tower, since in this case the holes in the masonry walls were covered by the construction of the crenellated crown at the height of 35 m in 1450 (frame 7, Fig. 2B).

Starting from the second half of the 19^{th} century, the settlements and inclination rate have been monitored by means of modern techniques (i.e. precision levelling). Between 1954 and 1977 the rotation of the Asinelli Tower was monitored using a pendulum (Borgia et al.,1978), whose results were consistent with those obtained by the precision levelling started in 1972. Nine benchmarks were installed for the precision levelling of the Asinelli Tower: four were installed in the edges of the foundation and the others in the nearby area. Since then, the precision levelling of the Two Towers has been progressively improved and was extended to Garisenda 18 years later, in 1990 (Giordano, 2000). The benchmark installed in the south-east edge of the Asinelli Tower was chosen as reference (assumed fixed) for the levelling of all the other points composing the closed polygonal grid.

To date, the levelling of the Two Towers and the surrounding square is performed quarterly by means of n. 14 benchmarks, eight of which installed in the foundation edges. The Asinelli Tower counts n. 183 levelling campaigns since November 1972, while the Garisenda Tower counts n. 111 since 1990.

In the time interval 1972-1983 (Borgia et al., 1977, Borgia et al., 1978; Bitelli et al., 2000), data suggest that the north-west edge of the Asinelli Tower was not only the most leaning, but also the one subjected to the highest differential settlement rate, with an average trend of 0.36 mm/year in the interval 1972-1977, and a slight increase in the period 1978-1983 (0.37 mm/year). Using the same data, the average inclination rate of the Asinelli Tower along the north-south direction passed from 0.0011°/year (period 1972-77) to 0.0013°/year (period 1978-83), while no relevant changes were detected along the east-west axis (0.0008°/year). Unfortunately, these data are not available for the Garisenda Tower, which was not monitored until April 1990.

It is worth noticing that, in the late 1970s, the widespread land subsidence phenomenon - of both natural and anthropogenic origin - that affects the Bologna area, underwent a significant acceleration. Since 1947, land subsidence has been monitored in this area using precision levelling (Pieri et al., 1977; Pieri et al., 1984; Pieri et al., 1985; Arca et al., 1985; Folloni et al., 1996; Bondesan et al., 1997 etc..). The analysis of the data collected during the last century suggested that the ground surface settlement (i.e. land subsidence) had a significant increase after the 1960s and reached its maximum in the period 1970-1980 (hatched area in Fig. 3), with an average rate of about 18 mm/year in Ravegnana Square.

Only a limited portion of the settlements registered in this period could be ascribed to the natural subsidence rate, which is about 2.5 mm/year in the quaternary deposit of the Emilia Romagna alluvial plain (Carminati & Di Donato, 1999). The remaining contribution was due to anthropic causes. Water supplied by the alluvial fan of the Reno and Savena Rivers was indeed pumped from deep aquifers (between 200-400 m of depth), with the effect of lowering the water table and thus generating the settlement increase.

On the basis of the water recharge system of the shallow aquifer in the area (see Section 3) and of the local levelling campaign data, it is possible to state that local differential settlements probably affected also the configuration of the Two Towers. In the proximity of Ravegnana Square, significant differential settlements produced severe damage to a number of buildings along Via Zamboni, the main road which originates from the square where the Two Towers are located (Alessi, 1985; Capra et al., 1991).

Unfortunately, no information is reported on the local variation of the shallow groundwater level due to deep withdrawals during the investigated period, which could have provided precious hints on the quantification of the occurred differential settlements. In addition, the subsidence monitoring data have not been directly correlated to the Asinelli Tower, whose benchmarks are only referred to the S-E edge of the Asinelli foundation (see plan in Fig. 3), assumed as the fixed point of the local levelling.

More recently, between 1992-2000, the rate of anthropic subsidence of the area of interest decreased to 17.5/15 mm/year, between 2002-2006 to 12.5/10mm/year, between 2006-2011 to 7.5/5mm/year and again between 2011-2016 to 5/2.5mm/year (ARPA, the Regional Environmental Protection Agency http://servizigis.arpae.it/).

To date, considering the limited size of the structures in the investigated site of the Two Towers and, at the same time, the continuous tendency towards the reduction of the phenomenon, subsidence should not represent a decisive factor for the critical issues of the towers. Nonetheless, the impact of this phenomenon should be constantly kept under control.

The levelling data in the period 1990-2010 suggest that the Asinelli settlement in the north-west edge increased with a rate of 0.22 mm/year, which corresponds to an inclination increase rate along the N-S direction of about 0.0005°/year, and about 0.0007°/year along the E-W direction. At the same time, a slightly lower rate of 0.20 mm/year was reported for Garisenda in the south-east edge (the one subjected to the greater settlements), with an inclination rate of about 0.0005°/year along the N-S direction, and about 0.001°/year along the E-W direction.

Finally, it is interesting to report the settlement increase rate in a more recent period (2011-2019): 0.14 mm/year for Asinelli (inclination increase rate along the N-S direction about 0.0003°/year, along the E-W direction about 0.0006°/year) and 0.16 mm/year for Garisenda (increase in the inclination rate along the N-S direction of about 0.00005°/year, along the E-W direction of about 0.0003°/year). It can be easily observed that, in the reported monitoring period, the Asinelli and Garisenda Towers both showed a constant reduction in the inclination rate from the ’90s in both directions (N-S and E-W).

Regarding the estimation of the total average vertical settlements that the Two Towers have experienced in their lifespan, their evaluation is extremely difficult because no historical records (images, documents by medieval witnesses) are available on their original configuration (i.e position of the tower with respect to the old ground level). The positions of the doors, often significant to this scope, cannot be used as a reference in this case, since the doors of the medieval towers of Bologna were not positioned at ground level for security reasons. The original door of Garisenda was located at a height of 7.6 m, and was used by an external wooden staircase. An effort was made to identify a unique metric with which the entire tower was designed, and then to find in an indirect way the probable distance of the elevated door from the old ground level. Unfortunately, the tower was dimensioned using partly the Roman foot and partly the foot of the town of Bologna. Another element, relevant for the evaluation of the stability of a shallow foundation, is the depth of the founding level at the time of construction and of the subsequent deposited filling soil, which provides important information on the lateral confinement to which the foundation has been subjected in its history. The old ground level was identified during the excavation of the surrounding area by the discovery of the old Roman street at a depth less than 2 m from the current ground level, which attests a reduced deposition of anthropic material since the roman domination, and thus a negligible influence on the lateral confinement of both foundations. An approximated estimation of the foundations settlement is provided in the final section of the paper, by means of the data collected in the most recent geotechnical investigation carried out in 2016, and described in Section 5.2.

The collected data are crucial for the back-analysis of the conditions of the tower and thus for the development of reliable predictive models of the future displacement evolution of the Two Towers.

2.3 Construction method of a medieval tower in Bologna

Medieval towers in Bologna show recurrent structural and foundation forms. The section of a medieval tower was traditionally squared, and its sides were commonly aligned with the roman roads (“cardo” and “decumano”). The external perimeter of the tower base was traced using an ancient Egyptian method: three ropes of different lengths (3, 4, 5 meters) that formed a perfect right-angle triangle. The architects used the two legs of the triangle to draw a perfect square on the ground (Fig. 4, image A), then the excavation could start. Depending on the depth and on the local properties of the shallowest soil layers, the excavation sides could be vertical, free or supported by wooden boards (Fig. 4, image B), or inclined (about 17° from the vertical axes, Bergonzoni, 1989). The bottom of the hole was kept dry during the operations.

Then the construction of the foundations started. It is interesting to notice that the fabric of historic foundations remained substantially unchanged until the beginning of the last century. The reason is that geometry and materials used for the construction of historical building foundations were the result of the raw materials available in the area of construction, environmental conditions and of the type of subsoil on which the construction was carried out.

The main body of the historic tower foundations of Bologna was made of a concrete block, cast in place, directly laying on the virgin soil or on wooden piles.

This second type of foundation, occasionally adopted also for towers, was characterized by the additional initial installation of short wooden piles by means of hammers. The purpose of the piles was to compact the soil and create a solid base for the concrete block.

The length of the compaction piles rarely exceeded 3 m and the diameter varied from 15 cm to 25 cm. The most used wood essences were alder and oak. The heads of the piles came up over the ground level and were thus included into the cast (figure 4 image C).
Figure 4, images D and E, shows the subsequent execution of two concrete castings (made of sand, gravel, fragments of bricks and slaked lime). The wooden boards all around the excavation area were removed after the casting.
Once the foundations were completed, the tower basement was created (Fig. 4 image F). It was made with squared selenite blocks all around the external perimeter of the tower. Subsequently, as shown by image G in Figure 4, the filling of the internal part of the tower basement, up to the final ground floor, was executed. Afterwards, the construction of the masonry walls was started. The latter were made up of two external walls and an inner filling of concrete and miscellaneous materials (rubble masonry walls), as sketched in Fig. 4 image H (Bergonzoni, 1989).
In Table 2, an estimation of the construction time schedule of a medieval tower of 60 m is provided, as deduced by Bergonzoni (1989), who made a reliable hypothesis on the production systems of raw materials, transports, available equipment, and execution techniques typical of the Middle Ages.
The proposed schedule represents the minimum time necessary to build the whole tower, but it could be extended up to 10 years, while the average time was estimated to be about 5 years. One of the last towers built in Bologna is the Bentivoglio Tower (in Zamboni street). Its construction was started in 1489 and was finished 5 years later (Gozzadini, 1875). It was probably almost 100 m high.
The successful use of direct foundations on fine-grained soils, which characterize the investigated area, was mainly due to the slow building process, thus allowing the development of the soil consolidation process and the adjustment of significant

settlements. At present, the only recorded case of a tower with piled foundations in Bologna is the one reported by Finelli (1976): the Ghisilieri Tower, built around 1150, was demolished during the last century and, at the base of its foundations, wooden piles were found. According to Finelli (1976), the installation of wooden piles, which were easily available in the city due to their transportation along local canals, could be ascribed in such specific case to the proximity of the tower to the western course of the Aposa river, which was possibly considered a major hazard for the stability of the tower. Given the proximity of the Two Towers to the natural eastern course of the Aposa River (see the following section), the presence of wooden piles is possible, but, as reported later in the text, it has not been clearly confirmed to date.

