SENSITIVITY ANALYSIS OF SEISMIC
SOIL-Foundation-Structure interaction
IN MASONRY BUILDINGS FOUNDED ON CAVITIES

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ABSTRACT

Historical urban centers are often characterized by cavity systems beneath the foundations or underground stories of masonry buildings. This may have an impact on the expected damage induced by earthquake excitations. This paper presents the nonlinear dynamic analysis of a historical multistory building made of stonemasonry load-bearing walls and horizontal diaphragms, taking into account the complex interaction between the foundation system and soil. The aim of this research is to evaluate whether and how the presence of an underground floor and cavity influences the Soil-Foundation-Structure (SFS) interaction. Dynamic analyses of 2D SFS models were performed with the finite difference method (FDM), by varying geotechnical and structural properties such as the soil stratigraphy, the basement depth and the number of building stories. The main results of 234 dynamic linear elastic analyses are presented in a dimensionless format. A new equivalent wave parameter was properly defined to take into account the presence of underground level and cavities in SFS interaction. Relationships between the most important parameters controlling the interaction phenomena are proposed. Since the geometric layouts considered in this study are rather recurrent in the Italian and European built heritage, the proposed procedure might be widely extended to comparable cases.

Keywords: Soil-Foundation-Structure interaction; cavity; masonry buildings; 2D FDM dynamic analysis.

1. INTRODUCTION

Although the fixed-base models are commonly adopted in the seismic assessment of buildings, it is well known that nonlinear structural response can be affected by the dynamic interaction with the underlying soil (e.g. Gazetas, 1983; Mylonakis & Gazetas, 2000; Kausel, 2010). With respect to the fixed-base structure, the fundamental period of the Soil-Foundation-Structure (SFS) system increases and additional energy is dissipated by wave radiation and soil hysteresis (Wolf, 1985; Mylonakis et al., 2006). Both effects are associated to the compliance of the subsoil with respect to the above ground structure, which is usually termed ‘inertial interaction’. If the foundation depth is relevant, ‘kinematic interaction’ due to the relative soil-foundation stiffness can modify the seismic motion that would be transmitted to the structure in free field conditions, as observed for instance by Elsabee & Morray (1977) and Kim & Stewart (2003).

To reproduce the effects of the inertial interaction, integrated SFS capacity models with different levels of sophistication are available in literature. In the simplest approach, the structure is reduced to a single
degree-of-freedom system standing on translational and rotational springs and dashpots, reproducing the impedance of a rigid foundation resting on a homogeneous, linear elastic halfspace (Bielak, 1975; Veletsos & Meek, 1974; Veletsos & Nair, 1975). The introduction of equivalent properties is necessary to take into account the flexibility (Pitilakis & Karatzetou, 2015) and the complex geometry of an actual foundation system, as well as the presence of a layered soil (Gazetas, 1983; Stewart et al.; 2003). This aspect is a substantial limit in the analysis of historical masonry buildings, which are generally endowed with an irregular underground level. Moreover, the masonry walls are frequently built by using the rock material available on site. Such quarrying activities often originate underground cavities close to the buildings, leading to peculiar interaction phenomena under static and seismic actions (e.g. Scotto di Santolo et al., 2016). In this study, the variation of the fundamental period of the SFS system associated with the presence of an underground floor and a cavity is examined through 2D full dynamic analyses through accurate finite difference models. Several geotechnical and structural properties were considered, including the relative size and position of the cavity, the soil layering, the basement depth and the number of building stories.

