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# Subsoil characterization and stability analysis for the Bourbon del Monte Palace in Piancastagnaio (Siena, Italy)

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ABSTRACT: The historical Bourbon del Monte Palace in Piancastagnaio (Siena, Italy) dates to the 17th century and represents an uncommon example of feudal architecture in Tuscany. It was inhabited until the end of the '80s of the last century when, due to the high degree of instability achieved, it was declared unfit for use by the Public Authorities. The Palace lays on a sloping site, on the edge of fractured trachyte blocks mixed with alluvial deposits. It is characterized by four floors above ground and a basement at the South-East corner, while the North façade has two floors. Severe degradation phenomena of the building consist of multiple cracks diffused along the external and the inner masonry; furthermore, significant water infiltration from the floor has been observed in the South-East basement since the '80s. Previous investigations have shown that the Palace has undergone two distinct settlements systems: one dates before the '70s and may have caused the cracks along the South wall of the building; the other, more recent and probably related to the water infiltration on the basement, may have caused the damage to the South-East wall. This paper investigates the source of this second settlements system by modeling and analyzing a 2D soil section close to the South-East corner of the building. Firstly, the collected geotechnical and geological data and the modeling of the analyzed section are presented. Afterwards, the results of the numerical simulations are shown and discussed, analyzing the effects of the estimated settlements on the observed structural damage.

## 1 INTRODUCTION

Piancastagnaio is a small Italian town located in southern Tuscany. It was established during the late medieval age close to the Amiata Mountain which is a part of a massif of volcanic origin in the Italian Central Apennines. Located close to the center of Piancastagnaio, the *Bourbon del Monte* Palace is a typical example of baroque architecture. It dates to the beginning of the XVII century and consists of a huge masonry building (≈ 31 m width and 34 m length) that was partially founded on ancient town-walls; the external walls thickness is approximately 1.2 m, and the texture of the masonry could be an infilled one; the floor levels are made of different types of masonry vaults (e.g. cross and cloister vaults). The geometrical configuration is quite regular, characterized by almost orthogonal masonry walls (Betti et al. 2010). The Palace rests on a sloping area, on the edge of fractured volcanic rock (trachyte blocks) mixed with silty deposits. It consists of two floors above ground on the North façade and four floors above ground on the South façade, in addition to a lower ground floor (basement) at the South-East corner. Specifically, as discussed in detail in the following sections, the outside East wall is partly built on trachyte (upward from the basement, toward the North wall) and partly on silty deposits (downward to the basement and to the South wall).

Originally belonging to the Bourbon del Monte Family, the Palace was sold in the XIX century. Thereafter it has been used for different purposes (e.g. for commodities recovery) and today it belongs to the Local Administration of Piancastagnaio. The building was inhabited until the end

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of the ’80s of the last century when it was declared unfit for use by the Public Authorities. Such a drastic decision was motivated by the high degree of instability that characterizes the whole building and that started growing significantly from the ’70–’80’s. Figure 1a shows the outside of the Bourbon del Monte Palace with the South-East corner in the foreground. Figure 1b shows the extreme degradation in the biggest central room inside the building.

Figure 1. The Bourbon del Monte Palace in Piancastagnaio: (a) outside view; (b) inside view.

At date, severe degradation phenomena consist of multiple cracks’ systems diffused along the external and the inner masonry, and of water infiltration from the basement at the South-East corner where the crack pattern is the most critical. Numerous investigations (geotechnical and geophysical surveys, numerical analysis of the building) have been performed in the past 30 years (e.g. Baldi 2008; Bartoli et al. 2008; Bartoli & Betti 2012; Betti et al. 2010; Montini 1990), trying to shed light on the origin of such a diffuse degradation. According to Bartoli & Betti (2012), the Palace has undergone two distinct differential settlements systems in the foundation soil underneath the South-East edge. The first dates before the 70’s and may have caused the crack system along the South wall of the Palace, letting the edge starting to detach, while the second, developed during the second half of the 80’s, may be the cause of the damage observed in the East wall. The latter system could also probably be related to the water infiltration from the basement, a phenomenon that has been observed since the ’80s. The reasons for the two settlements systems have never been univocally clarified, although research results from numerical analysis on the Palace showed that the two mechanisms are distinct (Bartoli & Betti 2012). Figure 2 shows the crack systems along the South and East walls, as reported in Picchioni (2008); Bartoli et al. (2009).

