Geotechnical Investigations and Monitoring of the Archaeological Site of Santa Croce in Ravenna (Italy)

Published Version:
Marchi, M., Bertolini, I., Gottardi, G. (2023). Geotechnical Investigations and Monitoring of the Archaeological Site of Santa Croce in Ravenna (Italy). Cham : Springer Series in Geomechanics and Geoengineering [10.1007/978-3-031-34761-0_65].

Availability:
This version is available at: https://hdl.handle.net/11585/957919 since: 2024-02-14

Published:
DOI: http://doi.org/10.1007/978-3-031-34761-0_65

Geotechnical investigations and monitoring of the Archaeological Site of Santa Croce in Ravenna (Italy)

Michela Marchi[1*[0000-0001-6944-8856]] Ilaria Bertolini[1[0000-0002-8891-045X]]

and Guido Gottardi[1[0000-0003-4944-8212]]

[1] Alma Mater Studiorum, Università di Bologna, DICAM Department, viale del Risorgimento 2, 40136 Bologna, Italy
michela.marchi@unibo.it

Abstract. The city of Ravenna, in northern Italy, is worldwide famous for the well-preserved late Roman and Byzantine architectures characterized by fabulous mosaics that have earned the UNESCO World Heritage status. The constantly growing attention towards their conservation has promoted research activities that focus on the effect of the considerable cumulated land subsidence on their current conditions. Today, the sum of long-lasting natural and more recent anthropogenic subsidence has brought the level of such ancient archaeological sites and monuments well below the current position of the phreatic water table, still close to the current ground surface of the city centre, as it is the case of the Santa Croce church and its archeologic area. The Church, dating back to the 5th Century AD, is surrounded by ancient Roman floor mosaics, located ~3.2 m from the main street level. In this site, a pumping system must permanently operate to lift to the external sewage network the water collected from the local subsoil by means of a rather old and no longer efficient drainage system. A geotechnical investigation campaign was carried out in 2022, together with the installation of a new piezometric monitoring system, with the aim of investigating the shallow aquifers underneath the monuments. Relevant data interpretation will enable to better understand the current situation and, above all, to devise a proper solution which can combine the long-term conservation of the area with its usability.

Keywords: Land Subsidence, Dewatering, Shallow Aquifers, Preservation, Santa Croce in Ravenna.

1 INTRODUCTION

The city of Ravenna is located in northern Italy, few kilometers far from the Adriatic Sea (Fig. 1B) and ~60 km from the Po river delta. It is well-known for its precious mosaics preserved inside the eight Early Christian Monuments, which are included in the UNESCO World Heritage List. The city has been always affected by the land subsidence phenomenon of both natural and anthropic origin. A significant deterioration to the urban as well as to the natural environments became evident since the late ‘70s. In the city centre, the crypt of monumental churches, such S. Francesco’s, and the basement of old buildings were permanently flooded. The same problem affects the excavated archaeological area of Santa Croce (see Fig.s 1C and 1D), which belongs to the buffer zone of the UNESCO world heritage site of Galla Placidia Mausoleum and San Vitale Basilica (see Fig. 1A). The configuration of this site, an excavated area up to 4 m deep from the surrounding ground level and about 2 m below the current groundwater level, requires continuous dewatering by means of a drainage system, in order to avoid the immediate flooding of the whole area. This condition is the result of the cumulated land subsidence and no doubt represents an emblematic case study of related cultural heritage preservation. The paper describes the investigations and the preliminary studies recently carried out to identify the local stratigraphy and soil properties, the original conception of the existing drainage system and the emerging critical issues produced by the continuous dewatering process.

Fig. 1. A) Aerial view of the Monumental area of S. Vitale-Galla Placidia (on the left) and of the Archaeological area of Santa Croce (on the right). B) Location of Ravenna in northern Italy. C and D) Photos of the Santa Croce Church and of the archaeological excavations around it.

