Geotechnical modelling for the structural assessment of the Two Towers in Bologna (Italy)

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ABSTRACT

The Two Towers of Bologna, Garisenda and Asinelli, are iconic medieval structures and cultural landmarks standing in close proximity in the historic centre of the city. Their historical and architectural value makes their preservation a matter of significant public and scientific interest. In particular, the Garisenda tower has long been the subject of debate due to its pronounced inclination, progressive deformation, and associated structural vulnerabilities. To better understand the causes of its current critical condition and to support future preservation and mitigation strategies, an extensive geological and geotechnical investigation campaign was undertaken in 2016. The investigation included several in-situ tests (continuous corings, CPTUs, DMTs, a downhole test), laboratory analyses and a sedimentological study of the alluvial subsoil, together with the installation of an advanced monitoring system. The investigation revealed a complex alternation of desiccated and microstructured soil horizons, characterised by significant vertical and lateral variability of geomechanical properties. These findings were incorporated into the stratigraphic and geotechnical model developed for the subsequent soil-structure interaction analysis. A finite element model was developed to assess the stress distribution beneath the foundations of both towers and to simulate the mechanical response of the coupled soil-foundation system. The aim was to inform potential stabilisation efforts and long-term preservation strategies, with particular focus on the Garisenda tower.

Keywords: historic towers, finite element modelling, soil-structure interaction, historic heritage preservation.

INTRODUCTION

Masonry tower structures are an essential component of the historical and architectural heritage of Italian medieval cities. Slender towers are particularly vulnerable to soil–structure interaction problems, as their stability depends on the interplay between the foundations and the supporting soils, responsible for sustaining both the vertical load and the overturning moment induced by the superstructure.

Towers that collapsed shortly after construction may have done so as a result of bearing-capacity failures associated with insufficient strength of the supporting soil-foundation system. In contrast, towers erected more gradually through incremental construction phases allow time for subsoil consolidation, resulting in a progressive increase in soil stiffness and shear resistance. Other mechanisms leading to long-term instability include local degradation of masonry (e.g., the San Marco Belfry in Venice and the Civic Tower in Pavia), interaction with adjacent structures and differential settlements on soft soils (e.g., the Frari Belfry in Venice, Gottardi et al., 2015, and the Ghirlandina Tower in Modena, Lancellotta, 2013), as well as leaning instability. The analysis of such complex systems requires advanced analytical approaches or numerical models capable of incorporating time-dependent soil behaviour (Marchi et al., 2011; Marchi et al., 2013; Pisanò et al., 2014; Lancellotta & Sabia, 2015). These models must rely on a robust understanding of the soil-foundation–superstructure system, supported by an accurate geotechnical characterisation of the subsoil and detailed knowledge of the foundation geometry.

Within this framework, the Two Towers in Bologna provide an emblematic case study. In particular, the Garisenda tower exhibits clear signs of structural distress, primarily associated with high stress levels developing within the masonry as a result of its pronounced inclination, induced by a compressible and heterogeneous subsoil. Additional deterioration mechanisms are linked to the progressive decay of construction materials, exacerbated by long-term environmental exposure and ageing processes.
This paper presents the results of past and recent geotechnical and structural investigation campaigns aimed at obtaining in-situ and laboratory data for material characterisation and discusses preliminary modelling results of the current stress distribution beneath the foundations of the Two Towers. The results are intended to support guidance for the design of stabilisation measures for the Garisenda tower.

THE TWO TOWERS

The city of Bologna has earned the title not only as “La Grassa” (“the Fat City”), for its celebrated cuisine, but also as “La Turrita” (“the City of Towers”). Historical studies have confirmed the existence of approximately 75 towers in the medieval Bologna, most of which have disappeared due to collapse, demolition, or incorporation into later buildings. Today, only 22 towers remain, yet the Two Towers—Asinelli and Garisenda—survive in the city centre. Their contrasting shapes, with Asinelli tall and nearly vertical and Garisenda shorter and distinctly leaning, have long been a symbol of the city (Figure 1A).