As previously pointed out by researchers (Bartoli et al. 2008, 2009; Bartoli & Betti 2012; Betti et al. 2010; Picchioni 2008), a soil settlement system located in the basement should be responsible for the diffused crack system along the East wall (Figure 2a), while the detachment of a portion of the South wall (Figure 2b) could be ascribed to slope instability. With reference to the former settlement system (Figure 2a), however, the mere difference in the mechanical properties of the foundation soils (trachyte upward the North wall, alluvial deposits toward the South wall, in the basement) can’t be the only responsible for the observed degradation phenomena, because the instability of the East wall dates to the ’80s, not before. It is likely that water infiltration, due to a change in the groundwater flow configuration (Baldi 2008) had modified the soil-structure interaction conditions.

This paper aims to investigate the most recent settlement system, probably related to a change in the mechanical characteristics of the foundation soil under the basement. Because the two settlements systems are distinct (Bartoli & Betti 2012), this paper deals with the geotechnical and numerical modeling of a subsoil section located along the East wall of the Palace, with the aim of clarifying the instability mechanisms observed in the East side of the building. After a brief description of the main geological characteristics of the subsoil in the area of Piancastagnaio, the geological and geotechnical data used to define the geotechnical model are presented. Finally, the numerical model implementation and the analysis results are shown and discussed.

Figure 2. The actual crack systems: (a) East wall; (b) South wall (from Picchioni 2008).

## 2 GEOLOGICAL FEATURES OF PIANCASTAGNAIO AREA

Piancastagnaio is located at the edge of a limited plateau of volcanic origin (the Amiata Mountain is an effusive extinct volcan), approximately 800 m above the sea level. The geological configuration of the area is related to the volcanic activity of the Amiata Mountain: generally speaking, the actual area configuration is characterized by volcanic rocks overlying marine deposits. The town is on the edge of the Val di Paglia graben; the East slope is mainly composed of pliocenic clays, while the South slope is composed of argillites with intercalated calcareous rocks. Piancastagnaio is at the South-East corner of the Basal Trachydacitic Complex, a formation of volcanic rock dating to 430.000 years ago. Due its evolution, this formation is today characterized by integer blocks in the upper plateau (where the newer village is located), and by fractured blocks under the older village, where the Palace is located (Baldi 2008). The volcanic rock lies on marine deposits characterized by the following stratigraphy (from the bottom to the top) (Baldi 2008): 1) Ligurian Tectonic Unit, a heterogeneous lithotype composed of tectonised grey clay (argillites) alternating with banks of grey calcareous rock; this formation outcrops at the South side of Piancastagnaio. 2) marine Pliocene deposits, outcropping at the East side of Piancastagnaio; 3) sandy, silty deposit with clay (Pleistocene age), interlaying between the pliocenic clays and the surficial volcanic rock.

## 3 SUBSOIL CHARACTERIZATION FOR NUMERICAL MODELING

### 3.1 *Data availability and soil types*

Data collected from previous testing surveys were used to get all the parameters needed for the numerical implementation of a 2D-model section. At date, the most recent and comprehensive results from geological/geotechnical analysis are reported in Baldi (2008) which was therefore taken as the reference in this paper. Other studies (e.g. Losito 2010) have been prevalently used for data integration, when possible.

