Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 268-277

ECCOMAS Proceedia

COMPDYN 2021
8th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Streamed from Athens, Greece, 28 - 30 June 2021

ANALYSIS OF THE DAMAGE STATE OF A MONUMENTAL BUILDING BY CONSIDERING THE VARIATIONS IN SOIL CONDITIONS

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Abstract

This paper investigates whether it is possible to identify the influence of soil conditions on the modal parameters of the structure for damage detection and overall structural health monitoring. To do so, the data gathered on a large monumental building damaged by differential settlements are analyzed. In particular, the dynamic response of the case study, a large monumental masonry building, was experimentally investigated within an operational modal analysis (OMA) campaign. Mechanical data obtained from the geophysical tests were in turn employed to build and characterize a numerical model of the soil underlying and surrounding the building. The resulting model was then used to study the sensitivity of the modal characteristics of the building with respect to variations of external environmental factors (e.g., the water table level) which affect the underlying soil.
The results obtained from this numerical study is deemed to represent a starting point for future experimental tests and investigations, whose final aim is relating ambient vibration measurement to the occurrence of differential settlements or subsidence, in order to detect progressive, and possibly pathological, behaviors.

Keywords: soil-structure interaction, degree of saturation, environmental data series, FEM, foundation settlements, Operational Modal Analysis, Structural Health Monitoring, groundwater table.

Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi: 10.7712/120121.8480.18885

1 INTRODUCTION

It is well-known that soil conditions may affect the response of a building. This is especially true for monumental buildings in masonry, which are unable to bear strong flexural internal stresses caused by differential settlements or subsidence [1]. Cyclic oscillations of water table levels may alter the soil characteristics and potentially activate or worsen these phenomena, damaging the superimposed structures. Dynamic monitoring systems are a widespread tool for Structural Health Monitoring (SHM) and consist of accelerometers installed on the superstructure [2]. However, alterations occurring at the foundation level are difficult to understand from the outputs of these systems. Moreover, the systems dedicated to dynamic SHM are usually not equipped with sensors dedicated to controlling the effects of the soil, as they are set to capture responses from the superstructure only.

The present paper wants to investigate how the modal behavior of the structure is affected by the variation of the soil characteristics, such as the degree of saturation and the water table evolution. The aim is to study how a dynamic sensing system mounted only on the structure would capture the evolution of these parameters correlated to the structure response. To this aim, the case study of the Chiarugi building in Racconigi (Piedmont, Italy) is presented as a benchmark. The "Chiarugi" pavilion is a monumental three-story masonry structure presenting a double quadrangular plan with two inner courtyards overlooking the walkways loggias at the various floors. The building, which has been used as a psychiatric hospital for over a century, is distributed in various wings, a common design solution adopted at the time for hospice and hospital in general, and it includes a baroque chapel dedicated to the Madonna del Buon Consiglio. The building covers about 4.000 m^2, with a total usable area of about 17.000 m^2 distributed between the basement and the various floors and reaches a maximum height of 21 m. The building, whose construction is dated between the end of the 18th century and the beginning of the 19th century, has been in disuse for more than twenty years and has been in a latent danger state. Currently, the building is affected by a condition of widespread degradation and severe damaging phenomena: internal collapse, local deformations, wide cracks scattered on the whole building. These damaging phenomena, documented for over 50 years, are distributed differently in the various wings in which the building is subdivided. The structural problems of the "Chiarugi" pavilion are essentially due to two main causes mentioned in all the static surveys carried out since 1972: the maintenance problems and the soil characteristics [3]. In fact, the structural damage affecting the building is caused by the hydrogeological conditions and the seasonal oscillations of the groundwater layer. Moreover, the maintenance problems had led to the deterioration of the roofs, causing infiltration and percolation of the meteoric waters into the walls, sometimes worsened by the absence or inefficiency of the gutters in the structure [4].

(a) (b) (c)

Figure 1: (a-b) some cracks on the various facade of the building (2015); (c) collapse of a portion of the southern façade (2016).

In 2016 a portion of the southern façade suddenly collapsed. The collapse is presumably due to the collapse of the masonry pillars that supported the vaults of the underlying plan. Another collapse followed in 2019.

