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Use of Copernicus satellite data to investigate the soil-structure interaction and its contribution to the dynamics of a monitored monumental building.

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Abstract. An advantageous opportunity in the context of Structural Health Monitoring (SHM) is represented by the use of satellite remote sensing data, which are becoming increasingly relevant in many areas with different purposes thanks to their wide temporal and spatial availability, versatility and low cost. As an example, recent applications of satellite *interferometric* data, which can detect centimetric even up to millimetric scale displacement, concerned the monitoring aggregated buildings in urban areas, the effects of land subsidence in built environments, and lately, the anomalies detection in single structures or infrastructures. However, there are still no applications in the SHM field of other types of satellite data in the literature, such as those coming from *multispectral* sensors. In the present paper, the application of satellite data from the Copernicus program of the European Space Agency (ESA) is proposed and explored. In particular, Land Surface Temperature (LST) parameter is selected to characterize the foundation soil of our case study - the sanctuary of Vicoforte - an 18th century Italian monumental church whose dome holds the world record of size among oval masonry domes. The study aims to address one key issue in the context of vibration-based SHM of buildings, i.e. the influence of the foundation soil and its changing properties on the dynamics of the system. Here, an early data-based approach is validated and supported through the use of a Finite Element Model (FEM), with the objective to simulate and quantify the effects of thermal variation on the global dynamic response of the system.

Keywords: Satellite data, Copernicus program, Sentinel, Land Surface Temperature, Structural Health Monitoring, Sanctuary of Vicoforte.

Introduction

In the last few years, the use of satellite remote sensing data is becoming a considerable opportunity for SHM. In particular, several recent research work [1, 2] have focused on exploiting *interferometric* satellite data obtained from radar instruments, e.g., Synthetic Aperture Radar (SAR), as they alone can detect displacement on the earth's surface in the order of centimetres and millimetres. To the best of our knowledge, the literature does not yet report applications in the SHM field of data acquired by other types of instruments installed on satellites such as *hyperspectral* and *multispectral* sensors, which are usually employed for environmental monitoring (i.e. fires, melting glaciers, droughts, etc).

The dynamic response of an exposed structure depends to a greater or lesser extent on some Environmental and Operational Variations (EOVs), as well as on the structural characteristics. These external factors have a double effect because they act directly on the emerging structure, and inevitably affect its foundation soil, altering and modifying its properties: it could give rise to a modification of the constraint conditions, which affects the stiffness of the entire vibrating system. Decoupling the two effects is very difficult as many causes (rain, snow, ice, temperature variation, humidity, etc) could act in combination, and in some cases, the relationships between variables are non-linear. The limited availability (and sometimes the absence) of continuous monitoring data of the soil makes the problem more critical, hindering the investigation of soil-structure interaction. Satellite data for environmental monitoring constitute a source of information regarding the state of the soil, ranging from thermal to saturation conditions and others. Furthermore, they are available on almost the entire surface of the planet continuously (with variable sampling) and are easily available on various online platforms. All this makes their application a convenient choice in the SHM field, where they could be useful for modelling the structural response also as a function of the state of the foundation soil.

In this research, the potential of the application of these data in a vibration-based SHM context will be evaluated, involving, in particular, the LST parameter, a satellite data concerning the thermal conditions of the soil surface supplied by the Copernicus program of the ESA. A combined model and data-based approach was followed: the data coming from satellites were processed and turned into percentages of variation of the mechanical parameters of the soil in the FEM of the case study considered through consolidated or empirical relationships available in the literature. The benchmark of this research is the Vicoforte Sanctuary, a monumental church in northern Italy, which has been dynamically monitored by a permanent system for more than two years: its experimental dynamic data were compared with the numerical ones.

The paper is divided as follows: Section 1 describes the satellite data involved and their processing for SHM purpose; in Section 2, the case study and its FEM are briefly summarized; in Section 3, the models used and the results of the simulations are exposed, and finally the conclusions are drawn in Section 4.