The geophysical/geotechnical tests described in Baldi (2008) consist of: 1) *in situ* tests, namely: a) 4 boreholes located around the building and equipped with a piezometer (1 borehole) and inclinometers (3 boreholes); b) 8 shallow survey excavations (7 located in the basement, 1 in the ground floor); c) Standard Penetration Tests (SPT) performed within the 4 boreholes; d) seismic refraction and *ReMi* (Refraction Microtremor) tests, with estimation of compressional and shear seismic waves velocities $V_p$ and $V_s$, respectively; 2) laboratory tests, namely: a) soil classification tests; b) shear strength tests (direct shear and unconfined compression tests) and oedometer tests on undisturbed soil samples collected at various depths in 2 boreholes.

Seven different soil types can be distinguished from the 4 litho-stratigraphic borehole profiles (Baldi 2008): filling soil (R), loose brown sand (Sa), sand with trachyte small clusters (Sa+Tra), fractured trachyte (Tra), grey silty sand (Sl), grey-brown sandy silt (Ls), and silt (L). Figure 3 shows the location of the 4 boreholes described in Baldi (2008) and the cross Section CC' that was used for numerical analysis (see Section 3.2).

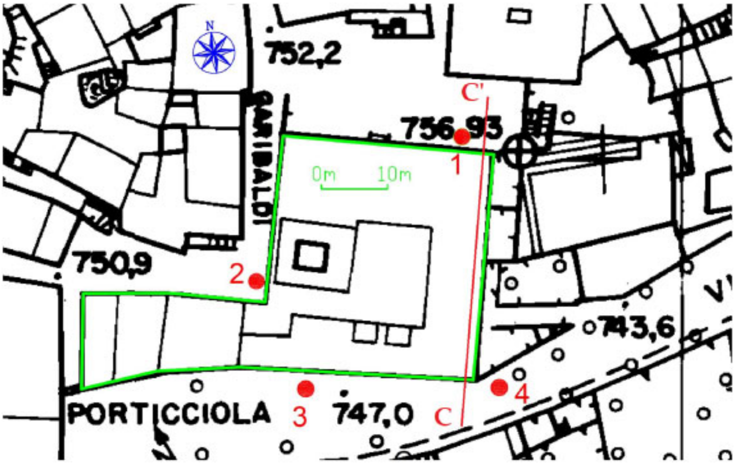

Figure 3. Survey Boreholes location (red dots) and Section CC'. The basement is located close to borehole n°4.

From borehole surveys, it follows that the soil profile at the Northern side of the building (borehole n°1) includes trachyte (Tra) blocks (≈26 m thick) overlying silt (L); at borehole n°2, it is characterized by ≈9 m-thick Sa+Tra layer laying above silt (L), while boreholes n°3 and n°4 show the presence of a thin sand (Sa) layer (≈1.5–1 m thick at boreholes n°3 and n°4, respectively) overlying ≈4.5 m constant-thick sandy silt (Ls) layer, placed above a silt (L) layer. Shortly, some important conclusions can be drawn: a) the Palace lies on heterogeneous soil and rock types; b) significantly different subsoil configurations can be found at the Northern and Southern sides of the building. The Northern façade stands on trachyte blocks, while the subsoil under the Southern side is characterized by a sandy silt lens included between a thin Sa+Tra layer and the underlying L. The transition between trachyte and sandy silt at this side of the Palace is somewhere located at the entrance of the basement, where outcropping rock was used in the past as the foundation of the masonry arch that leads downward to the basement (Figure 4a).

According to piezometric measurements within the borehole n°3, the groundwater table is located at a depth of 3 m; a piezometer installed in the Palace basement (thus, at the South-East corner) revealed that the groundwater table is 0.5–1.0 m below the ground level. 2D electrical resistivity tomography performed within the basement (Losito 2010) confirmed that the subsoil was water-saturated. During a more recent visual survey conducted in 2015 by the authors, the groundwater had emerged and filled the survey excavations carried out at the basement (Figure 4b).