3: Hydrogeological setting

The identification of the geological and hydraulic settings of the site where the monument is located (first and last columns of Figure 1) provides precious pieces of information for the geotechnical characterization of the site and for the interpretation of possible local soil properties (such as discontinuities in strata architecture, heterogeneity of mechanical properties, etc..) or areal phenomena (as subsidence). Moreover, it is well known that hydraulic conditions (e. g. fluctuation of water table) have a crucial effect on the stress state modification in soil and then on the evolution of settlement foundations.

It is also worth observing that, although the wide range of possible geological settings (alluvial plains, mountains, hills with different types of soil deposits) do not enable the extrapolation of general rules for the geologic setting, the alluvial environment context described in the present paper for Bologna’s city centre is the typical geologic setting of many large urban centres. Thereby, it is relevant to many historic monuments.

Bologna’s historic centre is located in the high Po Plain, in the northern foothills of the Apennines. Its geographical position, slightly elevated, corresponds to the core of the interfluve of the Savena and Reno Rivers. Nonetheless, recent geological studies (Amorosi et al., 2014b) demonstrated that the major river beds of Reno and Savena never reached this area, as attested by the lack in the subsurface of the town of thick fluvial-channel bodies. As a consequence, the geological architecture of the shallowest deposits within the mediaeval walls of the town results from the depositional processes of a network of small creeks and canals (Meloncello, Ravone, Aposa and Fossa Cavallina, in Fig. 5), rather than that of the major Reno and Savena Rivers. The sedimentation processes in these coalescing alluvial fans are characterized by low and very low hydraulic energy and the resulting subsoil is mainly composed of fine grained soil (clay and silt mixtures), whereas sandy lenses are rare and the gravels roof deep (about 110 m above ground level). In addition, the local geological history, characterized by paleoclimate changes, is recorded in the alluvial deposits in the alternation of paleosols and non-pedogenized silty clay deposits (Bruno et al., 2013; Amorosi et al., 2014b). Paleosols are ancient exposed soil layers formed from the interaction with the lithosphere, biosphere and atmosphere, which were buried and incorporated into the geological record. Due to the pedogenization processes undergone, they potentially record a number of physical, biological, chemical and climatic information on the past conditions near the Earth surface. More information on the encountered paleosols can be found in Section 5.2.

The hydrogeological setting of the area of interest shows the succession of three aquifer groups named A, B, C (Superficial, Intermediate, Deep respectively). Each aquifer group is composed of a succession of permeable (aquifers, made of a sandy-gravelly material) and permeable or semi-impermeable strata (aquitards, composed of fine-grained material). The aquifer group A, from the ground level up to a depth of 300 m, is recharged almost entirely by the Reno and Savena fans, and it is the most exploited aquifer for industrial and civil uses (Elmi et al., 1984).

The phreatic surface is part of the aquifer of group A1 (the shallowest aquifer of group A) and it is recharged only by small creeks, canals (Meloncello, Ravone, Aposa and Fossa Cavallina) and rainfalls. Its depth has been recently monitored by local piezometers, which provided a depth of the water table of about 5.6 m (see Section 4.2). This phreatic surface is located in the shallowest layer (known as anthropic fill), a sandy and gravelly soil matrix, which acts as an aquifer and is rich in Roman Middle Age historical remains. Its depth variation is mainly due to seasonal fluctuations, thus of limited extent, as probably occurred in the past. The same trend was recently confirmed by piezometers. Additional information about this aquifer and its seasonal fluctuations in the area of interest are reported in Section 4.2, as a result of the analysis of the data collected through the piezometric monitoring system installed in the area.

The minor fluvial network of Bologna's city centre, shown in Figure 5, still exists, and its actual configuration is the result of human interventions aimed at reducing flood damage and the exploitation of the water resource. The Savena Canal, for example, has its source in the Savena River, it was built around 1100, after the construction of the San Ruffillo Canal Lock (Fig. 5A and B). The Savena Canal enters Bologna's historic centre, where it branches into 4 smaller canals. One of the latter arrives in Ravegnana Square, very close to the Two Towers, where it branches into two little canals, one towards Via San Vitale and the other between Via Zamboni and Via San Vitale. The dimension of the canal section near Ravegnana Square is 70 x 70 cm. It flows at a depth of 150-180 cm below ground level and the bottom of the canal is not paved.

Due to natural factors and related exploitation, the water did not flow continuously inside the canal, thus producing alternatively dry soil and wet soil conditions (Giordano, 2000).

In the 1700s the canal was turned into a sewer and used to disperse organic materials into the ground. It worked until 1970.

The area of the Two Towers is also touched by the flow of Aposa, the only natural creek that crosses Bologna. This creek splits up into two stretches entering the town, the Western Aposa (also known as Avesella) and the Eastern Aposa. The latter flows close to Ravegnana Square, where the ancient roman street (Via Emilia) overcame the creek with a bridge, no longer visible from the outside but still visible from the underground covered creek. This riverbed is the original one, no changes in its course were carried out in the past. However, the original floodplain probably extended up to the Two Towers, then, after Bologna was built, it was limited in width (Curina, 2010).

It is worth noting that in 2011, an old well, dated back to the medieval period, was discovered in Ravegnana square, in the open area between the Two Towers (Fig. 5B). Its depth is 8.90 m below ground level (Ispra, 2011). The well is still visible but abandoned as of an unknown lapse of time. In the past, water extraction from the well and the reported variations of discharge in the nearby canals could have caused cyclic, although limited, variations of the water table in the subsoil surrounding the foundations of the Two Towers, with consequent limited settlements of the foundations. It is important to remember that the subsoil of the investigated area is a fine-grained material, with a coefficient of permeability of $10^{-8}/10^{-9}$ m/s, which therefore allows a very slow recharge of the civil wells, thus considerably limiting the water extraction from the shallow deposit. Another hypothesis is that, in the past, the well was hydraulically connected to the water that flowed in the nearby channels (Aposa or other channels connected to the Savena Canal). For the same reason, a very slow permeation of the water through the non-paved canal was possible.

4: Geotechnical Investigations

In order to create a reliable model of the soil-foundation system, specific geotechnical investigations must be carried out. As shown in Figure 1, field investigations are a powerful tool to obtain local information on soil properties and on the foundation architecture, with the support of data on the hydro-geological setting and the historical background, previously collected.

Investigations are often carried out at different stages of historic monuments' life. Therefore, firstly, results of past investigations must be collected and analysed. Secondly, new investigations can be planned and carried out. Eventually, monitoring devices can be installed for the control of water table fluctuations and foundation settlements. The following paragraphs describe the investigations carried out on the soils and foundations of the Two Towers.

4.1: Before 2016

The geotechnical investigations on the subsoil and foundations of the Towers were carried out in separate stages: 1973-75, 1995 and 2000 (maps in Fig. 6).

Between 1973-1975, the first investigation focused on the geometry of Asinelli's foundations and on the definition of the soil profile near the Two Towers.

The second geotechnical campaign (1995) enabled to identify, for the first time, a geotechnical soil profile at a depth of 45 meters.

In 1999, GPR (Ground Penetrating Radar) investigations were performed to acquire information on the superstructure of the Garisenda Tower (the east and south sides were completely inspected, the north and west sides up to 10 m) and on the foundations.

The third geotechnical campaign (2000) investigated Garisenda's foundations by means of four continuous corings (three of them vertical and one inclined by 10°). In addition, petrographic and mechanical tests were carried out on the extracted cores and an endoscopic investigation was carried out in three boreholes.

4.2: The 2016 geotechnical investigations and monitoring

More recently, between May and August 2016, a new geotechnical investigation was carried out with the aim to fulfil the lacunas of the previous investigations. The new investigations are listed in the legend of the map in Figure 6. In addition, 26 undisturbed soil samples were extracted during borings for the subsequent execution of laboratory tests, which enabled the geotechnical model (stratigraphy, mechanical properties of the subsoil, etc..) to be defined in some detail.

Four piezometers were installed at the depth of -10, -20, -30 and -100 m below ground level, in order to monitor the water table. Therefore, a pore pressure profile (i.e. water pressure) was deduced from the collected data. The shallow phreatic level is about 5.5 ÷ 5.6 m deep and it keeps hydrostatic up to 30 m of depth. From 30 to 45 m the hydraulic gradient is 0.0713, from 45 to 100 m it is 0.253, showing a limited downward seepage that at present should not affect the settlement of the foundations. Water pressure measurements with piezometers are still on-going. In the period August 2016-January 2021 the seasonal variation of the ground water height was modest: about 0.85 m, 0.97 m, 1.07 m for the piezometers at a depth of -30 m; -20 m, -10 m respectively.

5: The soil-foundation system of the Two Towers

The information acquired from historical documents, the hydrogeological setting and previous investigations were integrated with the data coming from the 2016 geotechnical campaign. The comprehensive collection of data enables the detailed definition of the foundation structures of the Two Towers and the subsoil conditions.

5.1: Foundation block architecture

Figures 8 and 9 show the detailed cross sections of the foundations of the Two Towers.

The geometrical structure of the Asinelli foundations was reconstructed using the borings carried out in 1973-75, initially interpreted by Bergonzoni (1977), and recently integrated with the 2016 inclined boreholes (Fig. 7 and Fig. 8). The existence of compaction piles at the base of the foundation block was conjectured many times in the past, as well as recently on the basis of geophysical investigations carried out in 2000. In addition, the Asinelli Tower has similarities with the Ghisilieri Tower (described in Section 2.3), in which piles were found: similar dimensions, erected in the same period and both close to the Aposa canal (East Aposa, see Section 3). Nevertheless, the existence of piles for the Asinelli Tower has never been actually proved. In fact, in the most recent direct investigations (boreholes INCL 1 and INCL2 in Fig. 6) traces of piles were not found. Considering the geometry of the foundations and the depth and inclination of the boreholes, even in the event that piles had been installed, they could not have had a spacing less than about 90 cm (for a total maximum amount of 144 piles).