2. SOIL-Foundation-STRUCTURE MODELS

Many masonry buildings in European historical centers have a geometrical configuration in elevation similar to those shown in Figure 1a-b. Shallow masonry foundations were generally adopted by deepening and widening the main walls below the ground floor. In most cases, an embedment of few meters was required to ensure building safety against gravity loads, so an underground floor with the function of crawl space or cellar to store food was built. A preliminary investigation by the authors (Piro et al., 2017) demonstrated that the presence of an underground floor can influence the dynamic behavior and reparability of the whole system, highlighting some of the most important parameters that control SFS interaction. As a follow-up of the pilot study, the present paper reports a sensitivity analysis in which geometrical and mechanical properties of the soil-cavity-structure systems were changed according to Tables 1 and 2. 2D structural models of a historical building were ideally taken out as transverse sections having two slender load-bearing walls, single-span floor systems consisting of steel joists, and a pitched roof with similar 1D elements. The following variables were considered: the height, \( h \), and the width, \( b \), of the building structure; the foundation depth, \( D \); the shear wave velocity of soil, \( V_s \); the mass density of soil or masonry, \( \rho \); the shear modulus of soil or masonry, \( G \); the Poisson’s ratio of soil or masonry, \( \nu \); the span, \( L \), and the height, \( H \), of the cavity. The ratio \( b/D = 4 \) reported in Table 1 is referred to the structure on embedded foundation shown in Figure 1a. The thickness of the main walls was reduced along the height, leading to a gradual increase in the floor span starting from the ground floor. By contrast, inter-storey height was assumed to be constant along the building elevation. The physical and mechanical properties of the masonry were inferred from the results of uniaxial compression tests performed by Augenti and Parisi (2010) on a brickwork wall made of Neapolitan Yellow Tuff. The values of the shear wave velocity, the density and the Poisson’s ratio of the soil were selected as representative of ground types A, B, C, D, as defined by the Italian Building Code (MIT, 2008). In addition to homogeneous soil cases, three variants of layered subsoil models were analyzed, accounting for the increase of soil stiffness with depth. The effects of an underground cavity were also investigated through the SFS models in Figure 1c-d.
Figure 1. SFS models under investigation: (a) embedded foundation; (b) underground level; (c) embedded foundation and cavity; (d) underground level and cavity.

Table 1. Geometrical properties of soil-cavity-structure system.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Cavity</th>
<th>Homogeneous soil A; B; C; D</th>
<th>Layered soil C-B; D-B; D-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>b (m)</td>
<td>h/b</td>
<td>b/D (m)</td>
<td>H (m)</td>
</tr>
<tr>
<td>8</td>
<td>1; 1.5; 2</td>
<td>4*; 2; 1.6; 1.3</td>
<td>5</td>
</tr>
</tbody>
</table>

*without the underground level.

Table 2. Elastic properties of soil and masonry.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>$V_s$ (m/s)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$G$ (MPa)</th>
<th>$\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>soil A</td>
<td>1200</td>
<td>2200</td>
<td>3170</td>
<td>0.20</td>
</tr>
<tr>
<td>soil B</td>
<td>600</td>
<td>2000</td>
<td>720</td>
<td>0.25</td>
</tr>
<tr>
<td>soil C</td>
<td>300</td>
<td>1800</td>
<td>162</td>
<td>0.30</td>
</tr>
<tr>
<td>soil D</td>
<td>150</td>
<td>1600</td>
<td>36</td>
<td>0.35</td>
</tr>
<tr>
<td>Tuff stone masonry</td>
<td>-</td>
<td>1600</td>
<td>1650</td>
<td>0.25</td>
</tr>
</tbody>
</table>

3. LINEAR DYNAMIC ANALYSES

A total of 234 plane-strain dynamic analyses in the time domain of the four SFS models shown in Figures 1a–d were carried out with the FDM code FLAC 2D ver. 7.0 (Itasca, 2011). The soil domain shown in Figure 2 is 50 m large and 30 m deep and the structure is placed in the center. The bedrock is simulated through a 5 m-thick layer placed below the soil volume and characterized by the properties of soil type A. The infinite extension in depth of the bedrock is simulated by dashpots attached to the bottom nodes along the normal and shear directions. To minimize the model size, the so-called ‘free-field’ boundary conditions were imposed along the lateral sides, simulating an ideal horizontally layered subsoil profile connected to the main-grid domain through viscous dashpots.
The SFS system was discretized into a huge number of square elements. The horizontal floor systems and the pitched roof truss were modeled through beam elements with 1 m-wide homogenized cross section having the following material properties: unit weight $\gamma = 17.5 \text{kN/m}^3$ and Young’s modulus $E = 30,000 \text{MPa}$ for the floor system; and $\gamma = 3.0 \text{kN/m}^3$ and $E = 1300 \text{MPa}$ for the roof system.