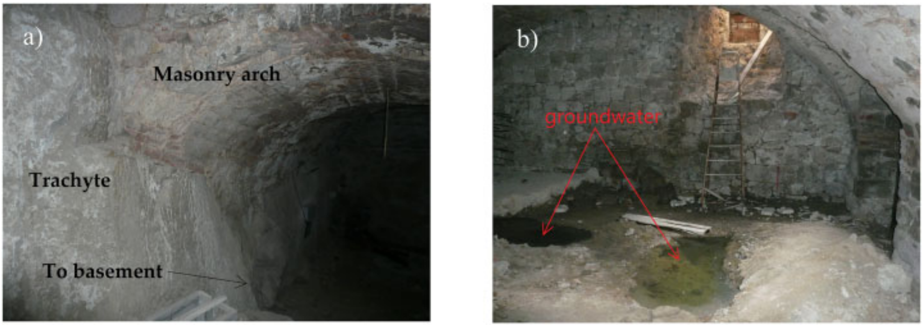

Figure 4. The basement: trachyte outcropping at the entrance (a); groundwater emerging from the floor (b).

## 3.2 *Section modeling*

### 3.2.1 *Geotechnical modeling*

The subsoil morphology of the analyzed Section CC’ was reconstructed based on the profiles obtained from boreholes n°1 and n°4 located close to the East wall (Figure 3), assuming each litho-stratigraphic profile as a boundary condition for lithotypes identification and location; an additional boundary condition was represented by the lithotype Tra, outcropping at the basement entrance (Figure 4a). The surficial morphology in correspondence of the Palace was easily obtained by architectural surveys and previous analysis (Bartoli & Betti 2012; Betti et al. 2010). The Section CC’ layout is shown in Figure 5. As can be seen, the separation between lithotypes Ls and Tra

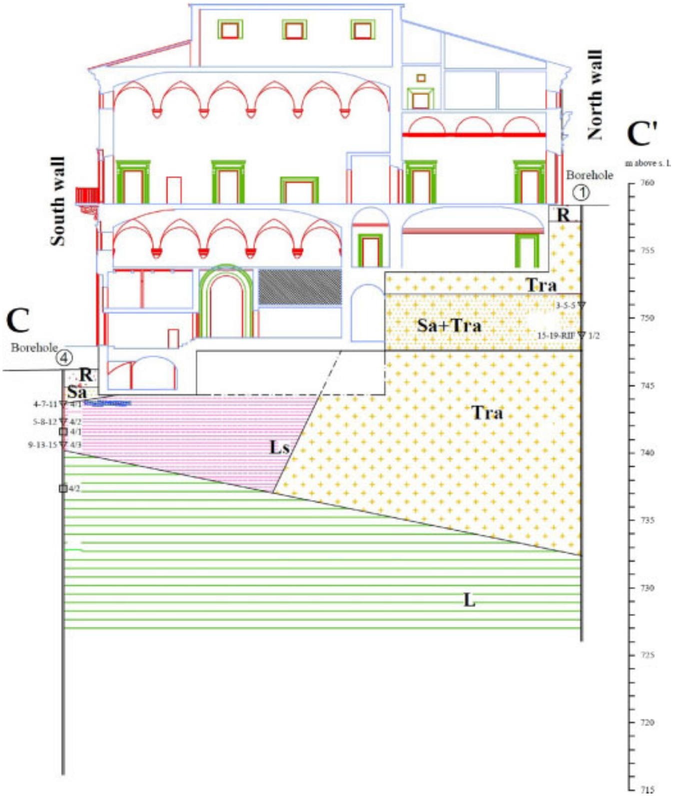

Figure 5. Section CC’.

occurs somewhere below the basement: due to the lack of data, the slope of the separating surface has been initially hypothesized in 45°.