It is worth noticing that a wooden fragment was extracted in the INCL2 boring (2016 investigations), at a distance of 78 cm above the bottom base of the foundations (see photographic detail A, in Fig. 7 and Fig. 8). Such fragment is about 2 cm large and 6 cm long. The study of its geometry and position in the extracted sample suggests that it cannot be part of the head of a pile. Its presence in the casting is not peculiar: in fact, huge quantities of wood were casted in Middle Age construction sites and used for multiple purposes (e.g. as formwork for castings, footbridges, for the transport of bricks and selenite blocks). Moreover, many other different materials have been found in the cast such as fragments of bricks, pieces of coal, shells etc.

The foundation block is a concrete massive structure with a squared base, 10.45 m wide and 4.70 m high. The outer walls are vertical and the founding level is 6.5 m below ground level. The concrete block is not homogeneous but divided into two parts. The lower layer (2.90 m thick) is very compact, with rare voids. On the contrary, the upper layer (1.80 m thick) can be easily scratched and is very powdery when touched. Not only the mortar is different, but also the inert materials used: in the first layer, limestone breccias and calcarenite were found; whereas, in the second layer, calcarenite and grey wackestone were found (Bergonzoni, 1989). The interface between the two concrete layers is irregular.

In 1488 the original nucleus of the Tower was enlarged to enclose a number of shops under a brickwork porch all around its basement. The enlargement of the foundations was discovered in the initial part of the continuous coring INCL2 (2016) (green frame in Fig. 7 and photographic detail in Fig. 8). Its global extension is not precisely known. Probably it is not continuous all around the base of the tower since it was not found along the east side in the continuous coring n° 5, 6, 7 and 10 of the 1973-75 campaign.

The geometry of the enlargement of the selenite basement, which rests on the top of the concrete block, is shown in the scheme on the bottom of Figure 8. This was deduced from a photo of the excavation executed in the 1953, during the demolition of the shops located in the ‘’Rocchetta’’ at the base of the tower, from two drawings of the same year found in the Technical Office of the Municipality (Bergonzoni, 1977) and from a new drawing, found in the Bologna Cultural Heritage Superintendency archive and carried out during the restoration of selenite blocks of the basement, in the 1970s.

The external walls of the basement are made of selenite blocks (38x38x76 cm), while the internal part is filled with polygenic materials and slaked lime (Andreon et al., 2011). Above the basement, the rubble masonry walls start. As described in Section 3, they are divided into three blocks with different thicknesses and heights (Rivani, 1966; Andreon et al., 2011; Palermo et al., 2015).

The structure of the foundations of the Garisenda Tower, shown in Figure 9, is similar to the one of the Asinelli Tower. The geometry of the foundation block was drawn up using the information acquired from the continuous borings performed in 2000 and 2016 and the results of the GPR investigation carried out in 1999 (Fig. 6, 7 and 9).

The foundation block is a massive concrete parallelepiped with a squared base, 8.75 m wide, and 3.30 m high. The outer walls are vertical and the founding level is 5.6 m below ground level. The foundations were casted in place using pebbles, sandstone, siltstone, and gray limestone breccias in a matrix of slaked lime. Continuous borings (S1, S2, S3 in Fig. 6), carried out on the soil around the base of Garisenda during the 2000 investigations, provided significant information on the area surrounding the tower. In particular, the S1 coring, on the south side of the Tower, just outside the foundations, showed, at the depth of 3 m from ground level, a concrete slab 50 cm thick, made of materials and texture very similar to those of the foundation block. This particular structural element was not found in any other investigated side of the tower (i.e. east and west sides; the north side was not investigated). Below the concrete slab, a layer of polygenic gravel, 30 cm thick, was found. The function and origin of this isolated structural element is still uncertain. It could have been part of the foundations of another building, older or more recent than the tower. Whereas, all things considered, it is less likely that it was an enlargement of Garisenda's foundations. It must indeed be considered that the square where the Two Towers were built was of great importance for the Middle Age Community of Bologna, even before the towers were built: an Early Christian church stood on the east-side of the square (today known as the Church of San Bartolomeo and Gaetano) and a big gate in the old selenite walls surrounding the city stood few meters from it. The square was crossed by the important Roman street (decumano massimo) around which the city had developed. Therefore, the presence of public buildings in the construction area of the Two Towers is very probable and this could explain the presence of the old foundations of the same fabric and materials of the foundations of the tower. Unfortunately, no historical documents report such structures in the area before 1100. It is worth noting that if, on the one hand, the presence of a pre-existing building on the tower subsoil creates a pre-consolidation state of the virgin soil (reducing future settlements), on the other it could produce differential settlements if the tower is built partly on the previous building shape and partly not. The position in which this old concrete layer was found is very close to the edge of major tilt of the Garisenda Tower (south-east edge) which, in light of the above, may suggest a different consolidation state of the subsoil of the Garisenda Tower at the time of its construction.

Between the main masonry walls and the concrete foundation block, a basement of selenite blocks is interposed. These blocks are locally intercalated with thin brick rows, as deduced from the inclined S4 boring.

The area included within the selenite basement and the top of the foundation block is filled first with miscellaneous filling material (90 cm of thickness), then by a concrete cast. From the top of the selenite basement the main rubble masonry walls of the tower start. Their geometry and mechanical properties are described in detail in Rivani (1966), Ceccoli (2001), Andreon et al. (2011), Palermo et al. (2015).

The novel and accurate reconstructions of the submerged parts of the towers enable to update the estimation of their weights and the positions of the centres of mass (h_G, measured from ground level) as reported in Table 3.

The geometrical characteristics of the superstructures of the Asinelli Tower and the specific weights of the materials, assumed in the calculation, were deduced from Palermo et al. (2015). The geometrical dimensions of the Garisenda Tower were obtained from a detailed survey carried out by the Bologna Municipality on the above-ground structure.

5.2: Geotechnical soil-profile and settlement estimation

The soil profile and the mechanical properties of the deposits were deduced from the investigations (laboratory and in-situ tests) described in Section 4. As shown by the stratigraphic column in Figure 10, the soil profile consists of an alternation of silty-clays and clayey-silts, down to the investigated depth of 100 m.

The soil samples extracted during borings and the geotechnical interpretation of the CPTU profiles (see the map of the investigation in Fig. 6), based on the Robertson (2009) approach, suggest that the deposits can be divided into:

- anthropic fill, between ground level and 4.5÷5 m of depth (anthropogenic deposits);
- a variable succession of lenses of silty clays and clayey silts to the maximum instigated depth (floodplain deposits).

The main physical and mechanical properties identified through laboratory and in situ tests are briefly summarized in Figure 10. This figure shows that, despite the macroscopic lithological uniformity of the deposits (see grain size distributions and Atterberg limits), their mechanical properties are heterogeneous both laterally and vertically. In particular, the CPTU analysis shows a subsoil discontinuity passing through the midpoint of the south side of Garisenda: CPTU 5 (2016), DMT1 (2016), DMT2 (2016), CPTU13 (1995), CPTU 12 (1995) have a data offset of ~1.30 m from the other cone penetration tests in Ravegnana Square. Moreover, it is worth noting that CPTU 5 (2016) and CPTU 13 (1995) near the north-east side of the Garisenda Tower (Fig. 6) show a significant difference of the mechanical properties of the soil between 8 m and 10 m of depth (see the comparison between the s_u and q_t in Fig. 10). Such a reduction is about 50% of the average tip resistance (q_t) of the surrounding soil. On the contrary, in the west side of the Asinelli Tower at the same depth, a layer with better mechanical properties than the surrounding soil was found in CPTU 4 (2016), which produces a different mechanical behaviour of the subsoil, between the north-east and south-west edge of the Garisenda Tower.

The geological setting with the identification of the sedimentary facies of the area (Section 3) provides a significant interpretative key of these soil conditions. In fact, alluvial deposits have typical lenticular geometries and poor lateral extent. This justifies the lack of uniformity found in a small area of the size of the Garisenda base. In addition, the floodplain successions are locally interrupted by paleosols (i.e. paedogenized horizons (horizons A, B_k, B_w). A sedimentological identification of paleosols in this site was carried out from borehole corings extracted during the 2016 geotechnical campaign (Bruno et al., 2020). These geologic markers are characterized by a characteristic dark colour in the A horizon, followed by lighter horizons with carbonate nodules (detail on the right of Fig. 10), the horizons B_k. The exposure to air (drying process) of horizon A, causes a volume reduction that generates micro-fractures (that became preferential channels to carbonate leaching) and the voids reduction goes with a decrease in local permeability. The mechanical behaviour of paleosols shows an increase in resistance (due to the over-consolidation state), which generates a variation of the mechanical properties depending on their maturity level.

Paleosols are an exception from a geometrical point of view, as they typically have a tabular shape and a great lateral extent. Nevertheless, the physical properties of paleosols (thickness, maturity, consistency) exhibit great lateral variability. They were created during a long period of interruption of the alluvial sedimentation process and the consequent exposure of the ground surface to sub-aerial conditions, with vegetation growth and then subsequent enrichment in organic matter (Bruno et al., 2013; Amorosi et al., 1999; Amorosi et al., 2014a; Amorosi et al., 2014b; Bruno et al., 2020).

A reduction in the carbonate content due to a leaching phenomenon, operated by percolation of rainwater, was observed in horizon A. Such carbonates enriched the horizon B_k forming carbonate nodules (centimetric size) and created also cementation and bonding at the level of the silty-clay particles originating a structured matrix. Since the global permeability of horizon A is influenced by the presence of micro-cracks, the accumulation of carbonate substance is not uniform, therefore a great lateral variability of mechanical behaviour is observed in horizon B_k.

We can therefore conclude that the geological and depositional history of the deposit has had profound implications on the soil response to loading. Layers of an over-consolidated, organic, with medium-high plasticity index, and a stiff behaviour (horizons A) overlap layers with a structured matrix by the enrichment in the carbonate content, showing very good mechanical properties despite the lower degree of over-consolidation (horizon B_k). The low-paedogenized horizons B_w, involved only to a limited extent in the carbonatation or over-consolidation process, show a poor mechanical behaviour; their presence was observed between 9-12 m of depth below ground level.