2 MODELING STRATEGY

The building is located on a plane with a slight slope of about -0.15% to the north, in an area concentric to the city of Racconigi (259 m above sea level in the northern part of the "Pianura Cuneese"), historically influenced by the depositional process of the Maira torrent whose riverbed is currently spaced about 800 m west of the building. The first stratigraphic indications of the soil were obtained from the documentation on the hospital's thermal power plant; however, specific analyses were subsequently carried out, which determined the characteristics of the soils more precisely [3].

Given the complexity of the problem, in a first approach to the study, the superimposed structure has been modeled through a low fidelity approach, essentially using finite shell elements and without considering the opening. Instead, for the soil-foundation system, brick and shell elements with 8 and 4 nodes, respectively (3 Degree of Freedom – DoF and 6 DoF at each node) have been used.

The superimposed structure has been modeled to consider in a simplified way the effect of its mass and stiffness distribution along the foundations. To this aim, the soil-foundation-structure system has been calibrated, going to update the equivalent values of Young's moduli of floors and masonry walls for the different sleeves. The updating was possible thanks to the availability of the experimental modes identified after an intensive experimental campaign carried out in situ by the authors. The results of the calibration, reported in Table 1, demonstrate how the grey-box representation of the updated superimposed structure is able to satisfactorily trace the first two modes of the building, providing a good estimate of the global stiffness/mass distribution of the system, which is the aim of the low-fidelity representation of the superimposed structure.

Identified natural frequencies [Hz]	Numerical frequencies [Hz]
2.233	2.195
2.464	2.382

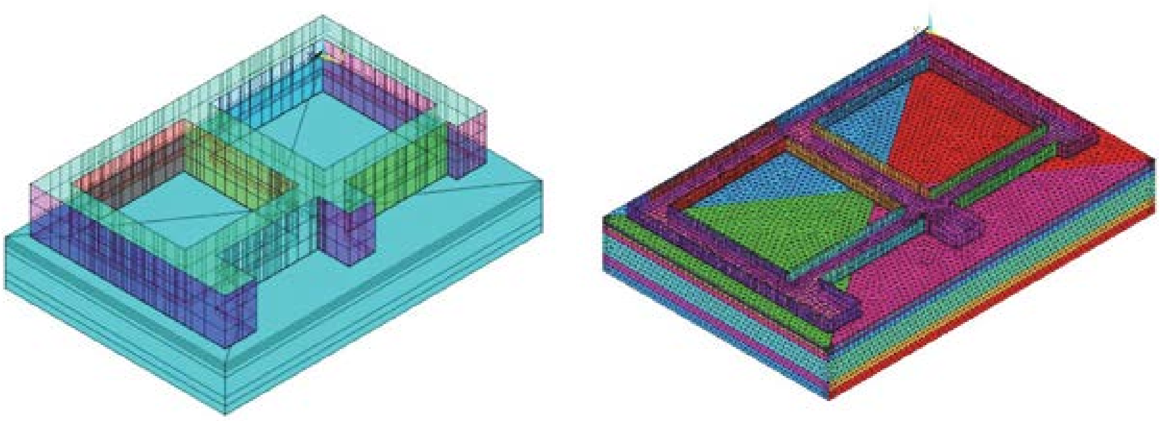
(a)

MAC between identified and predicted mode shapes	
0.841	0.000
0.004	0.741

(b)

Table 1: Results of the numerical calibration of the superimposed structure: (a) natural frequencies. (b) Modal Assurance Criterion (MAC).

The Finite Element (FE) model of the soil counts 219716 elements and 41754 nodes, with a maximum mesh size of 2 m. The main dimensions of the soil volume in the vertical and horizontal direction have been chosen starting from the geotechnical campaign results carried out by [3]. Starting from these data, the total depth of the volume was fixed to 18 m, while the distance between the soil edge and the foundation was fixed to 5 m in each direction. The total dimensions of the soil volume resulted in being 127 m in the East-West direction (X direction in the FE model), 88 m in the North-South direction (Y direction in the FE model), and 18 m in the vertical direction (Z direction in the FE model). The total number of soil layers follows the experimental findings (see Figure 2 for clarity). Finally, the foundations are laid at a depth of 3 m from the surface. The data of the elastic properties of the soil obtained by the geotechnical investigation are reported in Table 2.



(a) (b)

Figure 2: (a) Grey-box model of the superimposed structure and Finite Element (FE) model of the soil-foundation system. (b) FE mesh of the soil-foundation system (each color represents a different constitutive material).