1 Satellite data

1.1 Land Surface Temperature

The LST parameter is defined as the measure of the effective radiant temperature of the Earth surface in [3] and here is used as continuous monitoring data of the foundation soil in an SHM scenario.

Many types of satellite data are not provided raw but are processed through algorithms: LST has a processing level 2, i.e. that of the parameters obtained from the lowest level data (measurement and annotations). In particular, it is obtained through a Split Window (SW) algorithm, which takes into account the Brightness Temperature (BT) measured by a multispectral sensor [4], the Sea and Land Surface Temperature Radiometer (SLSTR), with a spatial resolution of about 1000 m, the land cover type, vegetation fraction, vapor water, season, time of day (morning in our case) and satellite zenith view angle. LST data were collected through the platform *CREODIAS* and refers to the morning acquisitions of A Sentinel-3 satellite for consistency with the dynamic data of the structure. Then, they have been specifically processed for use within an SHM procedure. In particular, as the platform allows the download of the data relating to different surfaces for each acquisition, the time series of a specific point need to be reconstructed, reordering the data sequentially. This required an intermediate step since the acquisition do not always frame precisely the same coordinates: the data were brought back through a triangulation-based linear interpolation on the nodes of a pre-established grid, centered on the coordinates of the Sanctuary. Fig. 1a shows the average LST value calculated over two years at the 11 km x 11 km grid points, while Fig. 1b reports the time series of 2018 referring to the coordinates of the Sanctuary.

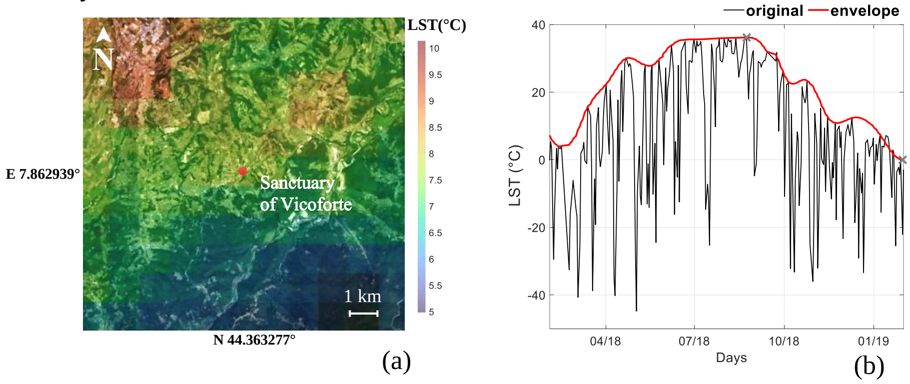

Fig. 1. Two-year (2018-19) average LST interpolated on the 11 km x 11 km grid around the Sanctuary superimposed on Google Earth view (a); LST time series: original and enveloped signal for S3A (morning) in 2018 (b).

At first glance, it is evident that the series show a seasonal trend that seems interrupted by sudden drops with very low values. Since the latter is not reliable temperature values (about -40 ° C) for the latitude of the sanctuary, as probably refer to a low value of BT rather than a true drop in temperature, they were neglected. In detail, the upper envelope of the 2018 series was calculated, in order to consider only the seasonal trend and ignore the fast variations which, even if they refer to reliable values, such rapid variations would be mitigated by the high thermal inertia of the structure.

2 Case study: the Sanctuary of Vicoforte and its FEM

Historical structures like the Sanctuary of Vicoforte are important as they represent the history of the countries in a specific era and their preservation is paramount. The Vicoforte sanctuary is an exemplary case as it has been statically and dynamically monitored for several years thanks to a network of sensors and has been virtually reconstructed in a software FE with very high accuracy. For the sake of brevity, details on monitoring systems and identification procedure have not been reported but can be found in [5], while, as regards the FEM, we limit ourselves to reporting the details useful for the following analyses, but the complete description is given in [6].