2 LAND SUBSIDENCE IN THE RAVENNA AREA

[1], [2], [3] among others, have investigated the evolution of the land subsidence of the Ravenna area in conjunction with the relevant causes, by means of precision levelling of a network of benchmarks scattered throughout the territory, collecting data spanning from 1897 to 2002. The land settlement in the Ravenna city centre passed from ~5.5 mm/year in the period 1900-1957 [2] to ~80 mm/year between 1972-73, when the peak was recorded [1]. The causes of the settlement increase registered from the ’50 have been ascribed primarily to groundwater pumping for industrial and civil uses (the latter resulting the prevailing in the city centre), and, to a lesser extent, to gas extractions. The greater settlement rates have been observed in the industrial district of Ravenna, where values touched 110 mm/year between 1972-73. The archaeological area of Santa Croce experienced experienced ~1.3 m of land subsidence in the period 1897-2002 [3]. To understand the relevance of the anthropic component with respect to the total settlement, the entity of the natural land subsidence component should be also estimated. To this scope, the data reported in [4] can be used. They provide and estimation of about

1.2 mm/year over the last 2500 years for the Holocene era, which correspond to ~0.10 m of natural subsidence in the period 1897-2002. This value is particularly high, near to the maximum values recorded in the eastern Po river Plain, due to the local higher thickness of Pleistocene sediments (>2500 m).

Corrective actions were undertaken by the Italian government starting in the ’70s in order to face the emergency. In the Ravenna area, the construction of a new industrial aqueduct (late ’70s) and the activation of the Ridracoli public aqueduct (at the end of the ’80s) greatly reduced the water demand [3]. The consequent drastic reduction of groundwater withdrawal generated an extensive pore water pressure (pwp) recovery in the artesian aquifer system underneath the Ravenna city centre, reducing the settlement rate to ~1.3 mm/y in the period 1998-2002, a value close to the natural subsidence rate reported by [4]. The positive trend observed at the beginning of the 21st century has been confirmed by more recent data [5]. Despite that, the relative distance between the groundwater table and the ground level has been irreversibly reduced, and, at present, its consequences must be faced.

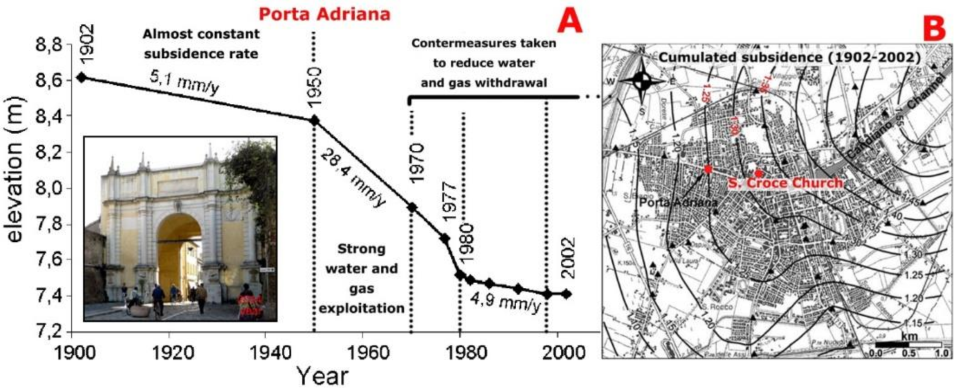

Fig. 2. A) Elevation in time of a benchmark located in Porta Adriana (200 m distant from Santa Croce) (modified from [4]). B) Cumulated land subsidence in the historic centre of Ravenna (in meters) in the period between 1902-2002 (modified from [3]).

3 THE CASE STUDY OF SANTA CROCE

Ravenna is located on the ridge of an ancient beach of Etruscan Age formed by the deposits of the ancient Po river delta, and located below another ridge of more recent Roman age [3]. These littoral sandy deposits of Holocene origin are about 20 m deep from the ground surface and they constitute the geologic Unit A. Geologic Unit B is constituted by a 400 m thick alluvial deposit of the Upper Pleistocene, characterized by a succession of sandy and loamy fresh water aquifers separated by clayey and silty-clayey aquitards (thickness ratio between aquifers and aquitards 1:1). Geologic Unit C is constituted by a continuous marine sequence of the Plio-Pleistocene, whose inferior border is found in the Ravenna area at ~2.6 km from the surface, symptom of a high tectonic subsidence [4]. The settlements of anthropic origin in the Ravenna area are mainly due to water withdrawal and they are confined within the Unit B, settlements caused by gas exploitation have a minor role and are instead confined within the Plio-Pleistocene marine deposits [4].

