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Experimental and numerical dynamic identification of a historic masonry bell tower accounting for different types of interaction

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ABSTRACT

Advances in dynamic numerical analyses and investigation techniques nowadays allow to simulate the seismic behavior of structures through increasingly detailed models, calibrated on in-situ dynamic surveys. The different factors affecting the calibration procedure should, however, be well identified and properly represented in the model. Usually various forms of interaction may influence the building response (i.e. soil-structure, surrounding buildings, etc.) and so their single contribution on the overall response of the coupled system should properly be ascertained. In the paper, the results of numerical analyses and on-site dynamic identification are compared, to quantify the role exerted by the structure, the foundation, the soil and the adjacent buildings on the overall dynamic behavior of the highest tower in Napoli (Italy). The experimental frequencies and the corresponding deformed shapes were reproduced through a simplified model on springs, simulating the soil-foundation impedance. The inferred dynamic behavior of the tower was observed to be significantly influenced by the restraint exerted from adjacent buildings and by the interaction with the soil.

The results were corroborated by the more refined predictions provided by a complete 3D Finite Difference model of soil, foundation and structure. In addition, a frequency detected from field records, which has not been identified in previous analyses on fixed base models, was found to be associated to the rocking response of the foundation.

1. Introduction

The performance of existing buildings under static and seismic loads can be reliably analyzed through numerical models, provided that material properties are measured from field surveys and laboratory tests. A higher degree of accuracy is required for the safety assessment of heritage buildings, due to the lack of knowledge on the original design and the construction procedures. In order to avoid any damage to the artistic value, non-destructive techniques are required to collect information on the hidden geometry and on the material properties of structural elements [1].

The global dynamic behavior of a structure may be identified through the interpretation of the displacement (or velocity or acceleration) time histories recorded under ambient vibrations through instruments placed on the building ([2–6]). The records contain the effect of the dynamic interaction between Soil, Foundation and Structure (SFS). For the accurate interpretation of the experimental results, as well as for the proper calibration of numerical models, the role of SFS interaction should be properly taken into account, since the resonant period of the compliant-base system increases with respect to those provided by the fixed-base model [7–9].

To simulate the effects of dynamic interaction, the structure, the foundation and the soil can be approximated with more or less refined models. In the most refined approach, both the structure and the soil are simulated through continuum models [10]. Conversely, in the simplest and most widespread approach, the structure is modeled as a lumped mass system and the presence of the soil is introduced through a combination of springs and dashpots placed at the base of the structure and associated to each degree of freedom of the foundation. The spring stiffness and the damping coefficients are computed from the impedance functions characterizing the foundation and the surrounding soil [11,12].

The oldest and most widespread solutions for the impedance functions are relevant to the case of rigid foundations vibrating on the surface of an elastic half-space [11–13]. This assumption is realistic only if the foundation is very shallow and significantly stiffer than the underlying uniform soil, whereas in most cases foundations are actually deformable and embedded in a layered soil. Soil in-homogeneity may

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be introduced in the calculation by assigning to the half-space appropriate visco-elastic parameters, making it equivalent to the layered soil volume involved in the interaction with the superstructure [14]. The main effect of the embedment is an increase of the stiffness, which is more pronounced for the rocking than for the translational modes. As a consequence, the embedment should be taken into account in the analyses of tall structures, for which the rocking behavior is usually more relevant due to their high aspect ratio.

Numerous formulae have been proposed in the literature, e.g. those collected by Gazetas [12] for circular, strip, rectangular and arbitrarily shaped rigid foundations. Nevertheless, the hypothesis of a rigid foundation is generally unrealistic for an ancient structure due to the ageing, weathering and other deteriorating phenomena. Pitilakis et al. ([15]) advised to take into account the foundation flexibility, since it implies a reduction of the impedance proportional to the relative stiffness between the foundation material and the underlying soil.

Several experimental and/or numerical studies on historical Italian towers are reported in literature, e.g. the Ghirlandina tower [16], the Giotto bell tower in Florence [17], the Pisa tower [18], the S.M. in Fabriago and S. Apollinare in Classe bell towers [19]. For all the mentioned cases, the vibration modes and frequencies detected on-site have been compared to the numerical results predicted by models of structures placed on springs provided of stiffness calculated under the assumption of rigid foundation resting on the surface of an elastic half-space.

In the present study, both simplified and advanced numerical models of the SFS system were used to assess the dynamic response of the Carmine bell tower in Napoli. The masonry bell tower is located between two buildings and is endowed with wall foundations extending in a deformable deposit of man-made ground and alluvial sands, overlying volcanic tuff (§2). The dynamic response of the simplified model was analyzed through modal analyses, considering the compliance of the soil and the flexibility of the embedded foundation (§3). Periods and deformed shapes of the advanced model (§4) were calculated in the frequency domain by exciting the model with a noise-type input motion. In both cases, the effect of the adjacent buildings was investigated, introducing lateral restraints in the models. Resonant frequencies and deformed modal shapes of the simplified and advanced models were compared and assessed with reference to the results of a previous experimental dynamic identification [20,21].