The soil underlying the sanctuary is made of silt and marl-stone. The disposition of the two materials is not uniform and in fact, 2 of the 8 buttresses of the sanctuary rest on the marl-stone layer and the others on silt. The foundations of the structure end about 5 m from the ground level. The structure is mainly made of masonry with the exception of some elements (reinforcement bars, exterior and dome struts), which were not considered in the temperature (and therefore of the Young modulus) change. The calibrated parameters of the involved macro-elements are reported in Table 1.

Table 1. FEM updated parameters of the main macro-elements.

Element	Young's Modulus [GPa]	Mass Density [Kg/m^3]	Poisson Ratio [-]
Silt	0.53	1900	0.35
Marl-Stone	3.99	2100	0.35
Foundation	1.42	1800	0.35
Main-Body	1.42	1800	0.35
Drum	1.63	1700	0.35
Buttresses	3.91	1700	0.30
Dome	3.99	1800	0.35
Lantern	3.99	1800	0.35
Towers	3.21	1800	0.35

3 Frequency temperature variations

In a previous work by some of the authors [7], the strong dependence between the experimental dynamic response of the Sanctuary (in terms of frequencies) and some environmental phenomena, among which the air temperature stands out, was shown. Here, to model this dependence within a FE software, as well as the thermal effect on the soil at different depths, the simplified model reported in 3.1 has been considered.

3.1 Temperature dependent elastic parameters

The simplified model in Eq.(1) for the Young's modulus of materials $E(T)$ and temperature T is considered [8]:

$$E(T) = (E_0 - rT)\left[1 + \left(\alpha_l(T) - \alpha_s(T)\right)T\right] \tag{1}$$

where r is the tangent at small relative temperatures (i.e. around 273.15 K) of the temperature-Young's modulus law that ideally describes the thermal agitation effects, while E_0 is a fictitious (fictitious because the law is linearised at small relative temperatures) zero Kelvin Young's modulus. Moreover, $\alpha_l(T)$ and $\alpha_s(T)$ are the coefficients of thermal expansion for liquid and solid part of the material, as a function of the absolute temperature T. Generally, $\alpha_l(T) >> \alpha_s(T)$ and thus $\alpha_l(T)$ - $\alpha_s(T)$ ~ $\alpha_l(T)$. For this study, in the first approximation, a negligible contribution is considered for the thermal agitation effect in the variation of Young's modulus with environmental temperatures values and, accordingly, r is assumed to be zero. Finally, since the liquid component in masonry (as in other materials) is mainly constituted by water, the law becomes:

$$E(T) \approx E_0[1 + \alpha_{H2O}(T)T] \tag{2}$$

where $\alpha_{H2O}(T)$ is the coefficient of thermal expansion of water. For $\alpha_{H2O}(T)$ at different absolute temperatures, the values reported at https://webbook.nist.gov/chemistry/ has been used to exactly fit a high order polynomial when T>273.15 K, while an average fitting with the same polynomial has been applied for T<273.15 K, as for temperatures lower than 0 °C, water in pores can coexist in a liquid and solid phase up to approximately -50 °C [9]. Thus, at a macroscopic scale, the coefficient of thermal expansion of objects will fit in an intermediate state. The phase transition between liquid water and ice also determines a high variation of the coefficient in the proximity of 0 °C. It is worth mentioning that this model has not been experimentally validated yet.

In Eq.(1) and (2), the absolute temperature T is the temperature of the material. For the structure, this temperature is provided by thermometers installed over the sanctuary as well as by data of air temperature [7]. For soil and foundations, instead, the temperature is estimated along the depth starting from the surface temperature supposed as obtained by the envelope of LST data. For this aim an approximate solution of the spatial damped diffusion equation is used in the present paper:

$$\frac{\partial \Delta T}{\partial t} = \alpha \frac{\partial^2 \Delta T}{\partial z^2} + \beta \frac{\partial \Delta T}{\partial z} \tag{3}$$