The archaeological site of Santa Croce is characterized by the remains of an old Roman domus dating 2nd – 3rd century A.D., whose mosaics have been found and preserved onsite, and of a 5th century A.D. Placidian Church, profoundly modified up to the 7th century A.D [6]. Today the Church shows the same configuration inherited from the 17th century, but excavations and restorations carried out between the 19th and the 20th century A.D. have brought to light the stratification of the archaeological remains. The excavations have reached a depth of ~2 m below the mean sea level, corresponding to the Roman remains, while the level of the street is at ~1.5 m above: then, the depth of the Roman ground level with respect to the current one is greater than 3.5 m [6]. The excavations have been left open to appreciate the peculiar archaeological stratification and to admire the beautiful Roman mosaics from Galla Placidia street (Fig. 3A).

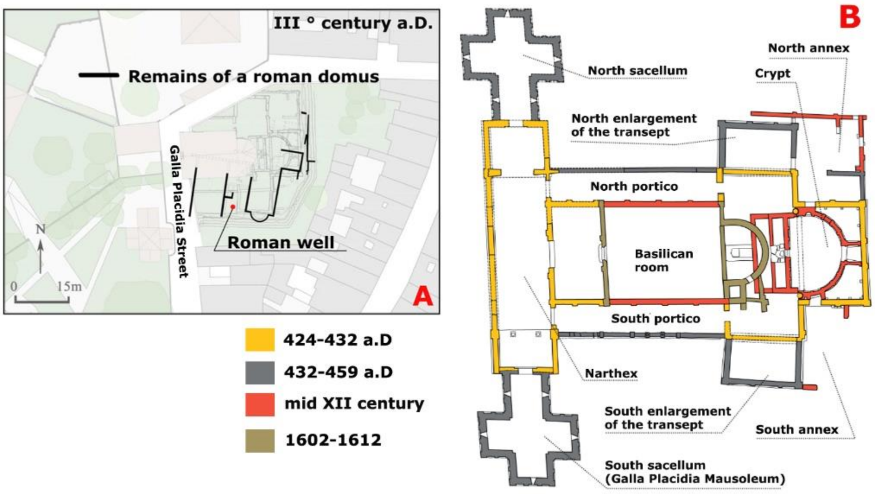

Fig. 3. A) Plan of the Archaeological site of Santa Croce, showing the remains of the Roman domus (II-III century A.D). B) Representation using different colors of the construction phases of the Santa Croce church (from ~400 to ~1600 A.D) (modified from [6]).

4 THE DRAINAGE SYSTEM OPERATING IN THE AREA

In the early ‘70s, a temporary drainage system was built to keep the archaeological excavations dry (Fig. 4C). Subsequently, in 1979, a permanent drainage system was built at the foot of the slope, along two sides of the excavated perimeter. The system, schematically represented in Fig. 4A, consists of perforated tubes connecting three wells (P1, P2 and C1). The water flows from P1 to C1; in the latter two submerged pumps lift the water into the public sewer of the higher street (Fig 4A). In 1984 a concrete tank was added to the system for the collection of the drainage waters and the pumps (see Fig. 4B). At present, the system suffers the lack of maintenance, is locally obstructed and water mainly runs at the ground surface eroding soil particles. Consequent severe differential settlements in the archeological remains of the area around the well C1 are evident, together with clear signs of instability in the close-by slope (see Fig 5A). In recent years (2002, 2016, 2019, 2021), the archaeological area of Santa Croce was flooded due to sudden breaks down of both pumps. In these occasions, the water table raised to its "undisturbed" level (about 0.03 m below the mean sea level), entirely covering the archaeological remains and causing a dramatic proliferation of aquatic vegetation on the remains (see Fig 5B).