Since FLAC software is not able to directly carry out modal analyses, the procedure developed by de Silva et al. (2017) was used to compute the effective period of the SFS system. The models were excited by a noise signal (frequency $f = 1\div10 \text{ Hz}$, duration $t = 10 \text{ s}$) applied as a shear stress time history at the bottom of the model. The structural response was numerically monitored over 20 s, to record the free vibration behavior of the SFS system after the end of the forced-vibration stage.

Firstly, the fundamental frequency of the subsoil was evaluated by computing the transfer function as the ratio between the Fast Fourier Transform (FFT) of the free-field acceleration at the ground level and that of the input motion. The results are reported in Table 3 for both homogenous and two-layer subsoil models. As expected, the natural frequency of a homogeneous soil is reduced by the presence of a softer uppermost layer (e.g., $f_{\text{soil}}=5 \text{Hz}$ for homogenous soil type B vs. $f_{\text{soil}}=4.3 \text{Hz}$ for C-B two-layer subsoil) and the reduction is more significant with the increase of the impedance contrast between the two layers ($f_{\text{soil}}=4.3 \text{Hz}$ for C-B subsoil vs. $f_{\text{soil}}=3.3 \text{Hz}$ for D-B).

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>C-B</th>
<th>D-B</th>
<th>D-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{\text{soil}}$ [Hz]</td>
<td>10</td>
<td>5</td>
<td>2.50</td>
<td>1.25</td>
<td>4.30</td>
<td>3.30</td>
<td>2.50</td>
</tr>
</tbody>
</table>

The frequency $f_0$ of the fixed-base structure, i.e. founded on the subsoil type A, is reported in Tables 4-5 for all the geometries considered, respectively without and with underground cavity. Note that such a frequency depends only on the structural pattern (here expressed through the $h/b$ ratio), while it is not affected either by the geometry of foundation (i.e. the $b/D$ ratio) or by the presence and the shape of the cavity (i.e. the $L/H$ ratio).
Table 4. Fundamental frequencies of SFS systems founded on subsoil type A

<table>
<thead>
<tr>
<th>without cavity</th>
<th>h/b=1</th>
<th>h/b=1.5</th>
<th>h/b=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>h/D</td>
<td>4°</td>
<td>2</td>
<td>1.6</td>
</tr>
<tr>
<td>f₀ (Hz)</td>
<td>5.0</td>
<td>4.9</td>
<td>4.9</td>
</tr>
</tbody>
</table>

*without the underground level

Table 5. Fundamental frequencies of SFS systems founded on subsoil type A, in presence of a cavity

<table>
<thead>
<tr>
<th>with cavity (L/H = 1, 1.2, 1.4, 1.6)</th>
<th>h/b=1</th>
<th>h/b=1.5</th>
<th>h/b=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>h/D</td>
<td>4°</td>
<td>1.6</td>
<td>4°</td>
</tr>
<tr>
<td>f₀ (Hz)</td>
<td>5.0</td>
<td>4.9</td>
<td>2.9</td>
</tr>
</tbody>
</table>

*without the underground level

As an illustrative example, Figure 3 shows the dynamic response of the whole SFS system, in the cases of structure with h/b = 1.5, foundation embedded with b/D = 1.6, and homogenous soil A, B, C, D. In detail, Figure 3a reports the displacement time histories, plotted at different structure elevations (see the reference points in Figure 1), and Figure 3b the Fourier spectra obtained by the FFT computed in the free vibration stage. In these latter plots, the resonant frequency of each SFS system, denoted as f₁, is clearly highlighted by the spectral peaks, while the dashed lines indicate the soil fundamental frequencies reported in Table 3.