with $\alpha > 0$ and $\beta > 0$ material constants; z indicates the depth (positive downward) and ΔT is the absolute (in Kelvin) temperature amplitude around the mean value. Imposing the amplitude of LST as a boundary condition in z=0 (surface) for any time, and imposing $\partial \Delta T(0,t)/\partial z = 0$, the following equation is derived:

$$T(z,t) = \overline{LST} + \Delta LST(t) \cdot e^{-\frac{\beta}{2\alpha}z}\left[\cos\left(z\sqrt{\frac{\lambda}{\alpha}\left(1 - \frac{\beta^2}{4\lambda\alpha}\right)}\right) + \frac{\beta}{2\alpha\sqrt{\frac{\lambda}{\alpha}\left(1-\frac{\beta^2}{4\lambda\alpha}\right)}}\sin\left(z\sqrt{\frac{\lambda}{\alpha}\left(1 - \frac{\beta^2}{4\lambda\alpha}\right)}\right)\right] \tag{4}$$

where α is the thermal diffusivity, $\overline{LST}$ is the mean value of LST over the observed time, $\Delta LST(t) = LST(t) - \overline{LST}$; β =$2\sqrt{\pi\alpha/T_0}$ [10], where T_0 represents the fundamental period of ΔLST. Finally, λ is theoretically equal to $-\partial \Delta LST/\partial t/\Delta LST$, and has been fixed equal to the median value of the observations after discarding the negative results. In order to cast these results in the FE model, the temperatures of the various layers of soil have been estimated as the average values between the thickness of the layers used to discretize the soil:

$$T_{z_i z_{i+1}}(t) = \frac{\int_{z_i}^{z_i+1} T(z,t)\,dz}{z_{i+1} - z_i} \tag{5}$$

where $z_{i+1} > z_i$ are the boundaries coordinates of the soil layer i. Being the estimate of T_0 available from experimental data, the only unknown in (4) is the thermal diffusivity. To find its value, the temperature at z=3.6 m measured in the inspection on December 17, 2020, was used to minimize the difference between the prediction obtained by (4) and the experimental read, i.e. 15 °C, on those specific value of z and time. The minimization is performed over a window of thermal diffusivity values that range from 0.1e-7 m^2/s to 100e-7 m^2/s with step 0.1e-7 m^2/s, in accordance with typical values of literature for silt and marlstone [10], [11] and using as a cost function the normalized error. Table 2 reports the values of parameters estimated by experimental records and by the numerical minimization, while in

Fig. 2, the temperature at changing time and depth and the average temperature of the soil layers are depicted.

Table 2. Parameters of the temperature-depth model.

T_0 [s]	λ [1/s]	α [m^2/s]
2.7034e+07 (about 312 days)	2.2451e-07	9.8000e-07

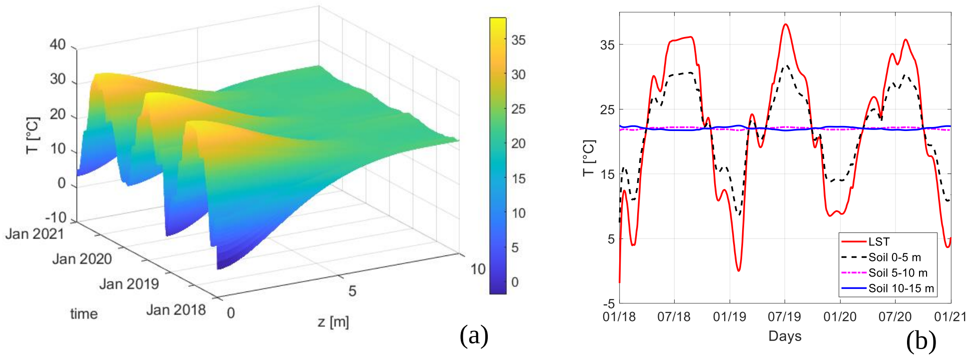

Fig. 2. Time-depth distribution of soil temperature(a), mean temperature at different depth (b).