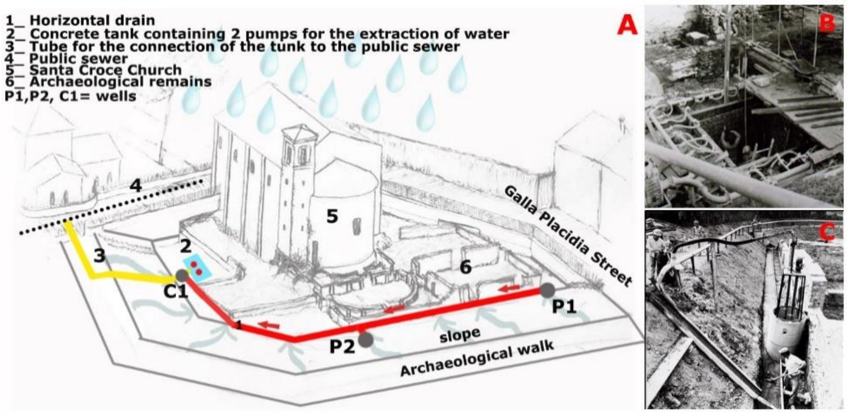

Fig. 4. A) Schematic representation of the drainage system in use in the archaeological site. B) Old photo dated 10/1984 showing a phase of the realization of the concrete tank for the collection of the drained water [AFSRA NEG. N. 63167]. C) Old photo dated 9/1979 showing the temporary drainage system and the excavation of the permanent one at the foot of the soil slope [AFSRA NEG. N. 34901].

Fig. 5. A) Evidences of the ground settlements and of the slope instability in close proximity of the tank. B) View of the archaeological site entirely flooded during the pump break down in August 2021.

5 GEOTECHNICAL INVESTIGATIONS

The definition of a detailed geotechnical model of the site is an essential step in the process of devising the preservation strategy of historic buildings [7]. In 2022, the subsoil underneath the archaeological site of Santa Croce was investigated by two continuous coring boreholes (S2 and S3), 2 cone penetration tests (CPTu), one seismic piezocone test (SCPTU1), one dilatometer test (DMT1), several SPT and Lefranc tests. Boreholes S2 and S3 were carried out up to a depth of 36 m and 13 m from the local ground level (~Galla Placidia Street), respectively; CPTU1, CPTU2 and CPTU3 to 30 m, 31 m and 17 m, while DMT1 to 20.6 m. In 1983, a previous extensive geotechnical investigation campaign had been carried out [8] (Fig. 6 Left), even if more focused on the near monumental area of San Vitale and Galla Placidia. The soil profile deduced from the investigations is shown in Fig. 6 (Right). The local stratigraphy is characterized by an anthropic unit, ~5 m thick, rich in archaeological remains (Unit R) belonging to geologic Unit A (alluvial deposit, Holocene era) and constituted mainly by sandy-silt mixtures. The natural water content is close to the Plastic Limit, symptom of a hard soil subjected in the past to superficial desiccation [8]. Traces of oxidation are compatible with the exposure to atmospheric conditions. Unit 1, below Unit R, is characterized by a clayey sand layer up to ~22 m of depth from the ground level, corresponding to geologic Unit A. The average coefficient of saturated permeability of this unit is ~4.6×10^{-6} m/s as estimated from CPT tests [9] of the 2022 campaign and confirmed by subsequent permeability tests carried out in triaxial cell. Unit 2, underneath Unit 1, is constituted by a low to high plasticity clayey, silty-clay material of olive-brown or dark brown color.