All things considered, the lack of uniformity in the subsoil conditions could be one of the main causes of the inclination of the Garisenda Tower eastwards. Less evident elements of heterogeneity have been found under the Asinelli Tower.

In conclusion, an approximated estimation of the average overall foundation settlement was carried out by means of simple analytical solutions that make use of the elastic theory and of the superimposition of effects (Fadum, 1948) for the calculation of the stress increment. To this scope, the subsoil was divided into three main sub-units, whose properties are summarized in Table 4, as deduced from CPT and laboratory tests.

The water table depth was located at 5.6 m below ground level, as provided by field observations. Then, the total settlement under the central vertical load was thus obtained in the centre of the tower foundations. The loads applied to the foundations are reported in Table 3. Both primary and secondary consolidation settlements were calculated. The settlement of Garisenda's foundations turns out to be approximately 1.3 m and that of the Asinelli Tower around 1.7 m. It is worth noting that such an approach, although well-known and widely used, tends to overestimate the settlement. Moreover, it is important to underline that analytical approaches, as the one previously applied based on the Theory of Elasticity, rely on strong initial hypotheses such as a homogeneous and isotropic compressible subsoil, validity of the superimposition principle in strain summation and elastic stress distribution in soil. Although, as found by many authors (e.g. Poulos & Davis, 1968), the elastic displacement theory is sufficiently accurate to give an estimation of the average settlement in practical applications, its use to predict the differential settlement developed in this context could be excessively forced. The back analysis of differential settlements suffered by the foundations of the towers could be carried out through the development of a numerical model, e.g. by Finite Element (FE) Analysis, which enables to take into account the complex interaction between soil and foundations and the spatial variability of soil characteristics. In this process, the information on tower inclinations and rate of differential settlements reported in the present study can be used to calibrate the numerical model.

6: Conclusions

The present paper outlines the methodologic approach, integrating several different aspects, followed to identify the soil-foundation system of the Two Towers of Bologna and all the elements that should be considered in the preservation process of such heritage structures. The mosaic of technical, cultural and historic issues, collected and analysed herein, enable a better understanding of the reasons why the two Towers of Bologna, despite their numerous similarities, have reached substantially different structural configurations throughout the centuries.

First of all, the noticeable variability of the mechanical properties of the subsoil layers and lenses - which show a poor lateral extent, due to a rather complex geological and depositional history - justifies the lack of settlement uniformity, especially shown by the foundations of the Garisenda Tower (the more leaning one of the two). This of course provides one reasonable cause of its current inclination. At the same time, historical documents and new investigations (i.e. the conglomerate layer found in the south side of the tower) suggest the existence of other buildings built in the proximity of the area of the Garisenda Tower, which might have produced additional inhomogeneities in the load distribution and in the subsoil stress history, again inducing further differential settlements. Water table fluctuations, although limited in the observation period, may also have had a role in the past and they are now kept under control through the purposely installed piezometer monitoring system (2016-2021).

Secondly, smaller foundations and a possible quicker construction sequence than the Asinelli Tower could have generated a potentially dangerous undrained (or partially drained) condition for the soil of the foundations of the Garisenda Tower, especially during the initial construction stages, with the subsequent generation of initial differential settlements.

The present paper retraces, step by step, the path followed in order to deal with the geotechnical issues connected to the preservation of the Two Towers of Bologna, providing a detailed collection of all the analysed data. Therefore, the aim of the present study is to create a fundamental starting point towards the advanced modelling of the involved structures, of the related subsoil and of the complex soil-structure interaction issue. The applied methodology integrates information coming from different disciplines and provides a necessarily robust scientific approach to the preservation of such heritage structures, in particular underlining the role of geotechnical aspects, as recommended by the international engineering societies.

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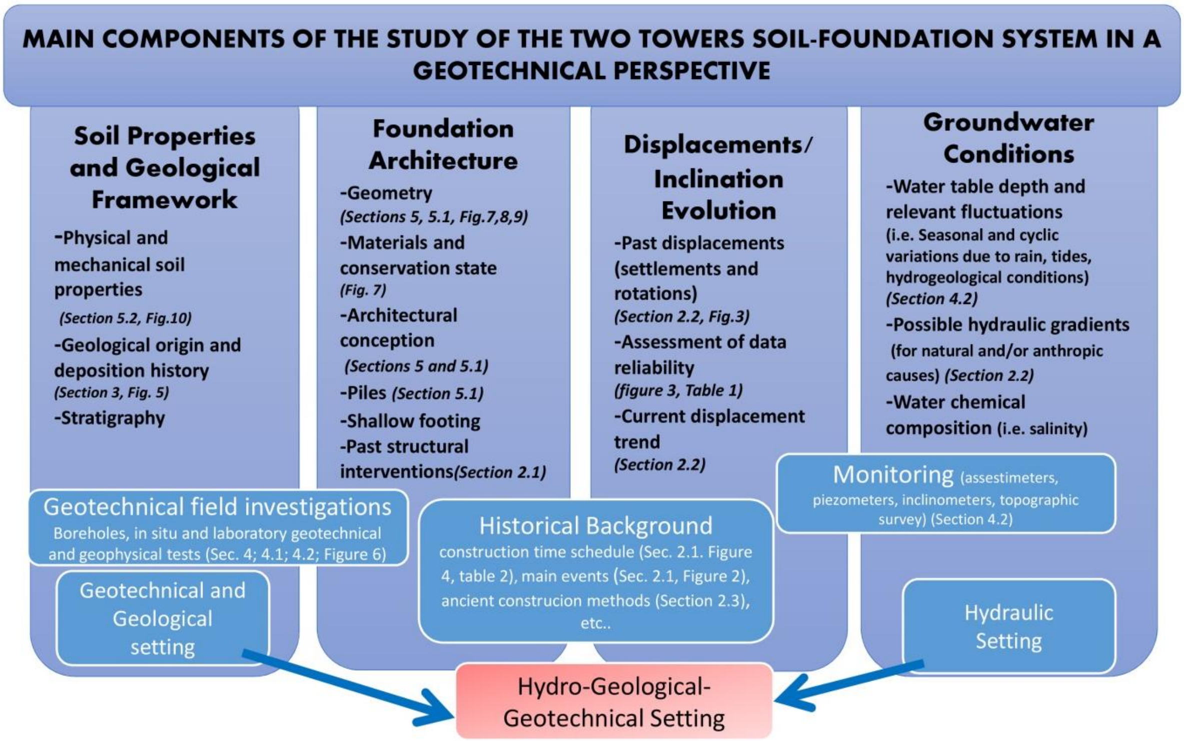


Figure 1: Conceptual map which shows the approach adopted for the definition of the so il-foundation system of historic towers.

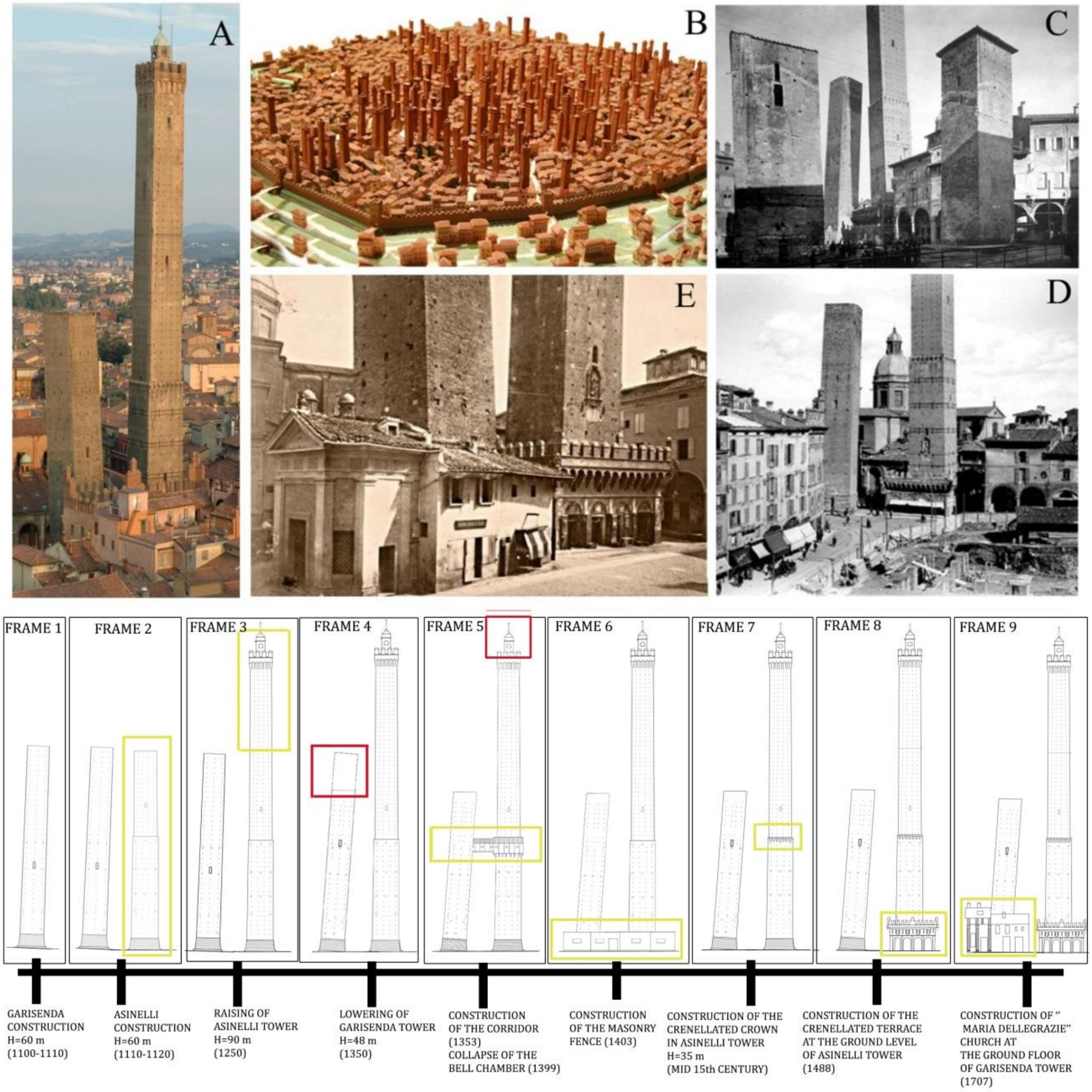


Figure 2. TOP: A) Recent view of the Asinelli and Garisenda Towers. B) Hypothetical r epresentation of Bologna between the 12th and the 14th centuries (Angelo Finelli's mode l of the city, 1917). C) View of the Riccadonna, Artenisi and Guidozagni Towers, locate d close to the Two Towers (visible in the background), before their demolition in 1917-1 918. D) Photo of Ravegnana Square after the demolition of the Riccadonna, Artenisi and Guidozagni (Conforti) Towers (Roversi/Ferri archive). E) View of the Two Towers at an unknown time before 1871, year in which the masonry chapel at the base of the Garisen da Tower was demolished. BOTTOM: Timeline of the Two Towers of Bologna, which s ketches the main events that involved their structures.

