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From geological and historical data to the geotechnical model of the Two Towers in Bologna (Italy)

A‘ partir des informations géologiques et historiques au modèle géotechnique des Deux Tours à Bologne (Italie)

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ABSTRACT: This paper outlines the multidisciplinary approach developed for the definition of the geotechnical model of the foundations of Asinelli and Garisenda towers in Bologna. Historical information and previous site investigations were collected and analysed. Then a new geotechnical investigation was carried out in 2016, which enabled accurate identification of the soil-foundation systems of both towers. In addition, the geotechnical soil properties were investigated taking into account the geological setting of the area. The latter, enabled the recognition of prominent stratigraphic markers within the ~100 m thick alluvial succession beneath the Two Towers foundations, thus providing a new key to soil mechanical properties. This study enabled the identification of the significant features of foundation structures and subsurface stratigraphy, characters of authenticity of the Two Towers which should be carefully preserved in any future conservation strategy of these valuable monuments.

RÉSUMÉ: Cet article décrit l’approche multidisciplinaire développée pour l’identification du modèle géotechnique des fondations des tours Asinelli et Garisenda à Bologne, Italie. Une enquête géotechnique récente a été réalisée en 2016. Les résultats ont été analysés après la collection de tous les informations pertinentes pour identifier les caractères d'authenticité des tours. En outre, le modèle géotechnique du sous-sol a été intégré à une enquête géologique détaillée, qui a permis d’identifier des marqueurs stratigraphiques importants dans la succession alluviale jusq‘à 100 mètres sous les fondations de Deux Tours. Cette étude a permis d'identifier les structures de fondation, la stratigraphie du sous-sol et les propriétés du sol, et de résumer les éléments cruciaux pour une analyse de stabilité future des tours de Bologne.

Keywords: foundations, historic heritage, palaeosol, towers, geological history

1 INTRODUCTION

The Two Towers, Garisenda and Asinelli (Figure 1), are medieval masonry towers located in the historic city centre of Bologna, one of the main urban centres in Northern Italy. Their structural peculiarities and heritage value have transformed them in a symbol of the town and of its Middle Ages architecture.

Their conservation is an intricate challenge for both local authorities and the scientific community. Thus, careful investigations and monitoring have been recently carried out first on the superstructure, and then on the soil and foundations. These latter were studied starting from the available historical information and previous site investigations. In addition, the idro-geological setting of the area was carefully analysed. The collection of these data, integrated with the outcome of the new investigations, enabled the creation of a geotechnical model of the soil foundation systems of the two towers and the clear identification of the characters of authenticity of the Towers.

Medieval towers are slender structures whose problems are mainly due to differential settlements of the subsoil, durability of masonry walls, stability, seismic actions, etc.. Thus, a reliable forecast of their performance in static and seismic conditions is essential for their conservation. In a geotechnical perspective, this could be achieved by means of advanced forecasting models (Marchi et al, 2011, Marchi et al, 2013, Pisanò et al, 2014), which necessarily require an accurate definition of the soil-foundation system as input.

2 HISTORICAL BACKGROUND

In the Middle Ages, a large number of towers were built inside the city walls, possibly 75 towers and tower houses. Thus, Bologna has gained the name of ''La Turrita'' (City of Towers). Towers construction started at the beginning of the second half of 11th century. In the subsequent centuries, many towers collapsed or were demolished. At present, only 22 towers are still standing (Roversi et al, 1989). Among them, Garisenda and Asinelli Towers are the best conserved and definitely the most well known. Figure 2 represents a schematic timeline, which summarises the main vicissitudes of the Two Towers, from their construction to date. As shown in this picture, both towers were constructed at the end of XI - beginning of XII century, but the exact construction times are still uncertain. From thermal-luminescence tests on masonry bricks, Asinelli construction was placed around 1075-1100, while Garisenda few years before (Bergonzoni, 1991).