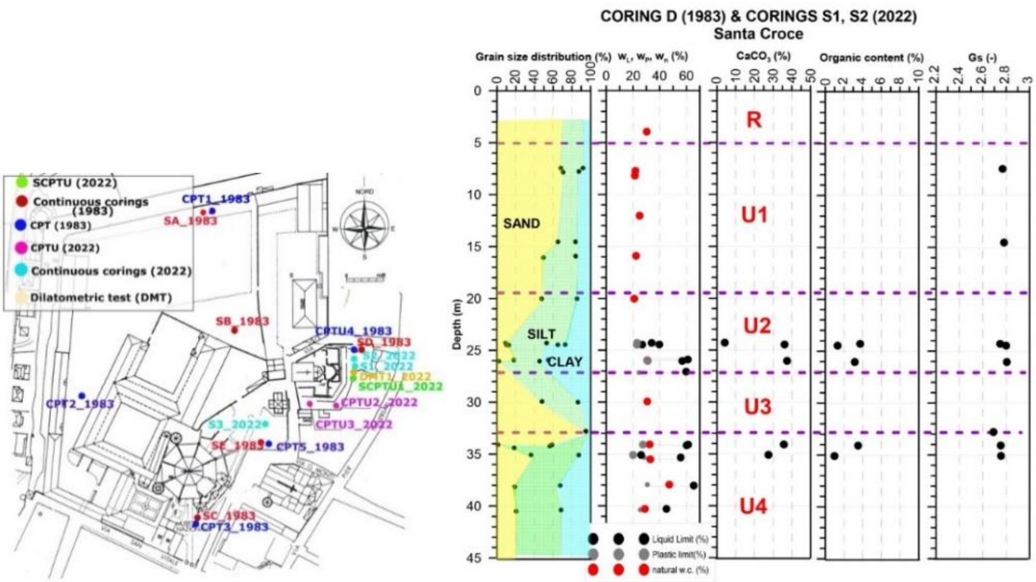

Fig. 6. Left: Plan of the field investigations performed in 1983 and 2022. Right: Soil profile including information on the physical characteristics of the units.

This unit is the first aquitard of geologic Unit B with an average coefficient of saturated permeability equal to ~3.3*10^{-9} m/s. Its thickness varies between 3.3 and 6.1 m (average 5.1 m). Below Unit 2, an alternation of grey sands and silty sands, corresponding to the first aquifer of Geologic Unit B, can be observed (Unit 3). The average thickness of this layer is ~5.7 m. This sandy formation has a coefficient of saturated permeability of 2.2*10^{-6} m/s as estimated from CPT tests. Below Unit 3, a silty clay layer of grey-green color is observable (Unit 4) which consists of fine-grained mixtures of the same nature of Unit 2 (the average coefficient of permeability of this Unit cannot be estimated from CPT tests that had to stop above). The lower boundary of Unit 4 was reached only in borehole S2 (geotechnical campaign 2022) and it was found at a depth of -35.5 m from the ground level.

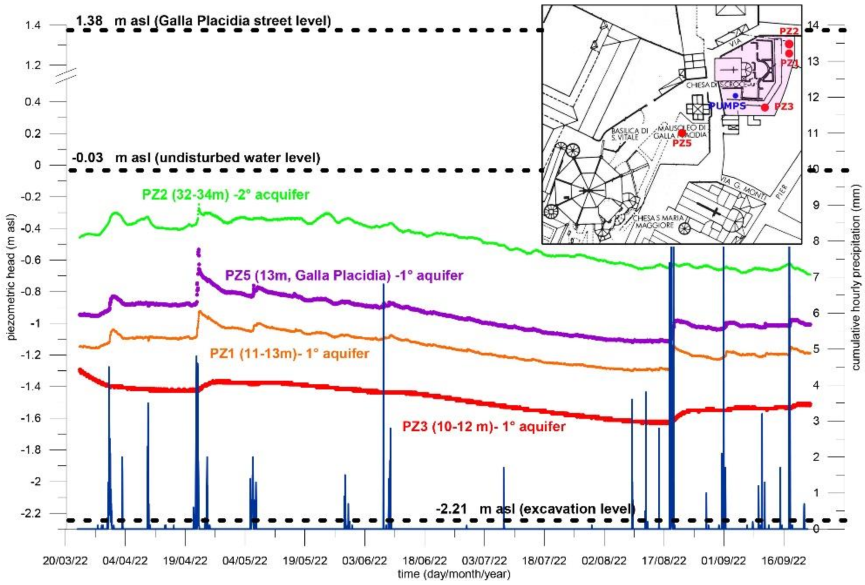

Fig. 7. Trend of the piezometric head (right) and cumulated precipitation data (left) vs. time, monitored in the area of S. Croce-Galla Placidia (time interval: ~6 months). On the top right, plan with location of the instruments.