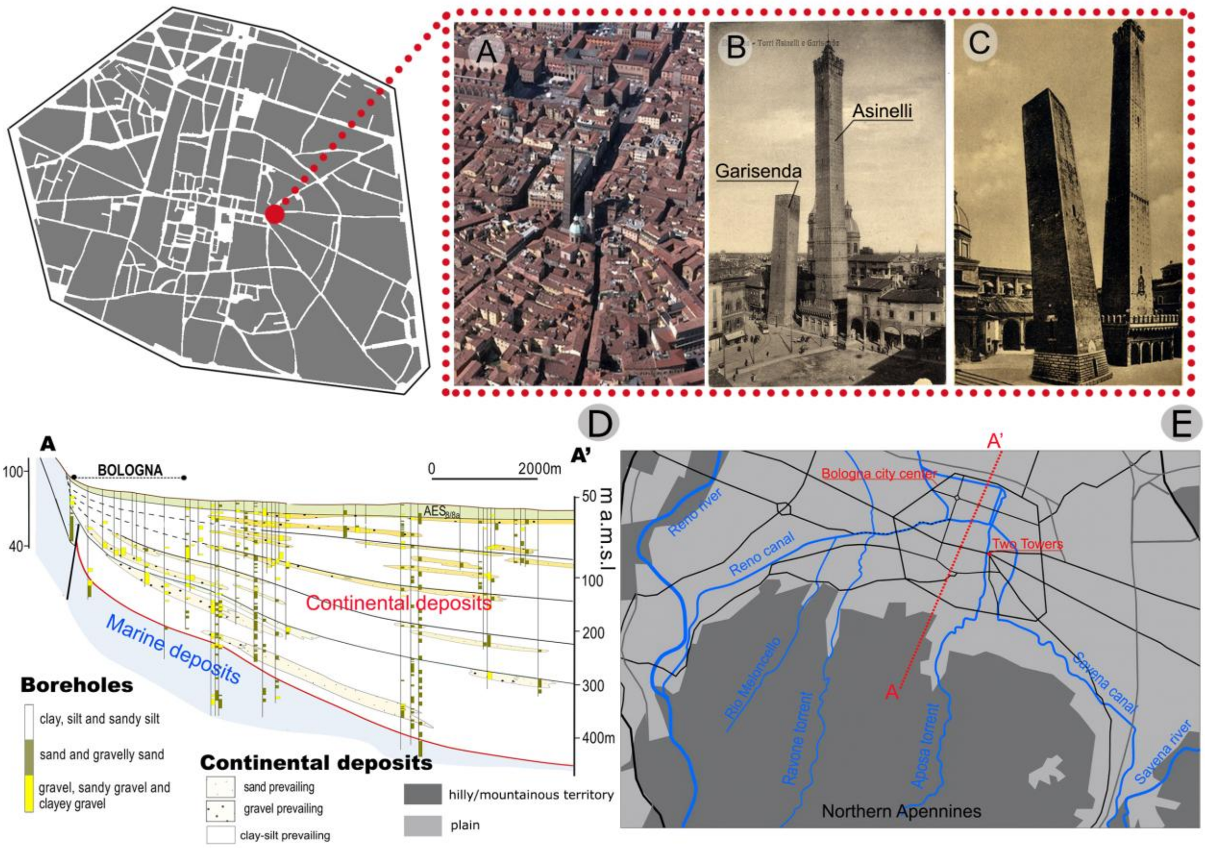

Figure 1. *The Two Towers located in the heart of the medieval city of Bologna (Italy): a recent aerial photo (image A) and two historical photos (images B and C).Geological and hydraulic setting of the study area: stratigraphic cross-section AA’ showing the late Quaternary stratigraphy beneath the city (image D, modified from Giacomelli et al. (2023)); schematic visualization of the hydraulic system that originated the deposits (image E).*