It can be observed that, as the natural frequency of the soil approaches that of the structure (cases A to B), the peak displacement amplitudes at each elevation gradually increase, but the fundamental frequency of the SFS system keeps the constant value of 2.9 Hz. For the subsoil type C, f_soil becomes 2.5 Hz, slightly lower than f₁; the peak displacements further increase and occur at frequencies varying from f_soil to f₁ with the elevation. A further increase of deformability of the soil (case D) induces a reduction in f₁, an increase in the foundation motion but reduced structural displacements, with much lower inter-storey drifts. Such a decay of the peak amplitudes is associated with the increase of the overall damping of the SFS system, since a higher amount of energy is dissipated by radiation through the foundation.

4. DISCUSSION OF RESULTS

Following the usual notation of studies on soil-structure interaction, the results of the whole parametric study are hereafter synthesized in a dimensionless format, i.e. in terms of relationship between the ratio f₁/f₀ and the soil-structure relative stiffness parameter, σ = V_S/f₀h. Veletsos and Meek (1974) defined σ in the simple case of a linear visco-elastic SDOF structure (with mass m, stiffness k and viscous damping coefficient c), supported by a rigid foundation placed over a homogeneous, linear elastic halfspace. In more realistic cases of structures with foundation or underground levels embedded in layered soil, V_S and h are not clearly defined. Therefore, in this study, the results of the dynamic analyses are reported in terms of the ratio f₁/f₀ and the parameter σ_ea representing the ‘equivalent’ relative soil-structure stiffness. The latter was defined by setting h as the height from the ground floor to the top of the structure and V_Seq as follows:

\[
V_{Seq} = \frac{V_{S,str}A_{str} + V_{S,up}A_{up} + V_{S,low}A_{low}}{A_{str} + A_{up} + A_{low} + A_{void}}
\]  
(1)

in which V_{S,str} is the shear wave velocity of the masonry, computed on the basis of the relevant shear
modulus, $G_{str}$, and mass density; $A_{str}, A_{void}$ are the areas of the underground structure and inner space; $V_{S,up}, V_{S,low}$ and $A_{up}, A_{low}$ are the shear wave velocities and the areas of the soil layers expected to be excited by the horizontal motion of the foundation. When the subsoil is homogeneous, $V_{S,up} = V_{S,low}$. The extension in depth of this zone of influence (shown in Figure 4a) was assumed as equal to the width of the building, $b$, as proposed by Gazetas (1983) and confirmed by Stewart et al. (2003) on the basis of experimental data.

![Figure 3](image)

Figure 3. (a) Time histories and (b) FFTs of horizontal displacements at different structural elevations (SFS system with $h/b = 1.5$ and $b/D = 1.6$, homogeneous ground types A, B, C, D).
Such formulation of the relative soil-structure system stiffness, $\sigma_{eq}$, implicitly includes the stiffening of the foundation due to the presence of the underground level. The variation of $\sigma_{eq}$ with the ratio between the shear modulus of masonry and that of the soil, $G_{str}/G_{soil}$, is plotted in Figure 4b. As the soil stiffness decreases (i.e. $G_{str}/G_{soil}$ increases), $\sigma_{eq}$ tends to a constant value mainly associated to the structural slenderness.

Figure 4. (a) Soil volume affected by the horizontal motion of the foundation and (b) dependency of $\sigma_{eq}$ on $G_{str}/G_{soil}$.

Figure 5 shows the numerical data points expressing the dependency of the frequency ratio on the relative stiffness, fitted with the following hyperbolic function:

$$\frac{f_1}{f_0} = 1 - \frac{\alpha}{\sigma_{eq} - \beta}$$

where $\alpha$ and $\beta$ are regression coefficients, reported in Table 5 and Table 6 along with the coefficient of correlation $R$.

For high values of $\sigma_{eq}$, i.e. increasing the soil stiffness, eq. 2 tends to unity, i.e. the frequency of the SFS system approaches the fixed base value.