2. The case study of Carmine bell tower in Napoli

2.1. Structure and foundation

The 68 m high Carmine bell tower is the tallest historic construction in Napoli (southern Italy, Fig. 1a). The bell tower is part of the "Carmine Maggiore" monumental complex, including a church, a monastery and the S.S. Rosario friary, all connected by a cloister as reported in Fig. 1b-c.

The first literature reference about the presence of a bell tower dates back to the XV century [22]. In 1456, an earthquake with magnitude $M_W \approx 7.2$ and the epicenter located in Ariano Irpino (63 km far from Napoli, see Fig. 1a) induced a macro-seismic intensity I_{MCS} = VIII at Napoli. The existing bell tower was severely damaged and in 1458 another structure began to be constructed on the top of the residual basement. Three levels of externally dressed yellow-tuff stone walls were built [20]. The actual bell tower was finished in 1615, when the octagonal brickwork cell (from 40 m to 56 m) and a pyramidal spire were built (see Fig. 2a-b).

An accurate investigation was performed on the structure by Ceroni et al. [20], including a geometrical survey as well as the measurement of the elastic properties and the peak strength through pulse-echo-technique and double flat-jack tests, respectively.

Geophysical surveys (electrical resistivity tomography, ERT, and ground penetrating radar, GPR) as well as vertical and inclined boreholes have been recently performed to investigate the foundations, as reported in detail by [1,23]. The foundation of the bell tower coincides with the E-W main walls, which extend 2 m below the ground level (see Fig. 2c). The foundation widens out about 0.30 m in the middle part and 0.5 m in the corners, i.e. approximately one and two 'spans' according to the Aragonese system of measure (1 span ≈ 0.26 m, see [24]).

Even though the bell tower is located between other constructions (see Figs. 1c and d), historical investigations [20] suggested to exclude any structural connection. Therefore, both the interaction with the adjacent church on the North side of the tower (up to the elevation of 19 m) and with the S.S. Rosario friary on the South side (until 16 m) can be assumed as due to only contact constraints. Dynamic in-situ tests were carried out, i.e. three days of continuum monitoring of the tower under environmental actions (traffic, bells, wind, and human activities) and localized impulses induced by an instrumented hammer [21]. Three tests were performed changing the instrumentation layout:

- four couples of horizontal orthogonal accelerometers were positioned along x-y directions at the heights of 49 m and 29 m, close to the corners of the main walls;
- four couples of horizontal accelerometers were placed at the heights of 56 m and 19 m, i.e. immediately above the contact between the tower and the lateral buildings;
- one vertical inner corner of the bearing walls was instrumented by placing a couple of horizontal sensors at each of the six levels indicated in Fig. 2a.

Through the basic instruments of the Operation Modal Analysis, the two main frequencies of the tower and the corresponding modal shapes were reliably identified. The two modes are both translational and uncoupled; in particular, the first modal shape is parallel to the North-South direction with a natural frequency of 0.68 Hz, while the second one is parallel to the East-West direction with a frequency of 0.76 Hz. Higher order flexural modes were experimentally identified at frequencies 2.28 and 2.35 Hz for the NS and EW direction, respectively. Finally, a further resonant frequency of 2.77 Hz was found in both directions, but not clearly associated to a modal shape. As discussed in the following, the complete soil-foundation-structural model enabled the clarification of the nature of this resonant frequency.

2.2. Soil investigations

A deep borehole was drilled down to a depth of 59 m, very close to the external access to the bell tower (black dot in Fig. 1c). For the uppermost 3.7 m, the ruins belonging to the ancient Aragonese wall were intercepted. As reported by de Silva et al. [23], the underlying lithological sequence (see Fig. 2d) is typical of the Eastern coastal area of Napoli [25]: Man-made Ground (MG) down to a depth of 10 m, Marine Sand (MS) interbedded with Pyroclastic Soil (PS) down to 31 m, constituted by volcanic ash lenses and pyroclastic silty sand, 'pozzolana', overlying a layer of lightly cemented Yellow Tuff (YT) followed by Green Tuff (GT). The water table was intercepted at a depth of 2 m, exactly at the foundation level of the tower (Fig. 2d). A Down-Hole test was performed in the borehole to measure the compression (V_P) and shear (V_S) wave velocity profiles down to 56 m (Fig. 2d). Below the ground level, an unusually high value of V_S (500 m/s) was found and ascribed to the Aragonese walls. Thereafter, the V_S profile showed the typical values of the cohesion-less soils, increasing with the depth in the underlying man-made ground and then nearly constant (about 300 m/s) in the upper layer of Marine Sand. A significant seismic impedance contrast was detected in the Tuff formation, with values of V_S gradually increasing from 650 m/s at the roof of the YT to 785 m/s in the GT.

The compression wave velocity profile, V_P, is clearly less variable than the profile of V_S. As the groundwater level is intercepted, V_P assumes the typical value of saturated soils.