The Garisenda tower has a square base with sides measuring 7.4 m at ground level. Originally about 60 m high, it was shortened by about 12 m between 1350 and 1353 at the request of the municipal government, which feared the increasing inclination of the structure. At present, the tower exhibits a lean of 3.32 m toward the south-east, corresponding to an inclination of 3.914° eastward and 0.665° southward (Bertolini et al., 2022a). Structurally, the tower rests on a conglomerate foundation block measuring approximately 8.75 m in width and 3.30 m in height, with the founding plane located about 5.5 m below ground level (Marchi et al., 2022). Above the foundation lies a selenite base, 4.8 m high, made of the gypsum stone widely employed in traditional Bolognese masonry and quarried locally. The base was built "*a sacco*", with two external selenite facings and an internal core composed of mixed materials and mortar. The original base is no longer visible: due to its poor state of preservation, it was enclosed within an additional selenite cladding at the beginning of the 20th century by the municipality of Bologna.

The Asinelli tower was most likely built after the Garisenda, partially replicating its geometry. Like the Garisenda, the Asinelli initially reached a height of about 60 m, but it was constructed on a larger foundation, approximately 10.45 m wide and 4.70 m high with a founding plane located at 6.7 m from the ground level (Marchi et al., 2022). This design choice was probably influenced by the early detection of the Garisenda's tilt, which became apparent soon after its construction (Marchi et al., 2017).
Around 1250, the Asinelli tower was raised to its current height of 97.2 m. It is believed that the Asinelli tower was constructed more gradually than Garisenda. Geometric analysis reveals the presence of three main construction blocks. Each block displays a different inclination, indicating that medieval builders attempted to correct the existing tilt during successive heightening. The result is the tower's characteristic slightly curved, or "banana-shaped", profile. The current average inclination of the tower's axis—calculated as the mean of the tilts of the three above-ground sections—is approximately 1.5° westward (Bertolini et al., 2022a).

The city of Bologna lies in the transitional zone between the Northern Apennines thrust-and-fold belt and the Po Plain foreland basin, representing one of the most complex geological settings in northern Italy. The basin is filled with Neogene to Quaternary continental deposits mainly of fluvial origin, derived from erosion of the Apennines and progressive transportation of the sediments into the plain (Figure 1D). The architecture of these deposits shows pronounced lateral variability in lithology and grain size, reflecting the combined influence of Reno and Savena paleo-channel migration (Figure 1E) and the buried Apennine fold-and-thrust structures extending beneath the Po Plain, controlling subsidence and the geometry of the stratigraphic succession (Giacomelli et al., 2023).

In particular, the investigated area beneath the Two Towers is located within the triangle-shaped interfluvial zone between Reno and Savena river outlets. The sediments characterizing this area were deposited by the activity of several minor streams originating from the Apennines, such as the Meloncello, Ravone, and Aposa, all of which are characterized by a torrential regime and low sediment transport capacity (Figure 1E).Looking more closely at the shallow Quaternary succession beneath Bologna, is revealed a complex alternation of fluvial aggradation phases and pedogenic stability intervals (Figure 1D). These have been extensively documented through the identification of paleosols — fossil ancient topsoils that mark periods of landscape stability, reduced sedimentation, and post-depositional modification of sediments through soil-forming processes (Bruno et al., 2020).

Detailed stratigraphic and sedimentological analyses by Amorosi et al. (2014) and Bruno et al. (2022) demonstrated that these paleosols are laterally continuous and represent key stratigraphic markers across the southern Po Plain. From a geotechnical perspective, these horizons exhibit increased strength and stiffness and are often associated with higher (apparent) overconsolidation ratio compared to non-pedogenized alluvial deposits, as evidenced by in-situ investigations (Bertolini et al., 2022b; Marchi et al., 2026).