The trends of the curves in Figure 5 (continuous lines) highlight that the presence of an underground level ($b/D = 2, 1.6, 1.3$) implies that:

- a sudden drop of the SFS frequency occurs approximately below $\sigma_{eq} = 15$ for $h/b = 1$ and $h/b = 1.5$, almost independently of $b/D$;
- the frequency of the most slender structures ($h/b = 2$) is hardly affected by SFSI.

The results obtained for the structure without the underground level ($b/D=4$) are expressed as a function of the classical expression of $\sigma$ (Veletsos and Meek, 1974) and plotted with dashed lines in Figure 5. They show a satisfying agreement compared to the curves (black dashed lines) proposed by Veletsos and Meek (1974) and those (black dot lines) proposed by Aviles & Perez Rocha (1998), for different slenderness ratios.
Figure 5. Variability of $f_1/f_0$ with $\sigma_{eq}$ in SFS models without cavity.

Table 5. Regression coefficients $\alpha$ and $\beta$ and Pearson coefficient $R$ of the hyperbolic curves fitting the numerical results.

<table>
<thead>
<tr>
<th>b/D</th>
<th>$h/b=1$</th>
<th>$h/b=1.5$</th>
<th>$h/b=2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.25 0.1 0.1</td>
<td>0.22 0.07 0.09 0.07</td>
<td>0.1 0.01 0.02 0.01</td>
</tr>
<tr>
<td>$\beta$</td>
<td>8 12 13 14</td>
<td>7.5 12.5 13 15</td>
<td>9 14 16 17</td>
</tr>
<tr>
<td>$R$</td>
<td>0.76 0.88 0.86 0.83</td>
<td>0.84 0.99 0.95 0.99</td>
<td>0.89 0.79 0.90 0.63</td>
</tr>
</tbody>
</table>

*without the underground level

Table 6. Regression coefficients $\alpha$ and $\beta$ and Pearson coefficient $R$ of the hyperbolic curves fitting the numerical results, in presence of a cavity.

<table>
<thead>
<tr>
<th>b/D</th>
<th>$h/b=1$</th>
<th>$h/b=1.5$</th>
<th>$h/b=2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.25 0.10 0.22</td>
<td>0.09</td>
<td>0.10 0.02</td>
</tr>
<tr>
<td>$\beta$</td>
<td>8 13 7.5</td>
<td>13</td>
<td>9 16</td>
</tr>
<tr>
<td>$R$</td>
<td>0.78 0.86 0.83</td>
<td>0.93</td>
<td>0.89 0.90</td>
</tr>
</tbody>
</table>

*without the underground level
No significant differences between the different structural geometries were recognized in the presence of the cavity, as shown in Figure 6. This depends on the fact that the soil volume affected by the foundation motion does not include the cavity. Further analyses are in progress to assess the SFSI sensitivity to the size and depth of the cavity.

Figure 6. Variability of $f_1/f_0$ with $\sigma_{eq}$ in SFS models with cavity.

5. CONCLUSIONS AND PERSPECTIVES

The seismic response of the soil-foundation-structure system depends on several geometrical and mechanical properties of the system components. This study was aimed at developing a simplified tool to evaluate the influence of the soil deformability on the fundamental frequency of the SFS system, in complex geometrical configurations to which existing simplified procedures do not apply. To this purpose, the variation of the fundamental frequency of the SFS system with respect to the corresponding fixed-base response was evaluated as a function of the relative soil-structure stiffness. Based on 234 linear dynamic analyses, a simplified hyperbolic regression model was developed. The relative stiffness parameter of the SFS system was defined so that the presence of an underground level and a cavity could be taken into account.

Since the analyzed geometric layouts are recurrent in the Italian and European building heritage, the proposed procedure might be extensively applied. Further research is ongoing to assess variations in the SFS damping and the effects of masonry stiffness and shallower cavities.

6. ACKNOWLEDGMENTS

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7. REFERENCES