During the 2022 campaign, open standpipe piezometers were installed in the Archaeological area of Santa Croce and in the Monumental Area of San Vitale-Galla Placidia. All of them have been equipped with pressure transducers and datalogger, for the real-time monitoring of the pwp regime in the aquifer system. PZ1, PZ3 and PZ5 are placed in the first aquifer, while PZ2 in the second (deeper) aquifer. The collected data show that the shallow aquifer is particularly sensitive to local precipitations (Fig.7). In proximity to the drainage system there is a remarkable drawdown in the pwp of Unit 1 (1° aquifer), which enables the area to be kept dry. The highest reduction in pore pressure is recorded by PZ3, consistently with its position closer to the pumps. Also, PZ5 appears to be affected by the withdrawal, but to a lesser extent, being outside the area of the drainage system. The hydraulic head in Unit 3 (2nd aquifer monitored from PZ2) tends to the undisturbed water level (black dashed line in Fig. 7), providing evidence of an upward seepage flow from Unit 3 to Unit1.

6 CONCLUSIONS

The paper describes some preliminary findings from the case study of the Archaeological Area of Santa Croce, located in the centre of Ravenna, historically subjected to critical issues connected to a significant phenomenon of land subsidence, remarkably worsened in the last decades due to anthropic causes. The new data obtained from a most recent geotechnical investigation campaign have been integrated with those coming from an extensive previous one carried out with the main aim of preserving the nearby monumental area of San Vitale and Galla Placidia (UNESCO World Heritage Site) in the '80s. The definition of a detailed soil profile and of the pore water pressure regime in the aquifer system is the first step for understanding the local hydrogeology affecting the excavation area and for subsequently devising the best strategy for the preservation of the site and for the future fruition of the whole complex.

Acknowledgments

This research has received funding from the EU Horizon2020 under grant agreement n° 821282 (SHELTER)

References

1. Carbognin, L., Gatto, P., Mozzi, G., Gambolati, G.: Land subsidence of Ravenna and its similarities with the Venice case. In: Proc. International Conference on Evaluation and Prediction of Subsidence, pp. 254–266, Saxena S.K. (ed), Florida, USA (1978).
2. Salvioni, G.:1 movimenti del suolo nell'Italia centro-settentrionale, Bollettino di Geodesia e Scienze Affini, I.G.M., anno XVI, Firenze (1957).
3. Teatini, P., Ferronato, M., Gambolati, G., Bertoni, W., Gonella, M.: A century of land subsidence in Ravenna, Italy. Environ. Geol. 47, 831–846 (2005).
4. Bertoni, W., Elmi, C., Marabini, F.: The subsidence of Ravenna. Giornale di Geologia Applicata 1, 23-32 (2005).
5. Bertolini, I., Marchi, M., Gottardi, G.: Heritage Learning from a well-documented geotechnical cold case: The Two Towers of Bologna. Intern. J. of Architectural Heritage (2022).
6. Bitelli, G., Bonsignore, F., Del Conte, S. et al.: Updating the subsidence map of Emilia Romagna region (Italy) by Integration of SAR interferometry and GNSS time series: the 2011-2016 period. In: Proceedings of IAHS, 32,39-44, Copernicus Publications (2020).
7. Cassanelli, R., Cirelli, E., Crociati, E., Civiletti, J.P. et al. La Basilica di Santa Croce: nuovi contributi per Ravenna tardo-antica. Curated by David M. Edizioni del Girasole (2013).
8. Ricceri, G.: Studi e ricerche nell'area di S.Vitale Galla Placidia e Santa Croce in Ravenna. SGEditoriali, Padova (Italia) (1992).
9. Bertolini, I., Marchi, M., Tonni, L., et al: CPT data interpretation for an improved characterization of the paleosol stratigraphy in the Po River Valley, Italy. In: Cone Penetration Testing 2022, CRC Press, 294-299 (2022).