Layer Id.	Depth at the bottom of the layer [m]	Soil type [3]	Density [kg/m^3]	East S-wave speed [m/s]	North S-wave speed [m/s]	South S-wave speed [m/s]	West S-wave speed [m/s]
1	1	- heterogeneous material (peat)	1200	300	250	200	250
2	2	- clayey silts (vegetable rind)	1500	300	250	200	250
3a	3	- fine sands, sandy gravels, and silty sands	1750	300	250	200	250
3b	5	- fine sands, sandy gravels, and silty sands	1750	300	250	200	250
4	12	- medium and coarse gravels and sandy gravels	1850	450	335	500	350
5	15	- medium gravels and silty gravelly sands	1950	450	500	500	350
6	18	- silty gravelly sands and gravels	1850	750	650	250	650

Table 2: Available elastic properties of the soil used to build the FE model.

Layer 3 was divided into 2 sub-layers because of the presence of the water table, which oscillates from a minimum of -5 m up to a maximum of -3 m, where it touches the building's foundations [3], [5]. In the absence of more information, the Poisson ratio was set to uniform in the model and equal to 0.33 at the time of the geotechnical investigations. For the foundations, Young's modulus of 2 GPa and a density of 1800 kg/m^3 were then assumed. The vertical faces of the soil volume were then fixed in the horizontal direction, while a total restrain was given to the bottom face (at -18 m).

3 SIMULATIONS AND RESULTS

The simulations are aimed to numerically study the influence of soil conditions on the modal and the static response of the structure for Structural Health Monitoring (SHM) of the building. The structure is known to be affected by the water table oscillation, which affects the elastic properties of layer 3 of the FE model. The oscillation of the water table affects the saturation of the overlying layers, as demonstrated by several literature studies, e.g. [6], [7], [8], [9]. This is mainly due to the capillary rise of water in the soils (in this case, mainly sands) and obviously to the infiltration properties of the surface layers, which allow the access of meteoric rains to the depth. Thus, the rain contributes not only to the direct modification of the degree of saturation on the surface but also to the modification of the height of the aquifer, and therefore (indirectly) to the modification of the capillary rise and the degree of saturation of the soil above the aquifer. Then, the elastic properties of the soil are affected by the degree of saturation as demonstrated by several studies, e.g. [10], [11], [12], [13], [14]. In this study, the elastic properties of layer 3 are supposed to vary in accordance to the wave speed laws derived and experimentally validated by [10] starting from the Van Genuchten relation [15]:

$$V_p(S_r) = V_p^s + \frac{V_p^d - V_p^s}{\left[1 + \left(a_p S_r\right)^{n_p}\right]^{m_p}} \quad (1)$$

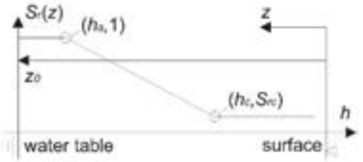
$$V_s(S_r) = V_s^s + \frac{V_s^d - V_s^s}{\left[1 + (a_s S_r)^{n_s}\right]^{m_s}} \quad (2)$$

where V_p^s, V_p^d, V_s^s, V_s^d and S_r are the *saturated* and *dry* P-wave and S-wave velocity and degree of saturation respectively, while a_p, n_p, m_p, a_s, n_s, m_s, are empirical model parameters. Starting from the P-wave and S-wave velocity it is possible to evaluate the Poisson ratio, ν, [13] by combining the theoretical formulations for the oedometric modulus *M*, Young's modulus *E* and shear modulus *G*:

$$M = V_p^2\rho; G = V_s^2\rho; E = M\frac{(1+\nu)(1-2\nu)}{(1-\nu)} = 2G(1+\nu) \quad (3)$$

$$\nu(S_r) = \frac{V_p^2(S_r) - 2V_s^2(S_r)}{2\left(V_p^2(S_r) - V_s^2(S_r)\right)} \quad (4)$$

where ρ denotes density. From equations (3) and (4), it is possible to conclude that having $V_p(S_r)$, $V_s(S_r)$ and ρ it is possible to derive the elastic properties of the soil as a function of the degree of saturation. In the present paper the laws (1) and (2) are those reported in [10] for sand (see [10] for the model parameters). Then the laws have been normalized to the values obtained from the geotechnical campaign in order to maintain a consistency of the analyses with the case study. Regarding the degree of saturation in the soil layer, it was assumed to be linearly variable between the *air entry height* region h_a, and the *maximum capillary height* region h_c, evaluated starting from the water table depth [6], [9]. For height lower than h_a the soil is known to be saturated (i.e., S_r=1), while for height over h_c the degree of saturation tends to be uniform, and in the first approximation it was assumed to be constant and equal to S_{rc}. Thus, the model that describes the variation of S_r along the soil depth *z* from the surface (positive downwards) is:



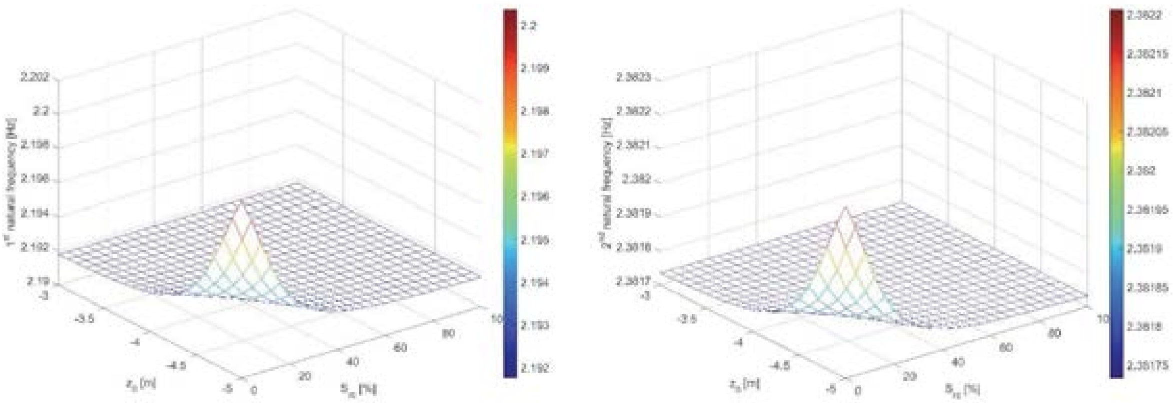
$$S_r(z, z_0) = \begin{cases} 1; & for\ h(z,z_0) \le h_a \\ 1 + \frac{1 - S_{rc}}{h_c - h_a}\left(h_a - h(z,z_0)\right); & for\ h_a < h(z,z_0) < h_c \\ S_{rc}; & for\ h(z,z_0) \ge h_c \end{cases} \quad (5)$$

Figure 3: Scheme of the linear model assumed for the degree of saturation S_r along the depth *z*.

where $h_c > h_a$. In the equation, $h = z_0 - z$ and z_0 represents the depth of the water table (i.e., variable from 5 m to 3 m in the present study), while z varies from 5 m to 2 m in the present application (thickness of the 3rd soil layer). For the study, the average values for sand reported in [9], [16], [17] have been used for the air entry height and the maximum capillary height ($h_a = 0.22\ m$ and $h_c = 0.59\ m$). Figure 3 depicts a schematization of the model defined by equation (5). Finally, to practically cast the results of (5) in the FE model, which is discretized in uniform soil layers, the average degree of saturation $S_{r,avg}$ along the 3 m of thickness of layer 3 has been calculated and used for the evaluation of the elastic properties with equations (3) and (4).

The aforementioned methods have been applied to carrying out a parametric analysis focusing the attention on the effect of soil characteristics on the modal response (in terms of the first two identified natural frequencies) and the static response (in terms of the standard deviation of foundation settlements). In the study, only the elastic characteristics of layer 3 have been changed, maintaining constant the properties of the first two soil layers.

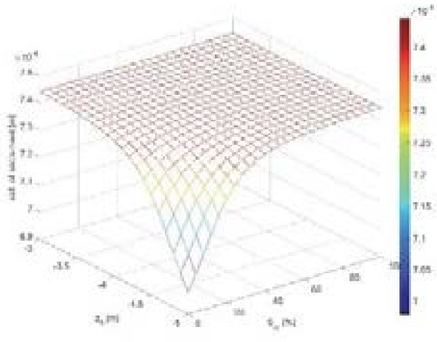
Figure 4 shows the variation of the first two natural frequencies of the model as a function of z_0 and S_{rc}. The figure demonstrates as a sudden decrease in frequency is detected when the soil saturation increases (decrease of water table depth or increase of S_{rc}). Extremely dry condition of the soil, such those one caused by extreme warm seasons, will thus result in an increase of natural frequency. The absolute variations are however very low and without intelligent feature extractions the effect of the alteration of the third soil layer in the "Chiarugi" pavilion could be confused with other Environmental and Operational Variations (EOVs).