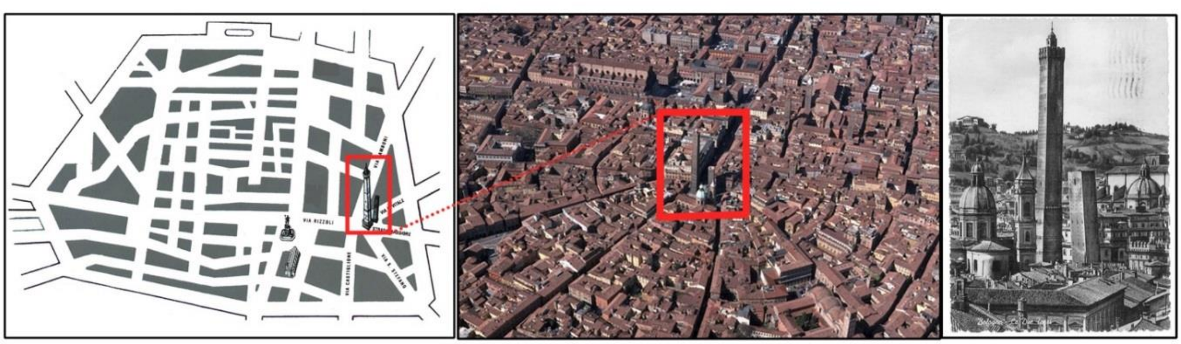

Figure 1. The Bologna Two Towers: their location is shown in a schematic map and in a picture of the historic city centre. On the right, the two towers in a postcard of the last century (Garisenda on the right and Asinelli on the left).

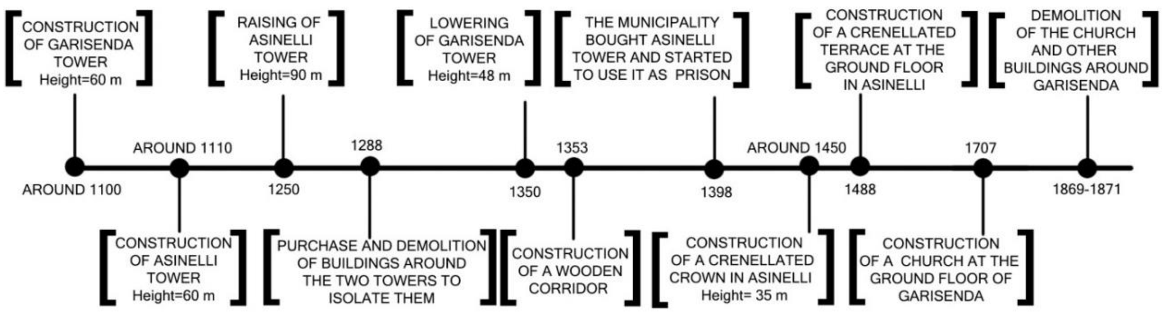

Figure 2 The main vicissitudes of the Towers shown on their timeline.

Originally, the Garisenda Tower was 60 m high. Then, in 1353, it was partially demolished to 48 m high, because of its dangerous leaning. Similarly, historians claim that Asinelli was originally 60 m high, like Garisenda (frames 1 and 2 in Figure 2). Afterwards, in an unidentified year between 12th and 13th century (frame 3 in Figure 2), the tower was raised to its present 97.20 m. From an historical point of view, after the demolition of the Garisenda top part in 1350, no significant structural interventions were carried out on the Two Towers, apart from the construction of a number of external adjacent smaller peculiar buildings, as described in the frames from sixth to eleventh in Figure 2. The construction method of foundations in Bologna remained unchanged until the beginning of the last century. Depending on the depth and on the local properties of the shallowest soil layers, the excavation sides could be vertical or slightly inclined, and the sides of the excavations free or supported by wooden boards. The main body of the foundation was a block made of sand, gravel, fragments of bricks and slaked lime. It was cast in place directly on the virgin soil or, occasionally, the foundation bed could be reinforced with short wooden piles. The whole construction process of a 60-m-high tower could last years. The average length of time has been estimated to be about 5 years (Roversi, 1989).

3 GEOLOGICAL SETTING

The town of Bologna is located at the southern margin of the Po Plain, close to the Apennine foothills. Alluvial gravels were deposited by Apenninic rivers close to their outlets into the plain (Amorosi et al., 1996). Two main rivers supply sediments to the Bologna area from the Northern Apennines (Figure 3A): the Reno River, which bounds the town to the west, and Savena River, to the east. The Apennine foothills, south of Bologna, are drained by small creeks, less than 10 km long (Figure 3a), with characteristic torrential regime and poor transport capacity. Close to Reno and Savena outlets, fluvial channel deposits are multistorey gravel bodies, hundreds of meters thick (Figure 3). Distally, they grade into rhythmical alternations of gravel bodies and mud strata (Figure 3b). Coarse-grained fluvial deposits are rare beneath the historical centre of Bologna (Figure 3). Sediment to this area was supplied by the minor drainage system between Reno and Savena Rivers. Accurate core examination in the subsurface of Bologna has recently revealed the presence of thin, repeated paleosol sequences within the seemingly homogeneous muddy succession beneath the Bologna city center (Amorosi et al., 2014).