Having LST and the temperature of the masonry, through Eq.(5) and (2) the Young's moduli of the different materials of the FE model can be estimated at several temperature values, and thus, natural frequency vs temperature relations can be drawn starting from FE analysis aimed to find the eigen-solutions for the sanctuary.

3.2 Simulations and results

In this part, the frequency variation due to the change of the temperature of the macro elements (listed in Table 1) due to the environmental thermal condition and LST has been studied. The FE model was used for assigning the Young's modulus related to a specific temperature based on the described laws. For each element, three temperatures (LST or masonry Temperature) were considered: the maximum, the minimum (see Fig. 1b) and the average recorded between 01/02/2018 and 31/01/2019, since the experimental frequencies are available for this period, without discontinuity. In this first study, it is assumed for simplicity that the dynamic response is mostly influenced by the temperature of the elements; the other EOVs are neglected. Temperature variation in each material was analyzed independently, and then it has been applied to all elements together. Results on the first two frequencies were reported in a double graph (Fig. 3) and superimposed on the experimental values of the sanctuary.

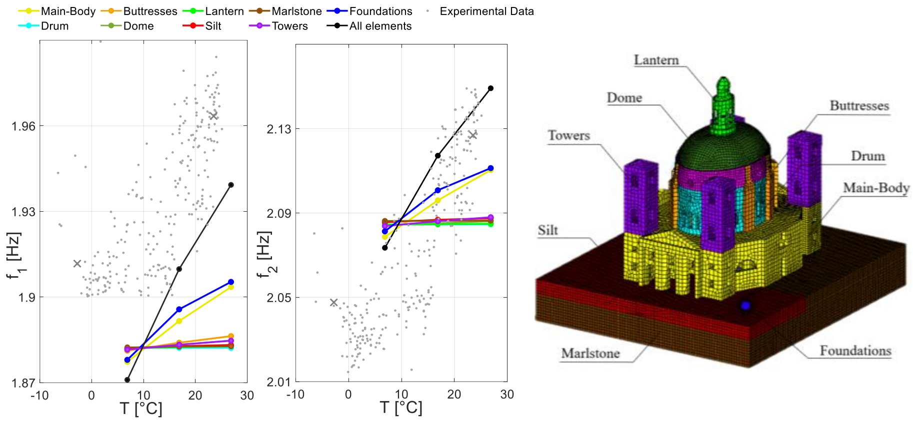

Fig. 3. Frequency-Temperature relation for: Silt, Marl-Stone, Foundation, Main-Body, Drum, Buttresses, Dome, Lantern, Towers, and All Structural Components.

It can be seen that most of the lines in the graphs tend to be horizontal, which means that the temperature change of those elements does not affect the frequencies of the structure. The elements that generate significative variations are the foundations and the main-body. When the temperature variation is applied to all elements together, the frequency change is even sharper and seems to follow the slope of the experimental data: the systematic difference between experimental and numerical frequencies can be resolved with a refinement of the FEM calibration.

4 Conclusions

From the analyses that have been conducted, bearing in mind the simplifying hypotheses and models considered, the following conclusions can be drawn:

- It is reasonable to think that remote sensing data, in this case multispectral data, can be used for SHM. The interpolation and calculation of the parameters on fixed points

solves the problem of the instability of the measurement points between one acquisition and another and filters designed for the specific parameter and aim make it possible to have reliable data over time that can be crossed with those acquired on site.
- Manifold hypotheses and models at different levels of complexity can be designed to couple remote sensing data to those on site and in this paper a basic example that also involves a FEM is shown. Based on the latter, the *direct* effect of the temperature on the ground seems to be less influential than that on the masonry. The ground is characterized by high thermal inertia and the deeper layers are subjected to very low thermal variations over the year compared to the emerging structure, directly exposed to climatic phenomena. Moreover, *indirect* effects, such as evaporation triggered by temperature and the consequent variation in saturation degree and mechanical properties of the soil, have not been considered here and require further studies. The authors are planning to apply a further satellite parameter, the Soil Water Index (SWI) concerning the degree of saturation, to overcome this simplification.

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