The geotechnical properties and parameters of each soil type were obtained from the results of *in situ* investigations and laboratory tests on specimens collected from the four boreholes. Literature correlations were used to estimate the relative density, $D_r$, the angle of shearing resistance, $\varphi'$, and the undrained cohesion, $c_u$, from the SPT parameter ($N_{SPT}$) (e. g. Gibbs & Holtz 1957; Hatanaka & Uchida 1996; Meyerhof 1957; Skempton 1986, among others). By way of example, Table 2 shows the *in situ* SPT test results. For the same lithotype, values of parameters obtained from $N_{SPT}$ pertaining to different SPT tests or boreholes were averaged excluding the maximum and minimum values. Data were obtained for soil types Sa+Tra, L, Ls. The shear and compressional wave velocities were determined using the results of seismic refraction tests (Baldi 2008); the Poisson's coefficient, $\nu$, for each soil type was thus calculated. Laboratory tests (direct shear tests, odometer tests, unconfined compression tests) were available for lithotypes L, Ls, and Sa, allowing to quantify the following soil parameters: unit weight, $\gamma$, angle of shearing resistance, $\varphi'$, effective and undrained cohesion, $c'$ and $c_u$, overconsolidation ratio, OCR, Young modulus, E, shear modulus, G, and bulk modulus, $E_b$. The obtained values, when pertinent, were averaged (weighted mean) with *in situ* test results, assuming a different weight depending on the level of test accuracy or on the reliability of literature correlations (e.g. a weight $= 0.6 < 1$ was used for $c_u$ estimated from $N_{SPT}$). Table 1 shows the properties for each lithotype assumed in the numerical analysis; further details on the geotechnical subsoil characterization can be found in Ciardi (2015). Despite the amount of test/site investigations, the obtained mechanical soil properties are rather uncertain; while for some lithotypes results from field and/or laboratory tests could be compared, for others few (or none) data were available. For instance, in the case of lithotype Tra, the parameters were inferred from literature data, in order to simulate a rock-like behavior.

Table 1. SPT test results.

| Borehole # | Depth (m) | Lithotype | $N_1$ | $N_2$ | $N_3$ | $N_{SPT}$ |
|---|---|---|---|---|---|---|
| 1 | 7.20 | Sa+Tra | 3 | 5 | 5 | 10 |
| 1 | 9.40 | Sa+Tra | 15 | 19 | 50 | 69 |
| 2 | 3.40 | Sa+Tra | 5 | 6 | 13 | 19 |
| 2 | 7.20 | Sa+Tra | 12 | 14 | 19 | 33 |
| 2 | 10.00 | L | 8 | 11 | 15 | 26 |
| 2 | 14.00 | L | 14 | 16 | 19 | 35 |
| 3 | 8.80 | Sl | 11 | 35 | 34 | 69 |
| 4 | 2.30 | Ls | 4 | 7 | 11 | 18 |
| 4 | 3.60 | Ls | 5 | 8 | 12 | 20 |
| 4 | 5.30 | Ls | 9 | 13 | 15 | 28 |

Table 2. Geotechnical properties of soil types in Section CC'.

| Lithotype | R | Sa+Tra | Tra | Ls | L |
|---|---|---|---|---|---|
| $\gamma$ (KN/m$^3$) | 17.5 | 18.5 | 22 | 20 | 21 |
| $D_r$ (%) | / | 64 | / | 75 | 65 |
| $\varphi'$ (°) | 28 | 38 | 40 | 30 | 32 |
| $c'$ (kPa) | 0 | 0 | 200 | 0 | 5 |
| $c_u$ (kPa) | 0 | 0 | 1e+4 | 182 | 153 |
| $\nu$ (–) | 0.44 | 0.38 | 0.46 | 0.40 | 0.48 |
| E (kPa) | 2.05e+5 | 6.38e+5 | 1.04e+6 | 5.16e+5 | 1.28e+6 |
| G (kPa) | 7.14e+4 | 2.31e+5 | 3.59e+5 | 1.83e+5 | 4.33e+5 |
| $E_b$ (kPa) | 5.69e+5 | 8.86e+5 | 4.33e+6 | 8.60e+5 | 1.07e+7 |