THE CENTURY OF THE INVESTIGATION CAMPAIGNS

The Garisenda tower's pronounced inclination has prompted systematic investigations since the early 20th century. Initial surveys in 1902 provided accurate measurements of tower geometry and tilt. Between 1990 and 1996, topographic and photogrammetric campaigns refined the assessment of Garisenda's geometry, out-of-plumb conditions, and crack pattern (Bertolini et al., 2022a).
The first investigation campaign aimed at characterising the foundation soil of the Two Towers was conducted between 1973 and 1975. It included twelve continuous-core boreholes with undisturbed

sample collection. Some of these boreholes were drilled at various distances from the Asinelli Tower to investigate the foundation geometry and materials. The first piezometric monitoring system was installed during this campaign down to 40 m (Figure 2A).
In 1995, an additional set of five continuous-core boreholes and four cone penetration tests with pore pressure measurements (CPTu) was carried out. Moreover, the number of installed piezometers in the square around the towers was increased from three to six. Later, in July 2000, a new set of vertical and inclined boreholes provided the first direct data on the geometry and materials of the Garisenda foundation, which had previously been unknown (Figure 2A) (Marchi et al., 2019).

The most extensive investigation campaign took place between May and August 2016. It included six CPTu, one downhole test, three vertical continuous-core boreholes reaching depths of 20, 40, and 100 m, two inclined boreholes intercepting the Asinelli foundation up to 12 m, and three vertical boreholes penetrating the Garisenda foundation down to 15.5 m. Additional tests included three dilatometer tests (DMT). The monitoring system was also expanded through the installation of four piezometers, measuring pore water pressure down to 100 m, and three deep settlement gauges placed beneath the Garisenda foundation to monitor differential settlements (Bertolini et al., 2022a). Subsequent investigations conducted in 2021 included eight continuous-core boreholes reaching depths up to 10 m, and two piezometers were installed at depths of 8 and 10 m (Figure 2A).

Focusing on the structural investigation campaigns of the Garisenda tower—currently the structure most affected by stability issues—the first diagnostic investigations date back to 1998–1999. These investigations involved a comprehensive structural assessment, including coring, endoscopic inspections, mechanical testing, and chemical and physical analyses of the masonry materials, allowing the extent of material degradation to be evaluated, the stress state to be estimated, and the mechanical properties of the structure to be assessed. The investigations led to the implementation of several remedial measures in 1998, including masonry consolidation through the replacement of weathered bricks and mortar injections, as well as the installation of a steel frame to improve the connection between the two leaves of the rubble masonry wall. Between 1999 and 2001, additional tie rods were installed, followed by a thin external steel belt at the base plinth level (Andreon et al., 2011).