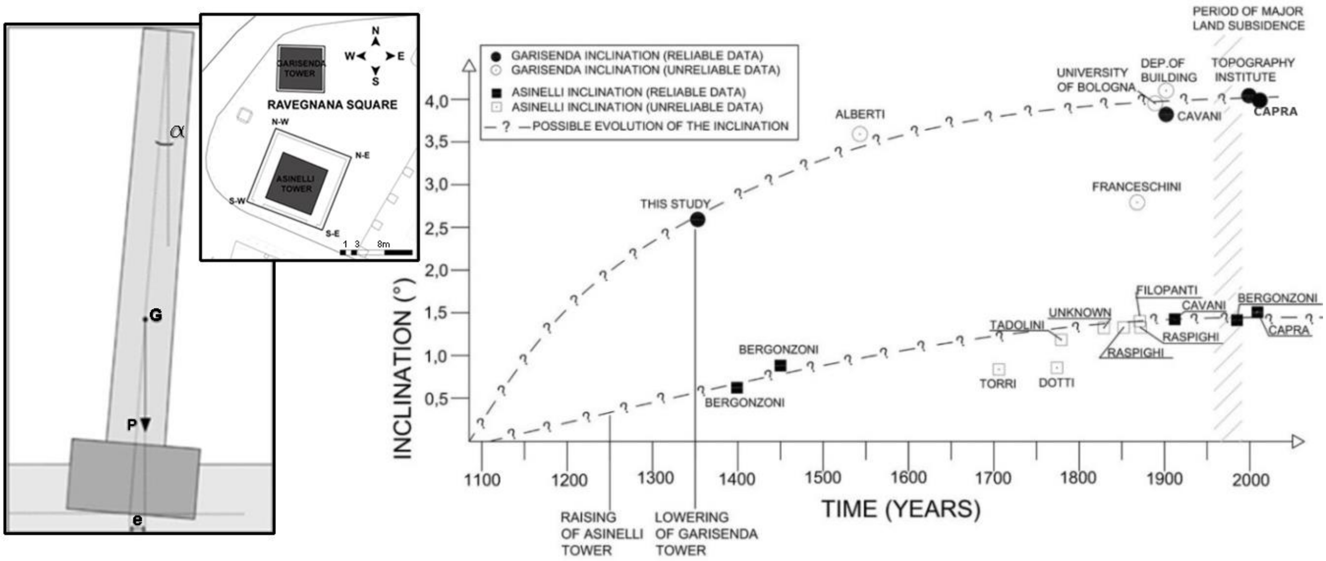
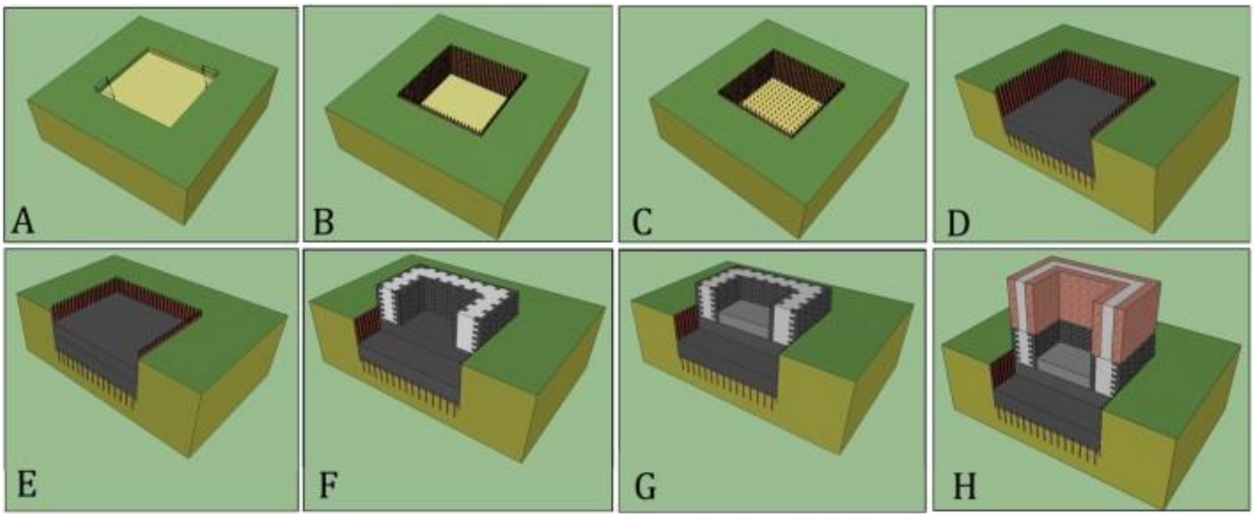


Figure 3: TOP LEFT: scheme of the geometrical variables used in Table 1: inclination (α) and eccentricity (*e*). TOP RIGHT: plot of the complete history of the rotations of the Two Towers (see details in Table 1). The empty marks refer to data that cannot be univo cally interpreted through historic sources or derive from measurements characterized by low precision, while full marks are univocal interpretations of the recorded data (for deta ils see the final column, "Notes'', in Table 1). TOP CENTRE: plan of Ravegnana Squar e with the indication of the main directions.

	YEAR	AUTHOR (REFERENCE)	INCLINATION (°)	METHODOLOGY	NOTES
GARISENDA TOWER	1353	THIS STUDY	**2.6**	Graphical reconstriction of the inclination of the wooden corridor, using the drawings from Bergonzoni's survey of the south side of Garisenda Tower (Bergonzoni, 1973).	INDIRECT MEASUREMENT
	1543	ALBERTI (CAVANI 1903, 1911; GOZZADINI 1875)	**3.62**	Unknown	The original measure refers to the eccentricity (8 feet) probably of the north-east or south-east side of the tower. DIRECT MEASUREMENT
	1868	FRANCESCHINI (CAVANI 1903, 1911;GOZZADINI 1875)	**2.86**	Topographic survey with teodolite	The measument identified the eccentricity of the east side of the tower (2.376 m) and of the north side (0.35 m). Thus, the average inclination refers to the inclination of a small part of the south-east and north-east side of the tower and not to the whole vertical axis. DIRECT MEASUREMENT
	1889	DEPARTEMENT OF BUILDING (CAVANI 1903, 1911; GOZZADINI 1875)	**N-W edge: 3.96** **S-W edge: 3.81** **N-E edge: 3.37** **S-E edge: 3.26**	Plumb lines	The eccentricity of each side of the tower and the inclination of the axis were defined. DIRECT MEASUREMENT
	1902	CAVANI (CAVANI 1903, 1911; GOZZADINI 1875)	**N-W edge: 4.11** **S-W edge: 3.74** **N-E edge: 3.48** **S-E edge: 3.19**	Two plumb lines inside the tower (47 m long)	Measurement given in terms of eccentricity (resulting inclination refers to a height of 48 m). Differences in the measurements in 1889 and 1902 could be due to different measurement technique and restoration works carried out on the top of the tower. DIRECT MEASUREMENT
	1999	UNIVERSITY OF BOLOGNA (BITELLI et al. 2000)	**0.17**	Photogrammetric survey of two sides of the tower (north and west) and use of plumb lines to determine the eccentricity of the axis.	DIRECT MEASUREMENT
	2018	CAPRA (SOING 2018)	**0.66 SOUTH** **3.91 EAST**	Laser scanner	DIRECT MEASUREMENT
ASINELLI TOWER	1399	BERGONZONI (BERGONZONI 1985)	**0.63**	Average inclination estimated from the masonry vault built after a fire in 1399. The vault was built in plan, but ''inclined'' in comparison with the masonry walls.	The estimated inclination is 1.1%. INDIRECT MEASUREMENT
	1450	BERGONZONI (BERGONZONI 1985)	**0.89**	In the mid-15th century, Bologna Municipality built a crown of battlements at the height of 30 m from the ground level. At the time, the tower was leaning toward the west side and to build the crown a triangle of masonry wall was added to have a plain surface for the battlements. Using this information it is possible to estimate an inclination of 1.7% (0.97° from the vertical axis for the first block of the tower).	inclination block 1 (0-35 m):0.97; inclination block 2 (35-60 m):1.008; inclination block 3 (60-90 m):0.695; INDIRECT MEASUREMENT
	1706	TORRI, TARUFFI (CAVANI 1912, 1913; GOZZADINI 1875)	**0.8429**	Plumb lines	The average eccentricity of the west side of tower was measured: 3 Bologna feet and 8 inches, this value is calculated between the crenelated terrace at the top of the Tower (''Rocchetta'') and the terrace at the first floor (10.16 m from the ground floor). DIRECT MEASUREMENT
	1774	DOTTI, TADOLINI (CAVANI 1912, 1913;GOZZADINI 1875)	**0.8263**	Plumb lines	The eccentricity of the axis was measured: 37 inches+1/4 inche. Inclination of the vertical axis calculated between the crenelated terrace at the top of the Tower (''Rocchetta'') and the terrace at the first floor (81,8 m). DIRECT MEASUREMENT
	1779	TADOLINI (CAVANI 1913; GOZZADINI 1875)	**1.3087**	Plumb lines	Eccentricity of the axis: 4 feet+11 inches. Inclination of the vertical axis calculated between the crenelated terrace at the top of the Tower (''Rocchetta'') and the terrace at the first floor (81.8 m). DIRECT MEASUREMENT
	1829	UNKNOWN (CAVANI 1912, 1913; GOZZADINI 1875)	**1.33**	Plumb lines	Eccentricity of the axis: 5 feet. Inclination of the vertical axis calculated between the crenelated terrace at the top of the Tower (''Rocchetta'') and the terrace at the first floor (81.8 m). DIRECT MEASUREMENT
	1852	RASPIGHI (CAVANI 1912, 1913;GOZZADINI 1875)	**1.3346**	Plumb lines inside the tower	Determination of the eccentricity for each block . The average inclination of the vertical axis is calculated in relation to a height of 89.84 m. DIRECT MEASUREMENT
	1856	RASPIGHI (CAVANI 1912,1913;GOZZADINI 1875)	**1.3294**	Plumb lines inside the tower	Determination of the eccentricity for each block. Inclination of the vertical axis calculated in relation to a height of 89.84 m. DIRECT MEASUREMENT
	1871	FILOPANTI, BURIANI (CAVANI 1912,1913;GOZZADINI 1875)	**1.41**	Unknown	Eccentricity: 2.40 m. Erroneous measurement of eccentricity between the top of the belfry and the ground level (97.29 m). DIRECT MEASUREMENT
	1872	RASPIGHI (CAVANI 1912,1913;GOZZADINI 1875)	**1.3346**	Two plumb lines, 80 m long and a mass of 13 kg at the extremity of the rope	Eng. Cavani stressed a possible error in this measurement of eccentricity due to plumb line vibration caused by wind of (+/-) 1/1.5 cm. Estimate eccentricity of 2.083 m. DIRECT MEASUREMENT
	1912	CAVANI (CAVANI 1912,1913)	**1.432**	Plumb lines fixed at the top of the tower (near the east side) and at the rope extremity a mass of 23 kg.	inclination block 1 (0-35 m):1.54; inclination block 2 (35-60 m):1.136; inclination block 3 (60-90 m):1.136. Inclination of block 2 and 3 calculated as an average between 35-60 m high DIRECT MEASUREMENT
	1985	BERGONZONI (BERGONZONI 1985)	**1.42**	Plumb lines outside the tower	inclination block 1 (0-35 m):1.55; inclination block 2 (35-60 m):1.611; inclination block 3 (60-90 m):1.110 DIRECT MEASUREMENT
	2009	CAPRA (CAPRA 2011)	**AVERAGE** **1.515 WEST**	Laser scanner	Inclination block 1 (0-35 m):1.653; inclination block 2 (35-60 m):1.718; inclination block 3 (60-90 m):1.184 DIRECT MEASUREMENT