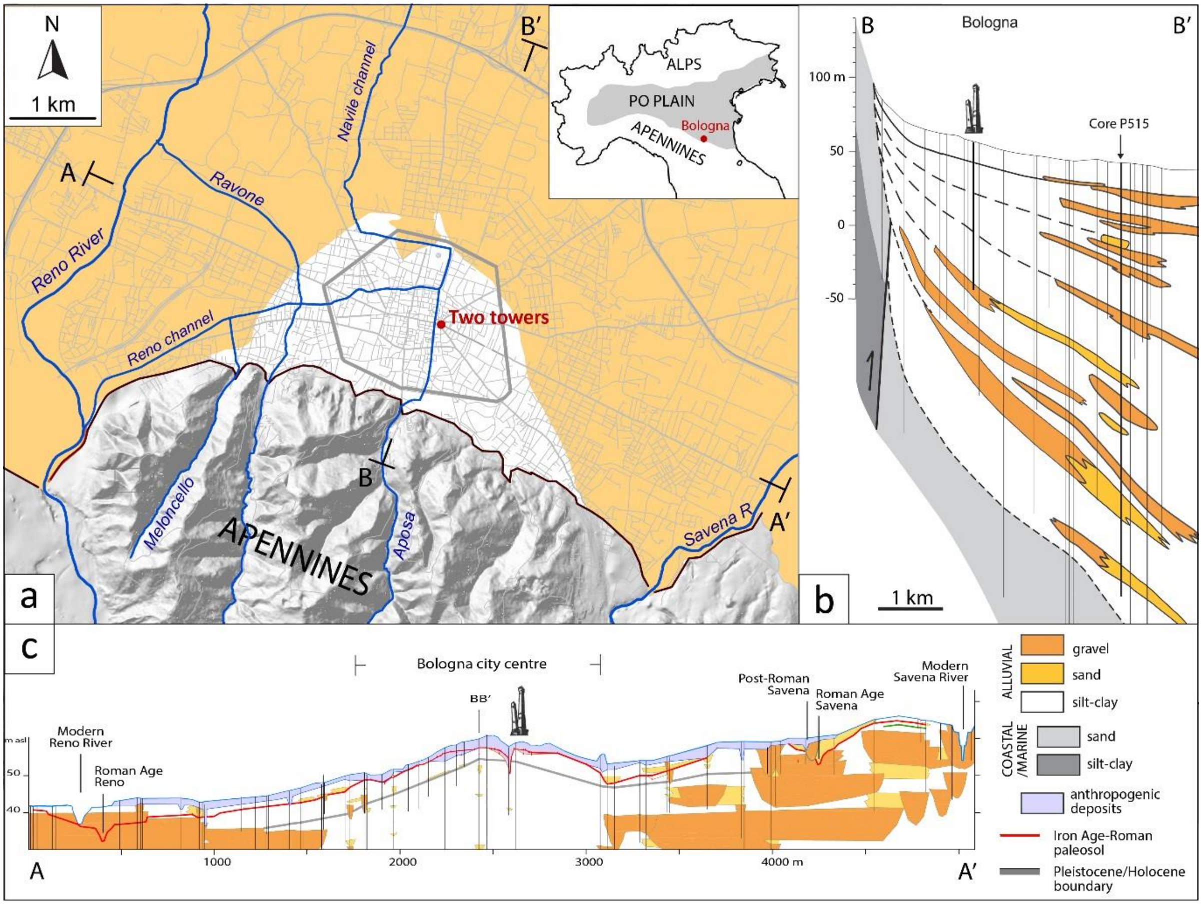

Figure 3 a) Geological map of the Bologna area. In orange, areas where gravels occur in the uppermost 100 m. In the white area, broadly corresponding to the historical centre, gravels are lacking (from Bruno et al., 2013). b) Stratigraphic cross-section, depicting the deep (350m) alluvial architecture beneath the town of Bologna (modified after Amorosi et al., 2001). c) Stratigraphic cross-section, depicting the shallow (30 m) alluvial architecture between Reno and Savena Rivers (from Bruno et al., 2013).