### 3.2.2 *Numerical modeling*

The numerical model of Section CC’ has been implemented using the finite difference code FLAC 2D (v. 7.0) (Fast Lagrangian Analysis of Continua) (Itasca 2011). The traditional Mohr-Coulomb constitutive model was used in the analysis. The presence of the Palace was simulated by normal distributed stresses applied to the soil surface obtained from the support forces calculated by a numerical model of the Palace (Picchioni 2008). A parametric analysis on the contact sloping surface between Ls and Tra was performed. Five different FLAC models were analyzed, with increasing complexity. Firstly, the presence of the slope at the South-East side of Piancastagnaio was neglected, extending the model surface horizontally, assuming the soil was dry (model 1). In model 2, the groundwater was considered, letting FLAC calculate the saturation contours after imposing the basement was fully saturated, as evident from field observations; in model 3, the mechanical properties of Ls were reduced. This simulates a decay in the mechanical characteristics of Ls due to the presence of water in the basement and it is justified by previous observations: Montini (1990) defined the base soil as a sort of “squished, pudding-like clay”. The angle of shearing resistance was therefore decreased of 50% and the moduli (elastic, shear and bulk) of an order of magnitude. This reduction is not related to any observation/test result; however, results of numerical analysis from model 3 were not used for a quantitative estimation of soil settlements, but rather for comparison with outputs from model 2, to appreciate the influence of Ls parameters on the shape/location of settlements basin. Model 4 is equal to model 3 with varying the inclination of the separation surface between Ls and Tra; the variation of the angle of inclination (positive clockwise), $\alpha$, was assumed between a minimum of 0° (vertical surface) and a maximum 80° (Ls is detected in borehole n°4 profile, thus representing a boundary for the upper $\alpha$ values). At last, model 5 considers the sloping ground at the South-East wall with varying $\alpha$. Topographic surveys showed that the slope has inclination of $\beta \approx 13°$ (positive counterclockwise). However, no geotechnical data are available for the soil within the slope, that was therefore assumed equal to lithotype L; thus, model 5 essentially represents a change in the boundary conditions. Furthermore, due to the presence of a road, a retaining wall and some buildings along the slope, it would not be possible to build a satisfactory model of the slope.

## 4 RESULTS AND DISCUSSION

The results of numerical models are described in this section for all models. Figure 6a shows the vertical displacements obtained from model 1; the maximum vertical displacement was ≈8.8 mm, located under the South-East corner of the East wall. Figure 6b shows a detail of the settlement basin under the South-East corner; all results are reported in meters. When groundwater is considered (model 2), the shape and location of the settlements’ basin did not essentially change; the maximum vertical displacement was ≈10 mm. It is worth observing that, despite the heavy simplifications of

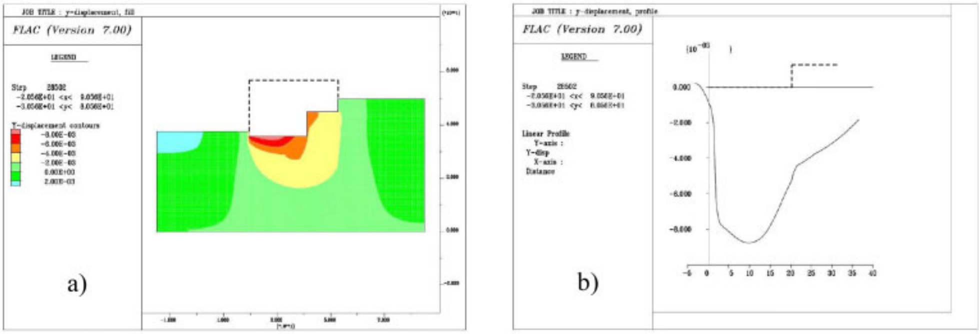

Figure 6. Section CC’. Vertical displacement from model 1 (a); zoom at the South-East corner (b).

the proposed models, the location and shape of the settlements' basin is compatible with the crack systems along the building East wall (Figure 2a).

Model 3 introduces the decay of mechanical properties of Ls lithotype, related to water infiltration. Figure 7 shows a comparison among the settlements' basin obtained from models 1–3: as can be noted, the shape and location are essentially the same. Despite the numerical values obtained from model 3 (as stated in Section 3, the reduction of Ls mechanical characteristics is not test-based), this model confirms that the settlements' basin is strongly influenced by Ls characteristics, as it may be hypothesized considering that the upper side of the East wall is built on rock; thus, a decay of Ls mechanical properties would have essentially increased differential settlements without significantly changing the location of the settlements basin.