Table 1: Summary of the direct and indirect measurements of the inclinations of the axes of the Garisenda and Asinelli Towers.



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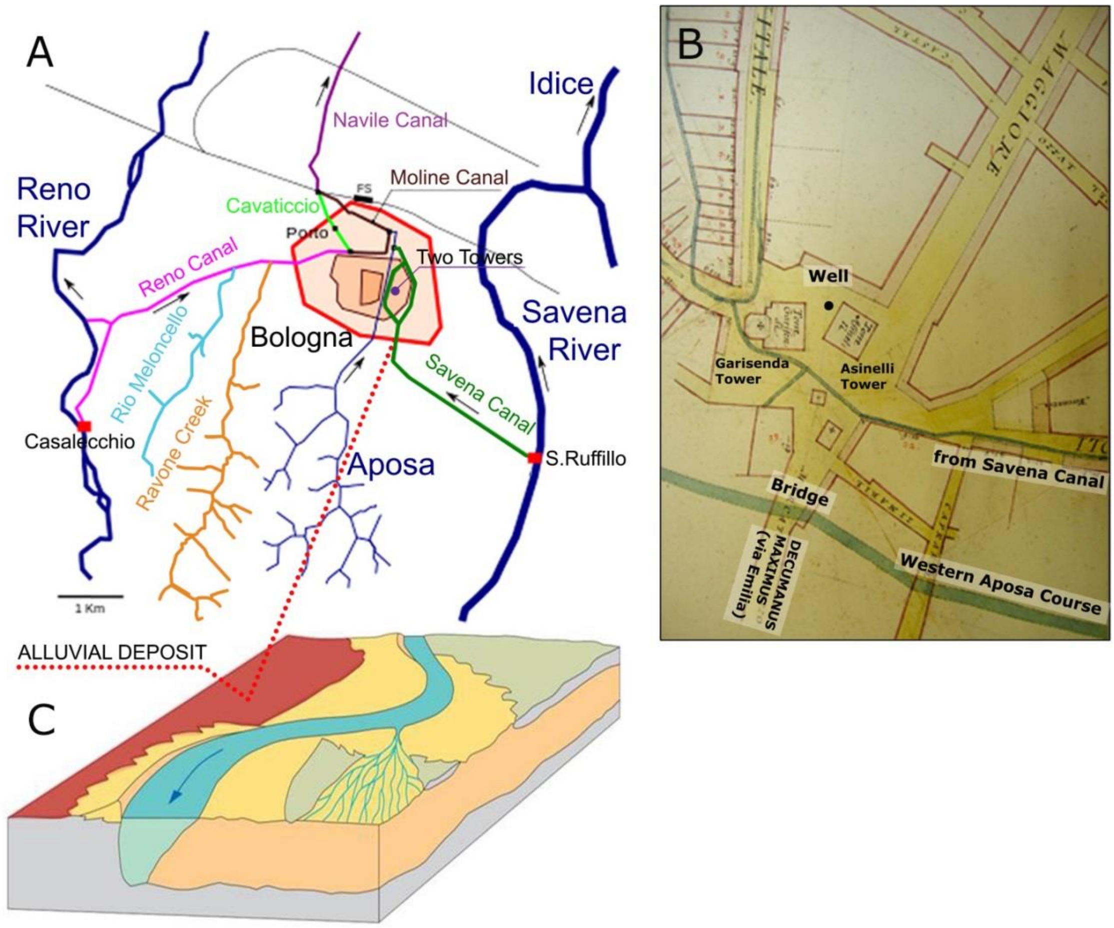

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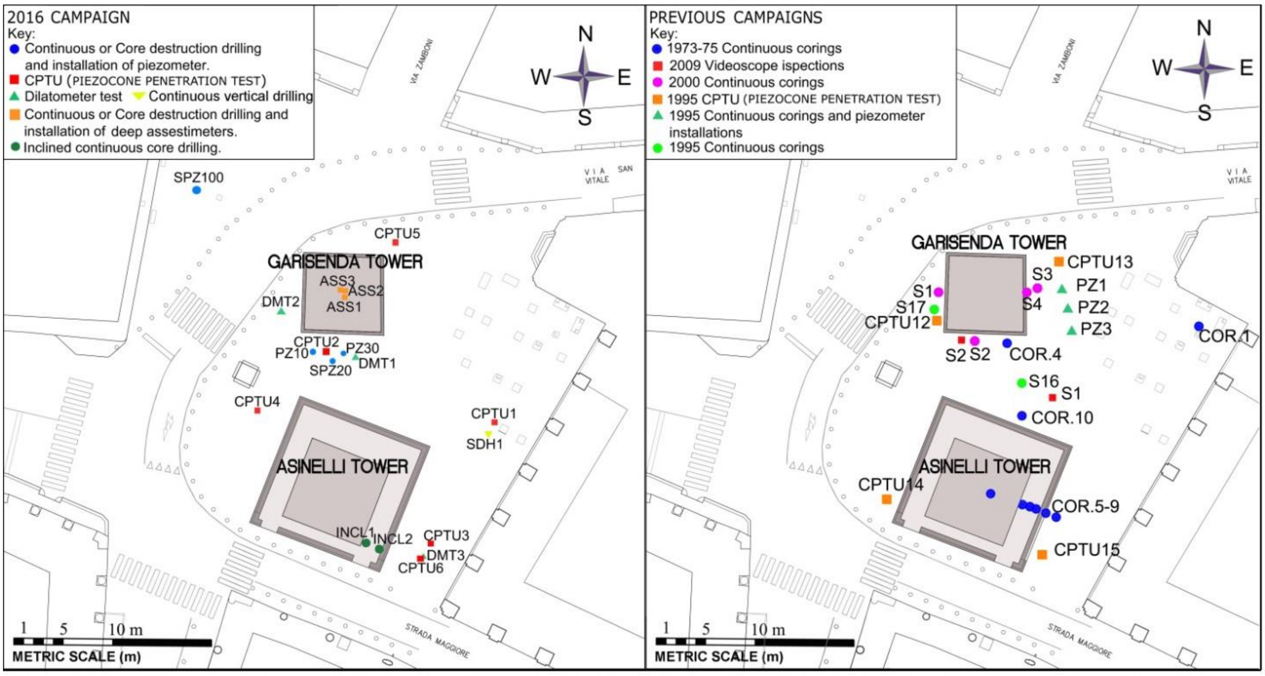