4 GEOTECHNICAL INVESTIGATION AND MONITORING

The Two Towers have been studied and partially monitored since the beginning of the 20th century by the local scientists and authorities.

Three geotechnical investigations campaigns on the soil foundation systems of the Towers were carried out in the past, in 1973, 1995 and 2000. More recently, in 2016, a new geotechnical investigation was carried out with the aims of fulfilling the missing piece of information and installing permanent geotechnical monitoring devices. The results of previous investigations were carefully analysed, during the preliminary stage of the 2016 campaign and taken into account for the development of the final model.

The new investigations of the summer 2016, shown in the map of Figure 4, consisted of:

- 1 vertical continuous coring borehole, 100 m deep, equipped with an open standpipe piezometer;

- 1 vertical continuous coring borehole, 20 m deep, equipped with a Casagrande piezometer;
- 2 vertical destruction borings, 10 and 30 m deep, equipped with Casagrande piezometers;
- 1 vertical continuous coring borehole, 40 m deep, equipped for a down-hole test;
- 6 piezocone tests (CPTU);
- 2 inclined continuous coring boreholes into the Asinelli foundation block (up to 12 m of depth);
- 3 dilatometer tests;
- 3 deep assestimeters under Garisenda Tower foundation to provide data on soil deformations.

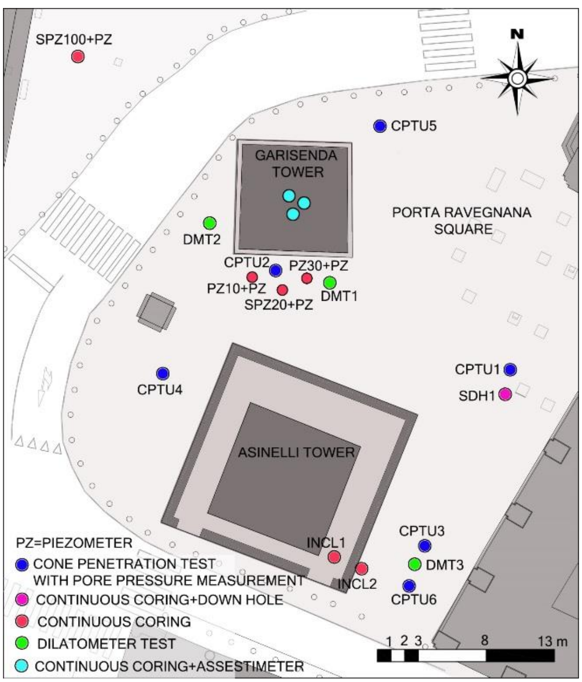

Figure 4 Plan of the Bologna Two Towers with the location of the geotechnical field tests carried out in 2016.

Detailed stratigraphic description and facies interpretation were carried out on the recovered core material. In addition, 26 undisturbed samples were extracted during coring operations for the execution of laboratory tests (grain-size distribution, organic content, percentage of carbonate, natural unit weight, plastic, liquid and shrinkage limits, oedometer tests, triaxial tests, direct shear tests, resonant column and torsional shear tests).

5 GEOTECHNICAL MODEL OF THE TWO TOWERS

The foundation structures were reconstructed combining a number of data collected from all vertical and inclined boreholes (of the 2016 and previous campaigns). An example of identification of the single parts of the foundation block through the observation of the recovered core material is shown in Figure 5 (bottom left). Eventually, a complete and detailed description of the foundation blocks of both towers was developed and it is schematically represented in Figure 5. The results fulfil the expectations coming from study of historic literature (Section 2), which also helped in the definition of the design (i.e. position) of the investigations and subsequently provided additional information regarding timing of the construction process and peculiarities of the construction materials.

The Asinelli Tower foundation is a block made with lime and well-graded cobbles, 6.5 m deep. The foundation width is 10.45 m wide. The block is not homogeneous, but divided in two parts: the lower one (2.90 m thick) is compact, with rare voids, the upper (1.80 m thick) is weak (can be easily scratched), very powdery when touched (Figure 5). No clear evidence of piles installation at the bottom of the foundation block was found.

The geometry of the Garisenda Tower foundation was investigated in 1999 using the georadar technique and afterwards, in 2000, using inclined boreholes. The vertical boring carried out in 2016 confirmed the findings of the previous investigations.