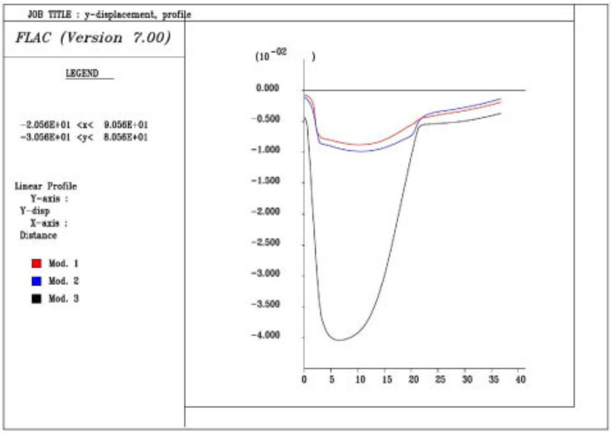

Figure 7. Vertical displacement comparison among Models 1–3.

Figure 8 shows the effects of the slope ($\alpha$) of the contact surface between the lithotypes Ls and Tra. The maximum vertical displacement, $y_d$, occurs for $\alpha = 45°$; absolute minimum of $y_d$ occurs for $\alpha = 80°$, which corresponds to a thinner layer of Ls under the basement, while a relative minimum occurs for the (unlikely) condition of $\alpha = 0°$ (vertical separation between Ls and Tra) (Figure 8b). When considering the sloping ground on the South side of the Palace, the maximum vertical displacements are expected to increase because of the change in boundary conditions. Figure 9 shows the displacement vectors resulting from numerical analysis ($\alpha = 45°$). The maximum displacement vector is located at the basement (with maximum vertical component ≈62 mm); the

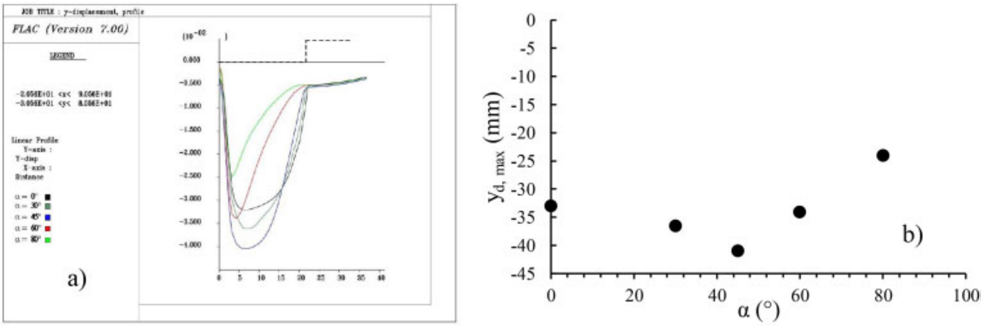

Figure 8. Section CC'. Zoom of vertical displacement from model 4 (a); maximum vertical displacement versus slope of Ls-Tra contact surface (b).