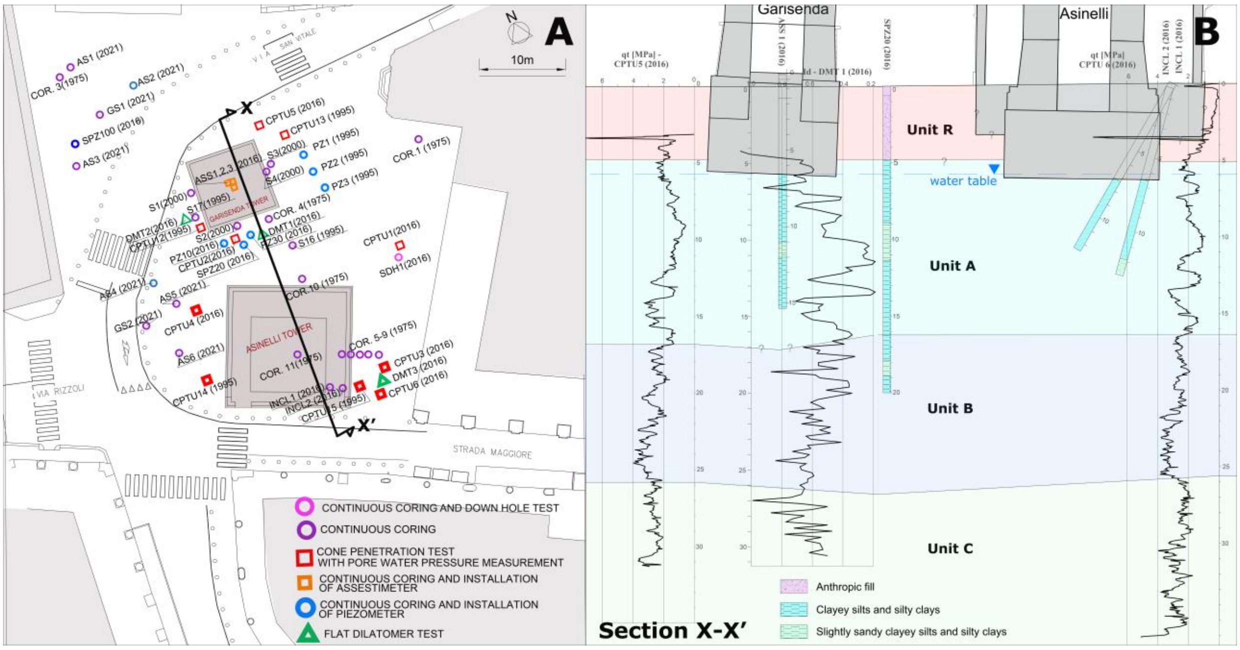

Figure 2. *A) Plan view of Ravegnana Square with the location of the geotechnical in situ tests and the monitoring devices installed at various stages of past geotechnical investigation campaigns. B) Stratigraphic cross-section of the subsoil beneath the Two Towers.*

In 2008, two external steel belts were installed above the tower base to provide additional confinement to the masonry (Figure 3A). No interventions were carried out on the selenite foundation until more recent times, when the observation of a swelling of the selenite cladding on the eastern side—corresponding to the direction of maximum inclination—raised concern about the conservation state of the material and the stress levels reached in this portion of the basement (Figure 3E). Mineralogical and crystallographic analyses showed that the selenite blocks forming the basement of the tower had been altered by exposure to high temperatures during major fires that occurred at the end of the 14th and 17th centuries. The basement cladding was rebuilt using new selenite blocks for both protective and aesthetic reasons, and a recess was cut into the original basement along the entire perimeter of the tower to anchor the new elements (Dallavalle et al., 2022).

In light of these findings, between 2019 and 2021, several reinforcement measures were implemented at the Garisenda basement. These included a permanent passive confinement system consisting of composite fabric bands inserted into the horizontal joints of the selenite cladding (Figure 3B), a permanent active confinement system with steel rods tensioned at the tower corners (Figure 3C), and a temporary active confinement system using tensioned funicular cables positioned at the mid-sides of the tower, with wooden spacers placed between the selenite cladding and the cables (Figure 3D) (Dallavalle et al., 2022).

Figure 3: *A) Perimeter belts confining the masonry wall; B) Passive confinement of the tower basement obtained through FRCM belting along horizontal joints of the selenite cladding, C) Active confinement of the tower corners by insertion of post tensioned stainless steel bars and corner stainless steel plates; D) Active confinement of the cladding through a funicular belting of the tower base. E) Bowing of the east side of the selenite cladding. Photos from A to D modified from de Miranda et al. (2025), photo E from Dallavalle et al. (2022).*

GEOTECHNICAL MODEL OF DEPOSIT BENEATH THE TWO TOWERS

The study of the soil cores extracted from continuous coring boreholes shows that the succession consists almost entirely of silty clays and clayey silts, highly interbedded with each other down to great depths (Figure 2B). The 100 m-deep borehole carried out in 2016 (SPZ100 in Figure 2A) encountered only two very thin gravelly layers (at 94.5 m and 97 m), interpreted as distal fan gravels. The main

textural variation with depth lies in the pattern of alternation between the more clay-rich and more silt-rich layers.
Although the deposits are homogeneous from a lithological point of view, the interpretation of in-situ tests indicates that the mechanical behaviour of the subsoil is both laterally and vertically heterogeneous. This heterogeneity can be attributed to the presence of numerous interbedded paleosols that interrupt the regular floodplain succession. Recent studies have shown that the mechanical properties vary not only between different paleosols—depending on the duration of surface exposure—but also laterally within the same paleosol. Such horizontal variability reflects local environmental, climatic, and geomorphological conditions, which may change even within an area comparable to the footprint of a tower. This variability could have significantly influenced the ground response under loading and may represent one of the causes of the Garisenda's initial tilting (Bertolini et al., 2022a).