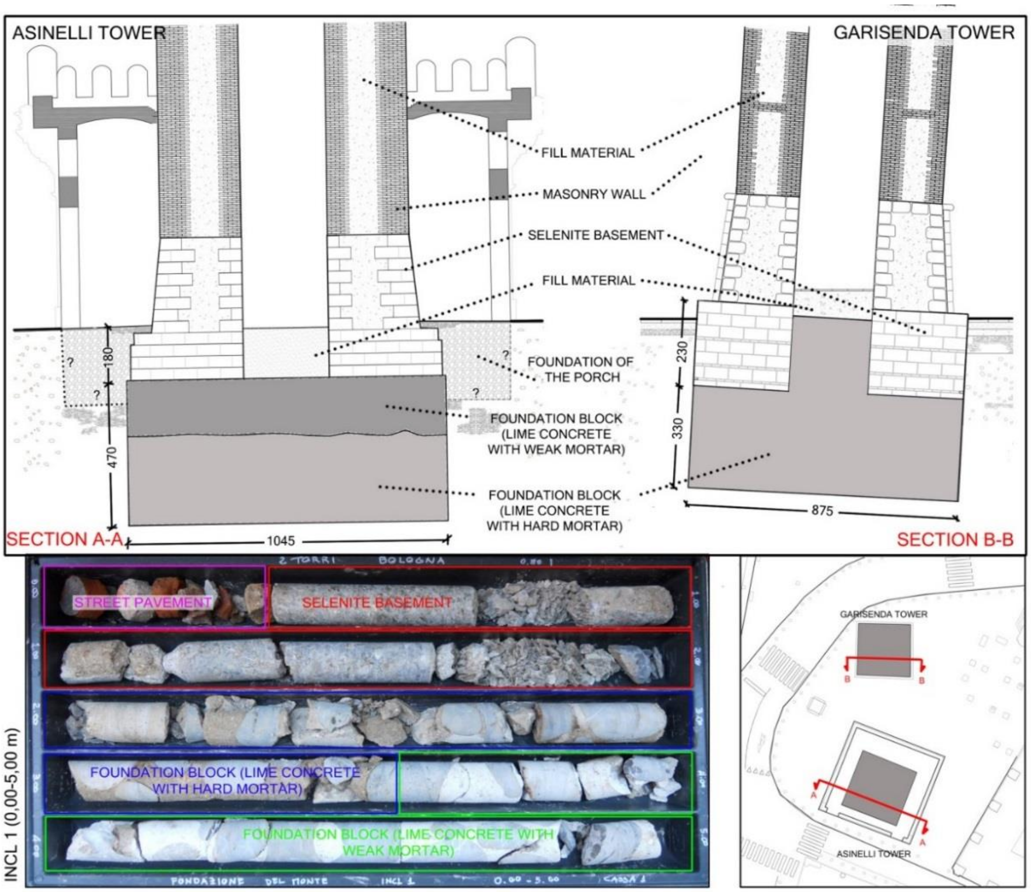

Figure 5 Schematic sections of the towers foundations (top) and picture of cores extracted from one of the two inclined boreholes executed on the Asinelli foundation (bottom, left).

The foundation block is a massive 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 deep from the ground surface. The synthetic soil profile of the Two Towers is shown in Figure 6. This picture summarises the results of some of the most significant field and laboratory tests of the 2016 geotechnical campaign. The soil classification was mainly deduced from observation of core samples, interpretation of CPTU tests via Robertson (2009) SBT (Soil behaviour type) and laboratory classification tests. The stratigraphic succession consists of an alternation of silty-clay and clayey-silt with low-medium percentage of sand (from 5 to 25%) and medium-high plasticity (PI from 13 to 36). The physical properties of soils are shown in columns from one to five in Figure 5. Between 4 and 16.5 m, the succession is made of silty clays and clayey silt layers about 1 m thick Between 16.5 and 26 m of depth, the layering structure changes into thinner alternations of cm-thick levels of the same materials, then again alternations of m-thick layers of silty clays and clayey silts.