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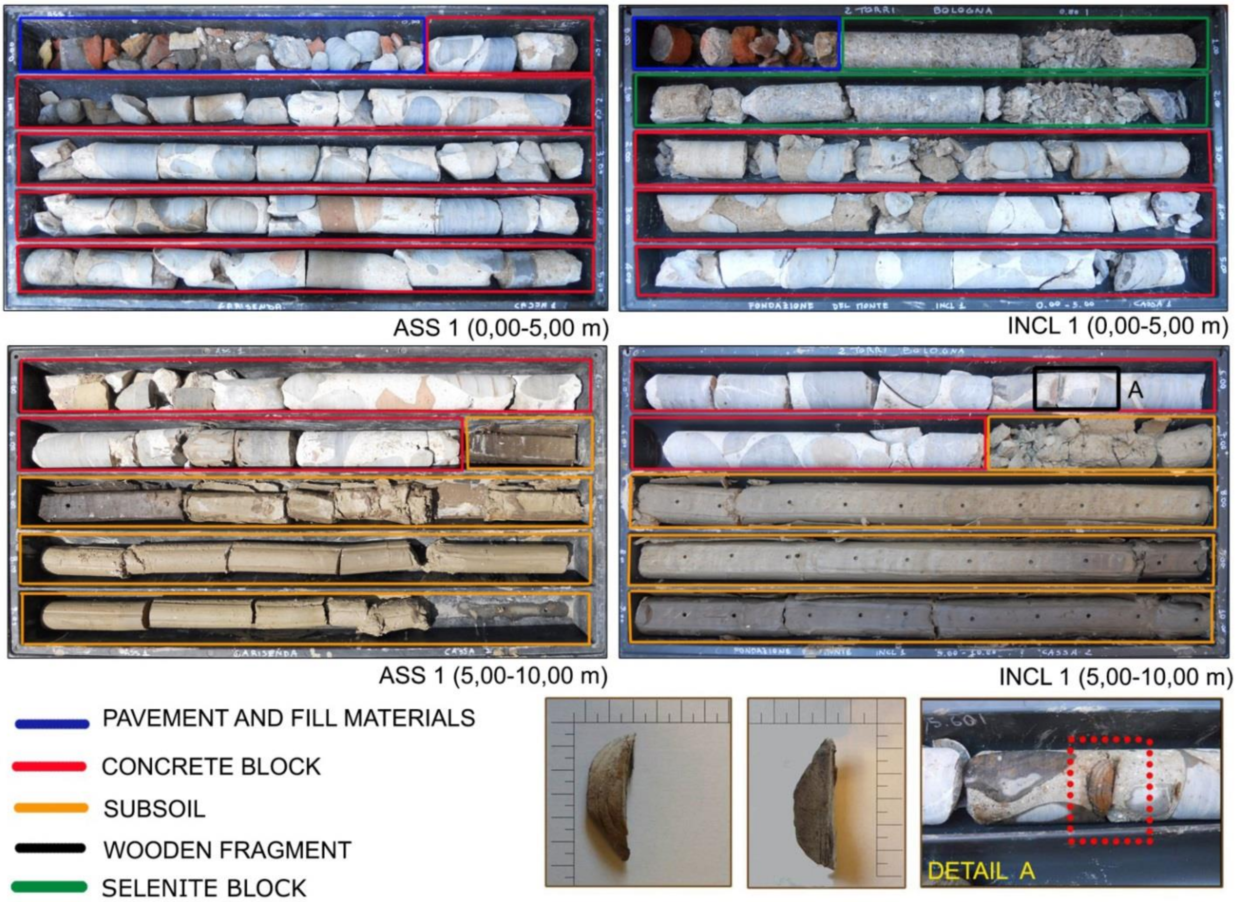

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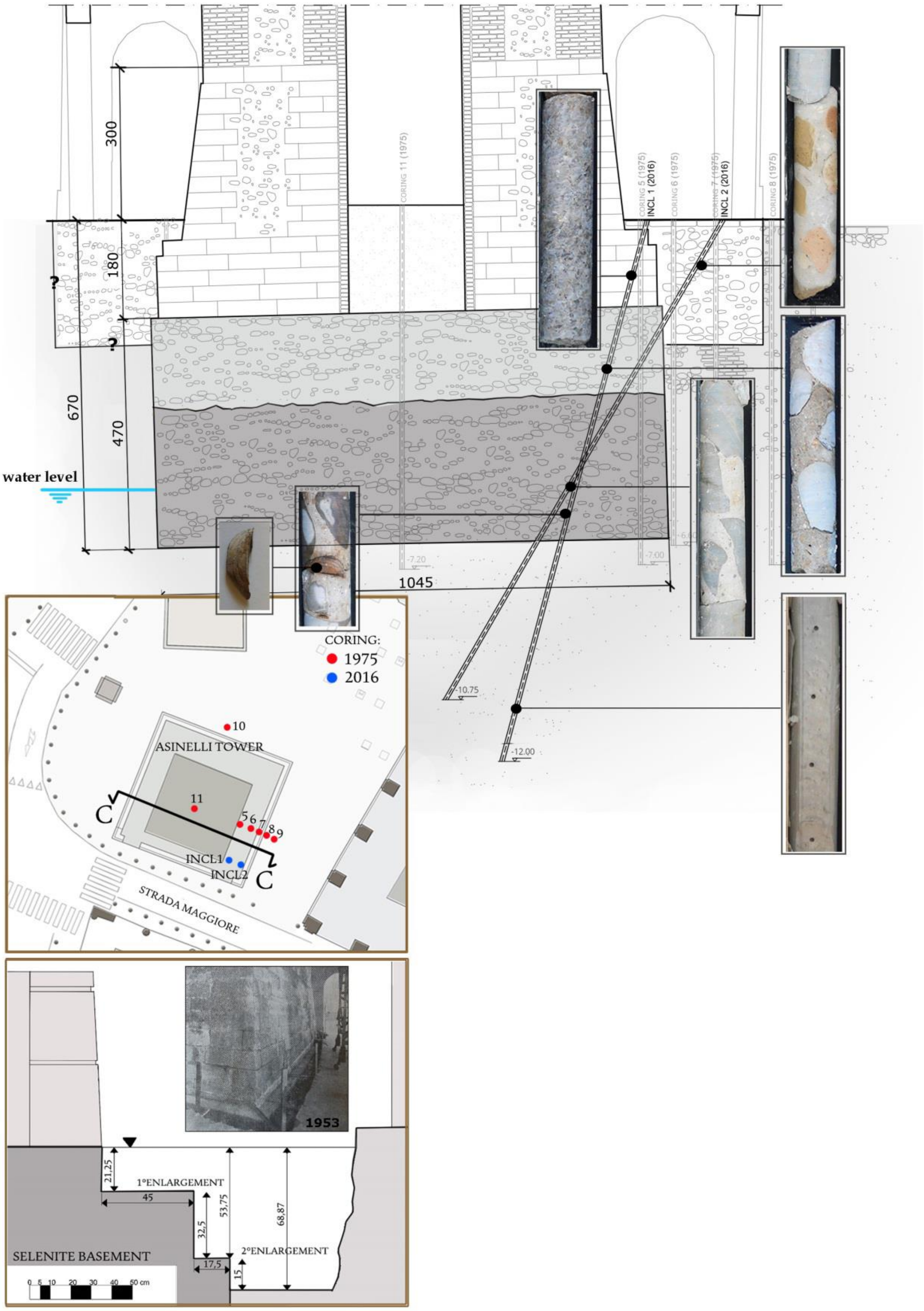

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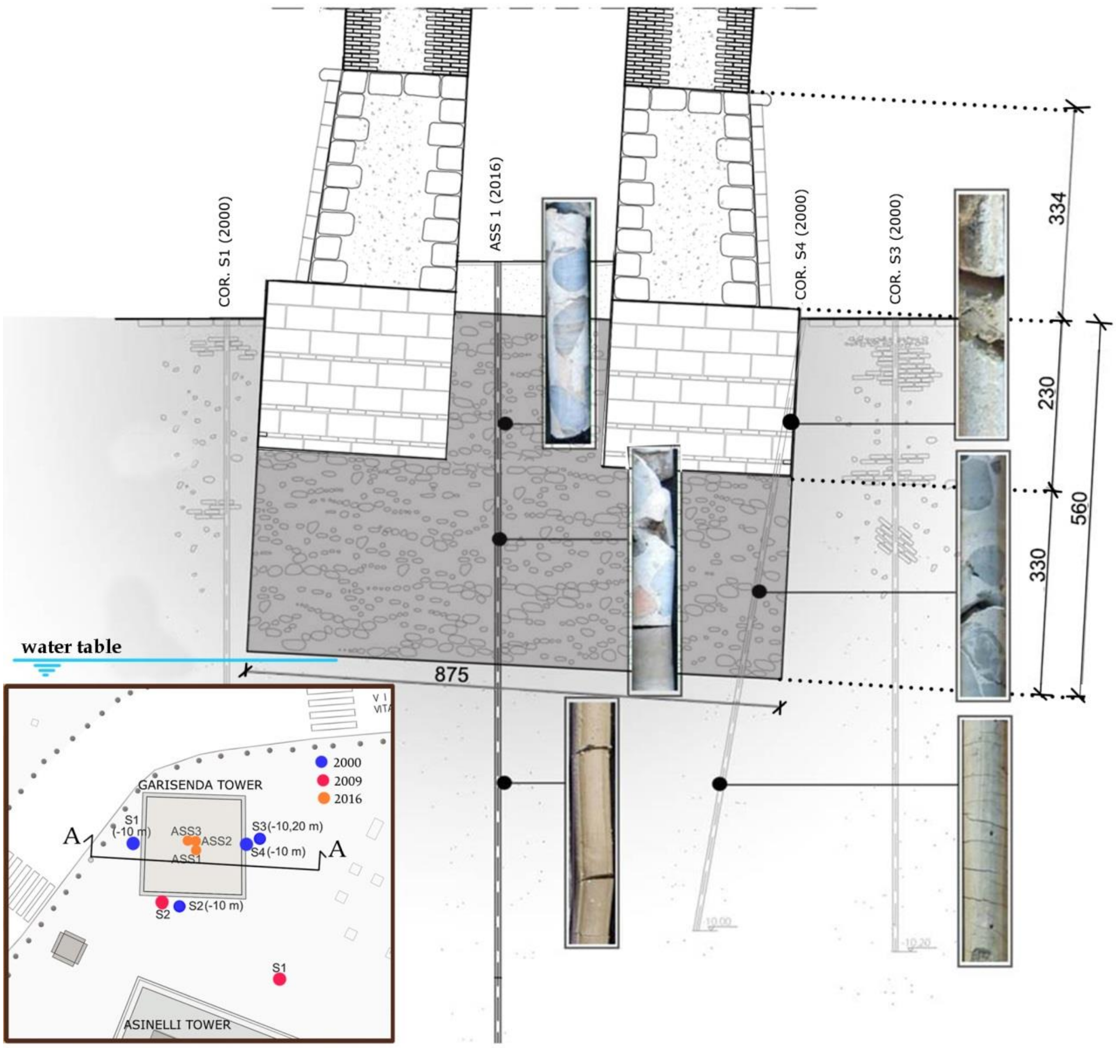