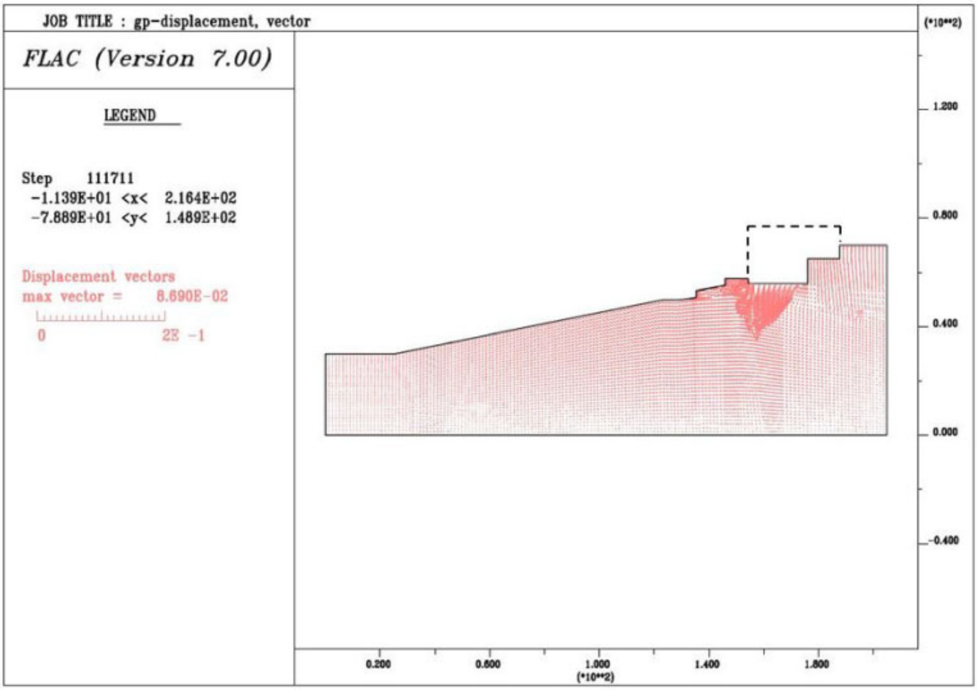

Figure 9. Section CC’. Displacement vectors from model 5.

shape of the settlements basin agrees with the actual crack systems on the East wall. As it was for model 4, the condition associated with maximum $y_d$ was for $\alpha = 45°$.

It should be noted that, in the numerical models, the Palace has been simulated by the normal stresses it applies to the underlying soil (see Section 3.2.2). This assumption, which implies neglecting the stiffness characteristics of the building, is essentially justified by the aim of this study (namely, to verify the relative influence of different soil types on the settlements’ basin at a side of the Palace). However, it is essential that a proper soil-structure interaction analysis, which considers the different stiffness of the soil and the structure, is performed in order to point out more realistic conclusions.

## 5 SUMMARY AND CONCLUSIONS

The Bourbon del Monte Palace in Piancastagnaio (Siena) is a historical building dating to the XVII century, located in southern Tuscany (Italy) in an area where the geological characteristics are related to the volcanic activity of the effusive, extinct Amiata volcan. The Palace is affected by extreme degradation phenomena, like multiple and diffused cracks systems, and water infiltration from the basement. It lies on a sloping ground, partly on fractured volcanic rock (trachyte), partly on sandy silt deposits. Many studies have highlighted that the Palace has experienced two independent settlements systems: the first connected to the crack system along the South wall of the Palace, which dates before the 70’s, and a second, more recent, that may have caused the damage observed in the East wall.

Attempting to account for this latter system of settlements, a series of extremely simplified numerical analysis have been performed in this study on a cross section located along the South-East wall. Firstly, the geotechnical characteristics of the subsoil are identified from previous studies;

then, five numerical models, with increasing complexity, are analyzed. As emerged from numerical results, some conclusions can be drawn:

- the shape of the settlements basin obtained in all models is compatible with the observed crack system along the East wall;
- differential settlements may have increased significantly due to a reduction of the mechanical characteristics of sandy silt soil (Ls), above which the South-East edge of the Palace is built on;
- the location of the settlements' basin is related to the different types of foundation soils;
- a change in the model boundary conditions did not lead to a significant change of the settlements' basin location.

The proposed numerical models suffer of a certain degree of uncertainty, especially related to the mechanical characterization of Ls lithotype, and they do not aim to a quantitative estimation of soil settlements. A supplementary in situ and laboratory testing survey, with the purpose of a comprehensive analysis of the subsoil underneath the South-East wall, should have been performed in 2015; however, due to various impediments, no further actions were undertaken. As a result, the Palace is still in a situation of profound crisis, and no solutions are, unfortunately, in sight.

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