Based on the interpretation of CPTu data following the Soil Behaviour Type (SBT) approach proposed by Robertson (2009), the deposit was subdivided into four main units (Marchi et al., 2026):

- **Unit R** (0–4.5 m below ground surface) – Anthropigenic fill, typically composed of a complex alternation of soils with variable grain size (clayey, silty–clayey, locally sandy or silty–sandy) and characterized by dark coloration. It often contains archaeological remains and carbonaceous traces.
- **Unit A** (4.5–16 m) – Fine-grained soils, consisting of alternations of ochre-light brown silty clays and clayey silts. Site data show a high dispersion of parameters describing strength and stress history, reflecting the dense interbedding of paleosols.
- **Unit B** (16–25.3 m) – Fine-grained soils, again composed of interbedded silty clays and clayey silts, but exhibiting less variability in geotechnical parameters compared to Unit A, as a consequence of a more limited and spatially uniform influence of post-depositional processes.
- **Unit C** (25.3–28 m; maximum investigated depth) – Normally consolidated soils, characterized by low variability in soil properties and lower mechanical parameters compared with the overlying units.

Piezometric monitoring system reveals that the shallow phreatic level lies at approximately 5.6 m below the ground surface, maintaining hydrostatic conditions down to about 30 m depth. Between 30 m and 100 m, a limited downward seepage is observed (Bertolini et al., 2022a).

NUMERICAL MODELLING OF THE SOIL-FOUNDATION INTERACTION

A numerical model of the soil–structure interaction of the Two Towers was developed using the commercial finite element (FE) code Plaxis 3D. Given the close proximity of the towers, the model explicitly accounts for the mutual influence of both structures on the stress transfer induced in the ground by their loadings. The main objective of the model was to reproduce the stress state generated in the soil by the towers in their current configuration.

A linear-elastic constitutive model was adopted for this purpose. This model is not intended to reconstruct the historical displacements of the towers through back-analysis, nor to predict their future movements — such goals would require more advanced soil constitutive models and data that are currently unavailable. Nevertheless, the model represents a solid starting point for future numerical developments and supports the design of the stabilisation measures for the Garisenda tower.

The computational domain consists of a soil prism measuring 35 m (z-axis) x 79 m (x-axis) x 98 m (y-axis). The vertical boundaries were positioned at a distance of approximately 35 m from the centre of each tower, corresponding to about three times the foundation width, so as to minimise boundary effects while controlling computational effort. The soil deposit was subdivided into the four stratigraphic units described in the previous section (Figure 4A), and Table 1 reports the linear-elastic parameters adopted for each unit. The Young's modulus, E, was estimated from the oedometer modulus, M, which was calculated from the loading cycle corresponding to the expected stress state.

The local stratigraphy was incorporated into the numerical model using the Boreholes function of Plaxis 3D, which interpolates the stratigraphic profiles defined at the investigation points corresponding to the in-situ tests carried out during the 2016 campaign. This campaign was selected because it provided the most comprehensive coverage of the entire study area and complied with current technical recommendations. Both towers were idealised as rigid prismatic blocks, with base dimensions corresponding to their foundation footprints (8.75 m for Garisenda and 10.45 m for Asinelli). Each block was assigned a concentrated load at its centroid, corresponding to the mass of the foundation and the selenite basement (1,149 t for Garisenda and 1,596 t for Asinelli). The towers were modelled by an additional vertical point load applied at the projection of the superstructure's centre of gravity onto the foundation, according to the actual tower inclinations, with masses of 6,252 t and 3,471 t, for the Asinelli and Garisenda towers, respectively.