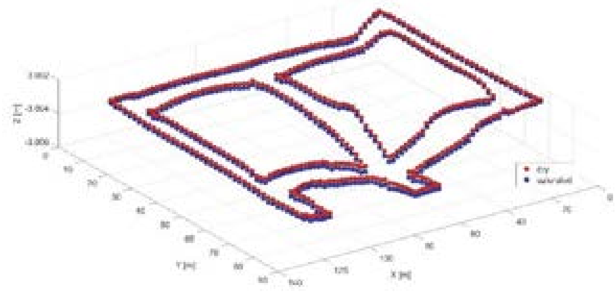
(a) (b)

Figure 4: (a) First natural frequency of the calibrated FE model as a function of the degree of saturation of superficial layers S_{rc} and the water table depth z_0. (b) second natural frequency of the calibrated FE model.

Figure 5 reports the results of the static analysis. In Figure 5a, the standard deviation of the foundation settlements is reported. From the figure, it is also clear that an increase of the saturation in the soil produces an increase of the standard deviation of the settlements. Figure 5b, instead, depicts the settlement profiles at the foundation's depth in case of dry (z_0=5 m and S_{rc}=0) and saturated (z_0=3 m and S_{rc}=1) conditions of the third layer. Comparing Figure 5b with Figure 5c (which depicts the actual condition of the building), it is possible to note how the corroboration of the FE model with the experimental data gathered during the geotechnical campaign can positively produce fitting results since the maximum depression zone foreseen by the model coincides with the area below the collapsed portion of the structure.



(a)



(b)

(c)

Figure 5: (a) Standard deviation of the foundation settlements as a function of the degree of saturation of superficial layers S_{rc} and the water table depth z_0. (b) foundation settlements for the dry (red) and saturated (blue) condition of the 3rd soil layer. (c) Google Maps picture of the structure (lat. 44.765470, long. 7.678842) on March 3rd, 2021 with highlighted (see the red circle) the collapsed portion of the building https://www.google.it/maps.

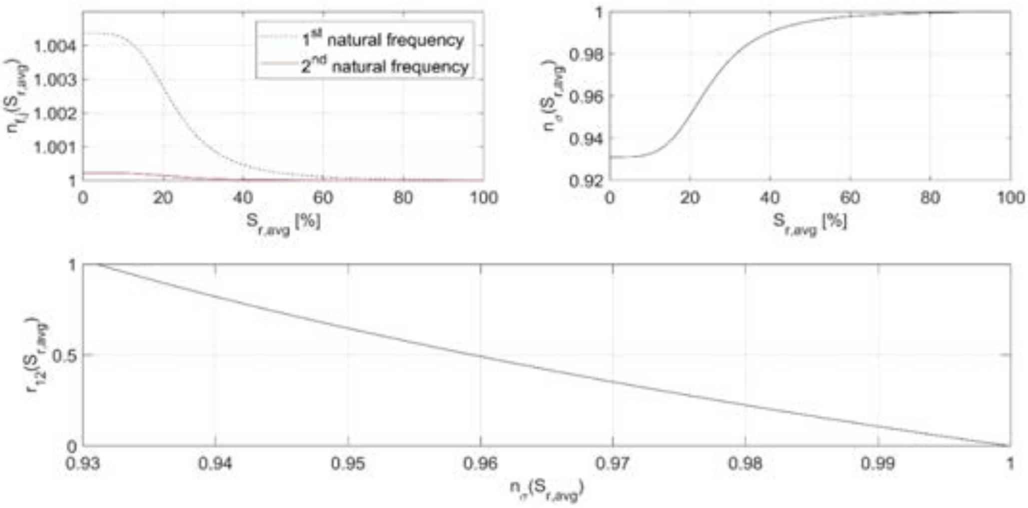


Figure 6: Results in terms of normalized values.