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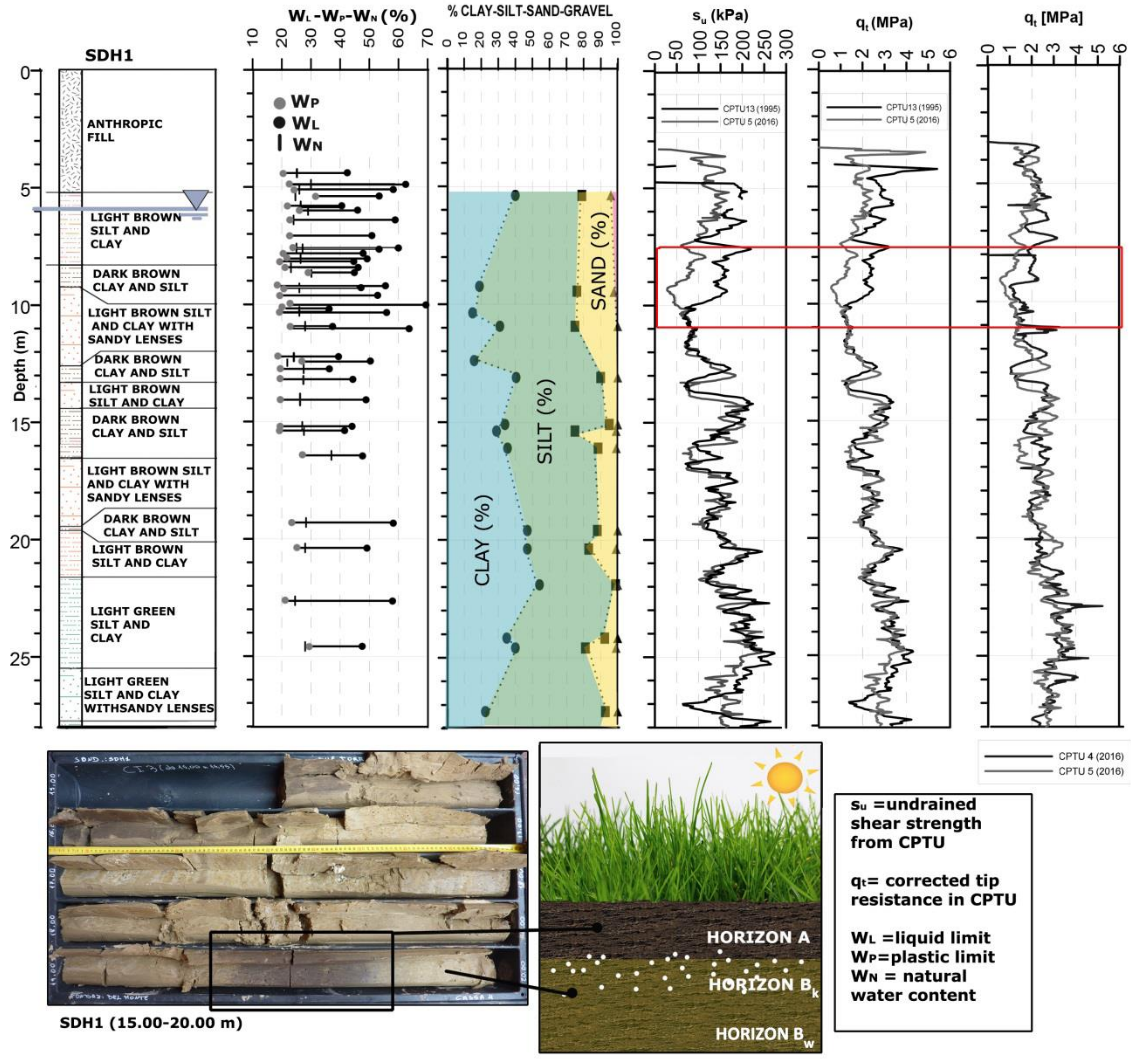

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Manufacture stage	**Minimum time of construction**
Excavation	2 months
Soil removing/fencing of the excavation/dewatering of the excavation	2 months
Wooden pile installation	2 months and 15 days
Casting of the concrete block	2 months
Execution of the selenite basement	6 months
Execution of the masonry walls up to 60 m of height	2 years
Total construction time	~3 years and 3 months

Table 2: Hypothesis of a minimum time schedule for the construction of a medieval tow
er.

GARISENDA TOWER	HEIGHT (FROM FOUNDING LEVEL)	SIDE LENGTH (m)	WALL THICKNESS (m)	γ (kg/m^3)	VOLUME (m^3)	MASS (ton)
FOUNDATION	0-3.3	8.75		2270.1	252.7	573.6
SELENITE BASEMENT (BELOW GROUND LEVEL)	3.3-5.6	8.75		2344.5	225.5	528.6
BASEMENT FILLING	3.3-5.6			1732.9	27.2	47.1
SELENITE BASEMENT (ABOVE GROUND LEVEL)	5.6-8.94	7.58	2.35	2344.6	164.1	384.8
RUBBLE MASONRY WALL	8.94-21.6	7.08	2.11	1783.9	530.3	946.0
RUBBLE MASONRY WALL	21.6-25.8	7.07	2.01	1783.9	170.8	304.7
RUBBLE MASONRY WALL	25.8-35	7.05	1.91	1783.9	361.3	644.5
RUBBLE MASONRY WALL	35-41.6	7.03	1.60	1783.9	228.9	408.3
RUBBLE MASONRY WALL	41.6-47.9	7.01	1.78	1783.9	234.6	418.5
RUBBLE MASONRY WALL	47.9-53.6	7.00	1.68	1783.9	203.8	363.5
TOWER TOTAL MASS (ton)						**4619.6**
AVERAGE CONTACT PRESSURE AT FOUNDATION LEVEL (kg/cm^2)						**6.03**
h_G (m) FROM GROUND LEVEL						**16.13**
TOTAL MASS (+12m OF TOWER)						**5384.9**

ASINELLI TOWER	HEIGHT (FROM FOUNDING LEVEL)	SIDE LENGTH (m)	WALL THICKNESS (m)	γ (kg/m^3)	VOLUME (m^3)	MASS (ton)
FOUNDATION	0-4.7	10.45		2270.1	513.3	1165.1
SELENITE BASEMENT (BELOW GROUND LEVEL)	4.7-6.5	10.17		2344.5	176.6	414.0
BASEMENT FILLING	4.7-6.5			1732.9	9.6	16.6
SELENITE BASEMENT (ABOVE GROUND LEVEL)	6.5-9.5	10.17	3.93	2344.5	294.3	689.9
RUBBLE MASONRY WALL (BLOCK 1)	9.5-14.8	8.10	2.90	1783.9	319.5	569.9
RUBBLE MASONRY WALL (BLOCK 1)	14.8-17.5	8.05	2.64	1783.9	154.2	275.2
RUBBLE MASONRY WALL (BLOCK 1)	17.5-22.58	7.96	2.48	1783.9	276.2	492.6
RUBBLE MASONRY WALL (BLOCK 1)	22.58-27.32	7.86	2.38	1783.9	247.3	441.1
RUBBLE MASONRY WALL (BLOCK 1)	27.32-30.72	7.78	2.29	1783.9	170.8	304.6
RUBBLE MASONRY WALL (BLOCK 1)	30.72-34.59	7.69	2.21	1783.9	176.6	315.0
RUBBLE MASONRY WALL (BLOCK 1)	34.59-41.69	6.93	1.79	1783.9	260.8	465.3
RUBBLE MASONRY WALL (BLOCK 2)	41.69-48.48	6.86	1.79	1783.9	246.5	439.7
RUBBLE MASONRY WALL (BLOCK 2)	48.48-53.16	6.82	1.75	1783.9	166.1	296.3
RUBBLE MASONRY WALL (BLOCK 2)	53.16-61.60	6.75	1.70	1783.9	289.3	516.0
RUBBLE MASONRY WALL (BLOCK 2)	61.60-65.34	6.71	1.46	1783.9	114.4	204.0
RUBBLE MASONRY WALL (BLOCK 3)	65.34-69.76	6.67	1.20	1783.9	115.7	206.3
RUBBLE MASONRY WALL (BLOCK 3)	69.76-78.91	6.59	1.10	1783.9	221.0	394.3
RUBBLE MASONRY WALL (BLOCK 3)	78.91-84.15	6.54	1.03	1783.9	118.5	211.4
RUBBLE MASONRY WALL (BLOCK 3)	84.15-95.5	6.47	0.97	1783.9	241.2	430.2
TOWER TOTAL MASS (ton)						**7847.708**
AVERAGE CONTACT PRESSURE AT FOUNDATION LEVEL (kg/cm^2)						**7.19**
h_G (m) FROM GROUND LEVEL						**26.17**

Table 3: The table reports the geometrical dimensions, the unit weights, and the mass of each volume into which the towers can be divided. h_G is the height of the centre of mass , provided as measure from ground level. The first table also shows the total weight of th e Garisenda Tower before it was shortened by 12 m in 1350.

depth from the ground level		γ_n (kN/m^3)	m_v (MPa^{-1})	c_α (1/min)	c_s (-)
1	0-15 m	19.2	0.063	0.00197	0.046
2	15-25 m	18.7	0.085	0.00198	0.039
3	>25 m	19.4	0.107	0.0036	0.026

Table 4: The natural unit weight of the soil (γ_n), the coefficient of compressibility (m_v), the secondary consolidation parameter (c_α) and the unloading-reloading compression index (c_s) are reported for each unit, as deduced from geotechnical investigations (CPT and laboratory tests).