Table 1. *Parameters of the linear–elastic model adopted in the numerical analysis. M is the oedometric modulus, v the Poisson ratio, E the Young modulus and γ_{sat} the saturated unit weight of the soil.*

	M [MPa]	v [-]	E [MPa]	γ_{sat} [kN/m^3]
Unit R	5	0.3	3.714	19.26
Unit A	20	0.3	14.857	19.40
Unit B	26	0.3	19.314	19.04
Unit C	16	0.3	11.886	19.69

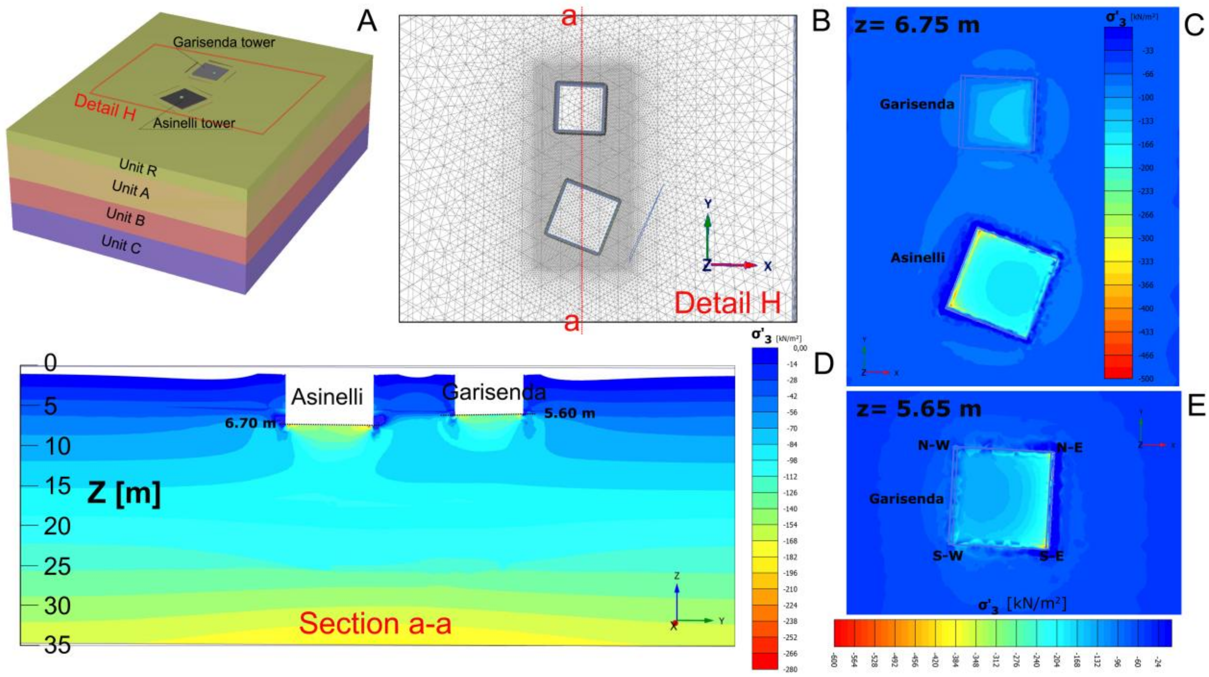

Figure 4. A) Three-dimensional geometry of the Two Towers foundations and of the underlying subsoil; B) Detail of the FE mesh adopted in the 3D numerical model; C and E) Horizontal cross-sections of effective vertical stress at z=5.65 m and 6.75 m from ground level. D) Distribution of effective vertical stress along section a-a.

A frictionless interface was introduced between the foundation base and the soil, allowing possible detachment at the contact surface. The pore-water pressure regime was assumed to be hydrostatic, with a phreatic level at 5.6 m below the ground surface. The model was discretised using a FE mesh consisting of 10-noded tetrahedral elements, with average element size of 1.2 m. The mesh was locally refined to 0.05 m beneath the foundations to improve numerical accuracy and resolution (Figure 4B).