The previous results demonstrate as the modal and the static response of the building are quite correlated. In particular, the standard deviation of the foundation settlements has been considered in this study since it is related to the potential damage of the superimposed structure.

The results of the study are presented in Figure 6 in a normalized scale. In Figure 6, the following quantities are depicted:

$$n_{f,j}(S_{r,avg}) = \frac{f_j(S_{r,avg})}{f_{j,s}} \tag{6}$$

$$n_{\sigma}(S_{r,avg}) = \frac{\sigma_c(S_{r,avg})}{\sigma_{c,s}} \tag{7}$$

$$r_{12}(S_{r,avg}) = \frac{f_1(S_{r,avg})f_{2,s} - f_2(S_{r,avg})f_{1,s}}{f_{1,d}f_{2,s} - f_{2,d}f_{1,s}} \tag{8}$$

with j=1,2; f_j j-th natural frequency; $f_{j,s}$ j-th natural frequency at saturation; $f_{1,d}$ and $f_{2,d}$ 1st and 2nd natural frequency in dry conditions; σ_c, standard deviation of the foundation settlements; $\sigma_{c,s}$, standard deviation of the foundation settlements at saturation, while $n_{f,j}$, n_{σ}, and r_{12} are the j-th natural frequency normalized to the saturated value, the standard deviation of the foundation settlements normalized to the saturated values, and the difference between $n_{f,1}$ and $n_{f,2}$ normalized to the difference between the values taken in $S_{r,avg} = 0$. From Figure 6a, the relative variation of the first two natural frequencies demonstrates as the main variations are detected for the first mode and are in the order of 0.4%. On the other hand, Figure 6b depicts a relative variation of the standard deviation of the settlements of about 6%. Despite the fact that these variations are not worrying for the immediate stability of the building, their cyclic nature can determine damage accumulation in the superimposed structure, bringing in time to brittle collapses such as those occurred in the South façade of the "Chiarugi" pavilion. It is worth stressing that data and parameters extracted from real dynamic monitoring systems would be affected by several EOVs (such as the temperature effect) that could hide variations due to soil conditions. Commonly these EOVs, acting on the whole system, do not affect only the first natural frequency. Thus instead of focusing the attention on the variation of single frequencies, intelligent algorithms could be applied to the relative variations of these parameters (see, for example [18]). In these terms, Figure 6c conceptually shows as the normalized difference of the normalized frequencies can provide a correlation to the static response that is more amplified.

4 CONCLUSIONS

The paper investigated the influence of soil conditions, in terms of water table depth and degree of saturation, on the modal parameters of the "Chiarugi" pavilion. The modal response of the soil-foundation-structure system has also been correlated to variables potentially associated with the occurrence of damage in the superstructure (i.e., the standard deviation of the foundation settlements). The results of the study can be summarized in the following points:

- The absolute variations of the natural frequencies with respect to the variation of the degree of saturation of the third soil layer are quite low (maximum variations of about 0.4%);
- A variation in the first natural frequency value is reflected on a variation of the standard deviation of the settlements, which is an order of magnitude higher than that of the frequency (i.e., about 6%);
- Despite the low variations of natural frequency, the cyclic oscillation of the water table and the meteoric phenomena in Racconigi can change the degree of saturation

of the 3rd soil layer between 0.13 to 1 (under the made assumptions), and this results in a slow material deterioration that can lead to the sudden collapse of the masonry structure, as happened for the "Chiarugi" pavilion in 2016 and 2019;

- The low variations in natural frequency can be amplified if relative variations of the modal parameters of the structure are considered instead of absolute ones and if intelligent algorithms are used to separate the effects of other EOVs.

It is worth underlining that the results of this study are valid under the made hypotheses. For example, in a real scenario, the actual behavior of the soil with respect to the water table oscillation could diverge from linearity. Then, due to the infiltration processes also the soil characteristics of the surface soil layers will be affected by the changes in the degree of saturation, and thus the frequency variations could be even higher than those one reported in the study. These and other aspects (such as a full physical representation of the superimposed structure) will be addressed in future works, which might also focus on the prognosis of the "Chiarugi" pavilion thanks to nonlinear representation of the time degradation of the soil-foundation-structure system and the availability of some experimental variables in time, such as the time histories of water table depth and the degree of saturation of surface soil layers.

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