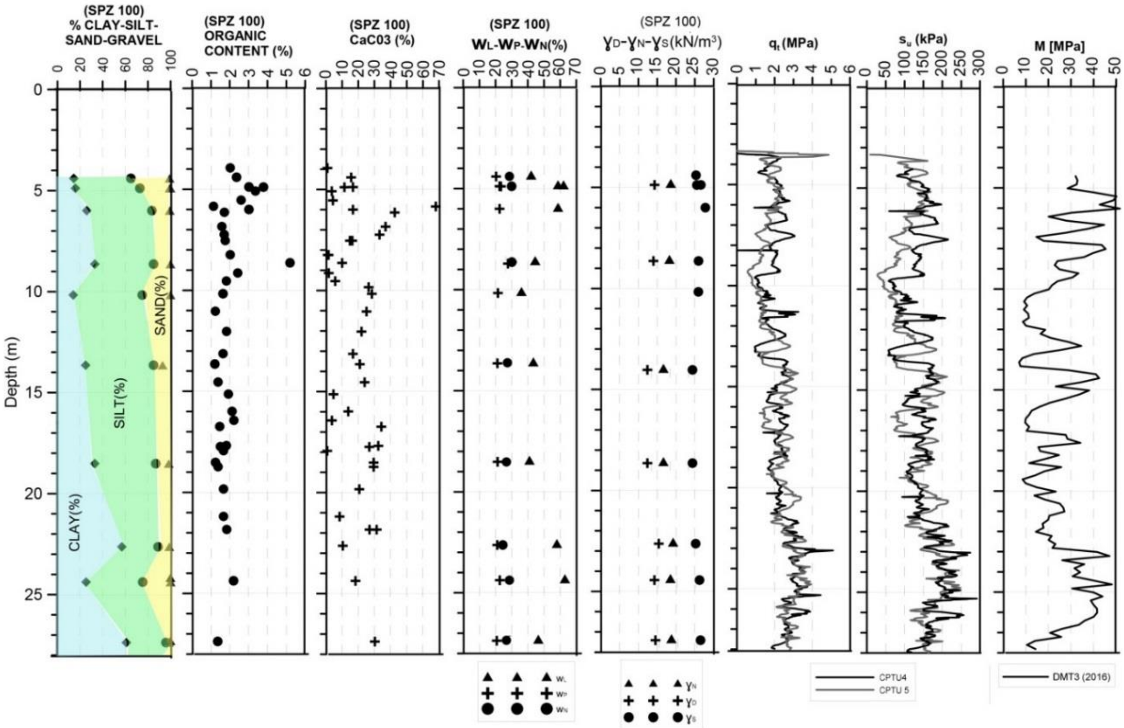

Figure 6 Foundation soil profile, as deduced from in situ and laboratory tests.

Despite the macroscopic lithological uniformity of the deposits, their mechanical properties are heterogeneous both laterally and vertically (see CPTU 5 and CPTU 4, near the north-east side of Garisenda Tower, in the sixth and seventh columns in Figure 6). The sedimentological study of the core material, with the identification of sedimentary facies of the area (Section 3), provides a significant interpretation of these soil properties. The floodplain succession beneath the Garisenda tower is locally marked by paleosols (i.e. pedogenized horizons) characterized by organic-matter-rich dark horizons, overlying lighter horizons enriched in carbonate nodules. Paleosols have a typical tabular shape and great lateral extent. They developed during long periods of sub-aerial exposure of the ground surface, due to interruption of the alluvial sedimentation. The exposure to air (drying process), causes a volume reduction and an increase in resistance (over-consolidation), which generates changes in the mechanical properties (Amorosi et al., 2014; 2015; 2017). Due to subtle lithological variations, mechanical properties may vary along a single paleosol horizon. 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 towards the east side. Less evident elements of heterogeity were found beneath the Asinelli Tower.

6 CONCLUSIONS

The Bologna Two Towers, Asinelli and Garisenda, have been kept under close observation since the beginning of the last century. A modern monitoring of the differential settlement at the base of the Asinelli Tower by precision levelling started in 1972; 18 years later, in 1990, the levelling network was extended to Garisenda Tower. Such readings are still ongoing and suggest that, in the last century, the Asinelli Tower differential settlement increased with an average rate of about 0.22 mm/year. In the same period of time, a slightly lower average rate of about 0.17 mm/year was found for the Garisenda (Traversa, 2011). Such displacements are still under investigation and need to be carefully considered. A recent geotechnical field investigation was carried out in 2016, with a special focus on the foundations of the towers and on their subsoil conditions. This paper outlines the multidisciplinary approach developed for the identification of the geotechnical model of the towers, which takes into account not only the geotechnical characterization of soils, but also the historical background and the stratigraphic framework of the area. The definition of an accurate geotechnical model represents a fundamental step toward the development of a successful preservation strategy of the Bologna Two Towers.

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