Since an elastic constitutive model was adopted for the soil, the actual load sequence is negligible. The model was developed following an iterative strategy aimed at reproducing the actual geometrical configuration of the two towers. This strategy was implemented in six steps as follows:

- Step 1: Generation of the initial geostatic stress field;
- Step 2: Initial configuration with vertical towers and horizontal foundation planes. Application of the loads from the foundation blocks and the tower superstructure. The latter applied in the projection of the centre of gravity of the superstructures on the foundation planes.

- Step 3: Since the elastic deformations induced by soil loading were not able to reproduce the current inclinations of the towers, the initial tower configurations were modified introducing an initial inclination to foundation planes. This is obtained by imposing displacements at the four corners equal to the current observed settlements minus the elastic settlements generated by the load application in Step 2.
- Step 4: Application of loads as in Step 2 to the (new) initial tower configurations developed in the previous step.
- Step 5: A further modification to the initial configuration of both foundations is introduced to correctly adjust the position of the foundation planes relative to the ground level. The average elastic vertical displacements of foundation centres of gravities, obtained in Step 4, is used to set the new founding depth, as the current distances from ground level minus the computed elastic vertical deformations.
- Step 6: Application of loads as in Step 2 to the (new) initial configuration of foundations developed in Step 5. The resulting stress state refers to the current configurations of the foundation systems, in terms of load, inclination and depth.

The stress distribution beneath both foundations resulting from the final simulation shows no significant tensile zones, except for a very thin layer of material at the Asinelli foundation-soil interface at the two lesser-loaded corners. The highest compressive stresses were observed beneath the Garisenda tower, reaching approximately 570 kPa of effective vertical stress near the south-eastern corner, corresponding to the deepest edge of the footing (Figure 4E). These stresses decrease with depth, reducing to about 140 kPa at 1 m and 80 kPa at 2 m below this corner. Beneath the Asinelli tower, maximum compressive stresses were recorded near the north-western corner, where they reached approximately 470 kPa (Figure 4C). At the same location, stresses decrease to around 100 kPa at 1 m and 70 kPa at 2 m below the footing.

At these stress levels, local yielding of the soil is likely to occur, leading to limited stress redistribution in the surrounding zones. Employing an elasto-plastic constitutive model would allow for a more realistic simulation of the soil–structure interaction. Likewise, the total settlements computed with the purely elastic model—equal to 0.23 m and 0.22 m beneath Asinelli and Garisenda, respectively—represent a lower-bound estimate of the actual displacements expected with a more advanced soil model. Further confirmation comes from on-site observations. In fact, a previous study by Marchi et al. (2026) estimated, based on the bending of the buried paleosol horizons beneath the foundations, cumulative settlements of approximately 1.4 m for Asinelli and 1.2 m for Garisenda, from construction to the present day. The cross-section shown in Figure 4D highlights the interaction between the two stress bulbs, which fully develop within the upper 30 m of the subsoil; below this depth, both stress variation and settlement become negligible.

CONCLUSIONS

The study presented the results of the geotechnical characterisation and three-dimensional numerical modelling of the soil–foundation system of the Two Towers in Bologna (Italy). The integration of extensive in-situ and laboratory investigations enabled the reconstruction of a detailed geotechnical model of the subsoil, revealing a complex alternation of fine-grained alluvial deposits with interbedded stiffer paleosol horizons. Finite Element analyses performed using the Plaxis code reproduced the stress distribution beneath the two foundations, highlighting the strong interaction between the stress bulbs of the towers. The results confirmed higher stress concentrations beneath the Garisenda tower and lower, yet still significant, stresses beneath Asinelli, consistent with their different geometries and inclinations. Although the adopted linear–elastic soil model represents a simplification, it provides a valuable insight into the current stress state and serves as a robust preliminary framework for future analyses. Further developments will include elasto-plastic constitutive models and parameter calibration based on monitoring data to predict settlements and assess the long-term stability of both towers. Overall, the study provides an essential geotechnical basis for the ongoing design of stabilisation measures for the Garisenda tower and contributes to a broader understanding of soil–structure interaction in historic leaning towers founded on heterogeneous alluvial deposits.

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