Proceedings 10th NUMGE 2023
10th European Conference on Numerical Methods in Geotechnical Engineering
Zdravkovic L, Kontoe S, Taborda DMG, Tsiampousi A (eds)

https://doi.org/10.53243/NUMGE2023-426

Modal analysis of 3D soil models for solving coupled soil-structure interaction problems

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ABSTRACT: Recent advances in hardware and software computational tools allow complex 3D modelling of both soil and structure to be developed. The choice of a proper volume of soil interacting with the superstructure is a crucial issue in seismic soil-structure-interaction analysis. As a prerequisite, the dynamic response of the soil deposit needs to be properly reproduced. The fundamental frequencies of the soil deposit may be obtained numerically by simulating the propagation of an input signal within the soil deposit and computing the transfer function between top and base acceleration signals or by modal analysis to minimise the computational efforts of long time-domain analyses. Modal analysis is very popular in the structural field but it is rarely applied to identify the dynamic response of coupled systems made of both soil and structure. Due to the presence of the soil domain, the modal analysis provides for many more vibration modes and a further cumbersome procedure to identify the real modes of the structure among the many calculated needs to be performed. In this study, 3D time-history and modal analyses were carried out on soil deposits with different geometrical and stratigraphic features. It was found that modal analysis provided straightforward results for simpler subsoil configurations while for the more complex ones, characterized by relevant stratigraphic and topographic variability, it allows to discriminate the local modes of vibration from the global ones in relation to the participating mass involved.

Keywords: 1D, 2D and 3D numerical models; finite element method; soil frequencies; modal analysis; topographic and site effects.

1 INTRODUCTION

The seismic response of natural soil deposits may be strongly influenced by geometrical factors, such as stratigraphic and topographic irregularities, other than peculiar soil and earthquake features. Field evidences collected worldwide and numerical modelling have highlighted that ground motion modification, amplification or deamplification, occurs in correspondence of valleys, ridges and slopes (Amanti et al.,2020; Luo et al. 2020¸Massa et al.,2014; Barani et al.,2014; Assimaki et al.,2004; Paolucci, 2002; Bouchon et al.,1996). In these cases, the fundamental frequencies of the subsoil cannot be evaluated straightforwardly through closed-form solutions or simple 1D numerical computations with plenty of codes specific for site response analysis (Shake, EERA, STRATA, Proshake, DeepSoil, etc.).

Starting from the 1980's of the last century, many research works were devoted to identify the effect of valleys or ridges on soil fundamental frequency with respect to the 1D solution (Bard and Bouchon, 1985; Bard and Gariel, 1986; Bard and Riepl-Thomas, 2000; Kumar and Narayan, 2018). With reference to valley configurations, the above studies have highlighted that the fundamental frequency of the soil inside the valley mainly depends on the valley shape ratio, i.e. the maximum depth of the valley over its half-width.

Nowadays, due to advances in hardware and software computational tools, it is much more affordable to per form three-dimensional modelling for complex and large soil domains. However, the estimation of the dynamic response of such domains, even in the linear range, i.e. at low strain levels, represents a crucial aspect of earthquake geotechnical engineering. For 3D models, the dynamic identification of the soil deposit, with estimation of its natural frequencies, may be achieved by simulating the propagation of an artificial low-amplitude accelerometric signal (white noise) from the base to the top of the model. By converting both input and output signals from time to frequency domain, the dynamic features of the soil deposit may be obtained by means of transfer functions, for example, between the signals at the top and the bottom of relevant vertical lines within the soil deposit. This procedure, however, is heavy and time-consuming especially for large analysis domains as those involved in soil-structure interaction analysis of linear infrastructures (dams, embankments or bridges).

To reduce the above computational efforts, the classical modal analysis turns useful to quickly identify the dynamic response of complex soil deposits. The soil domain, especially in case of 3D complex configurations, is characterised by a very high number of degrees of freedom. Therefore, the identification of the significant modes from the overall vibration modes calculated from the modal analysis is computationally very intensive. Among all the obtained modes, the identification of the modes relevant to the soil is of paramount importance to filter out the dominant modes of the structure in the coupled system. The knowledge of the fundamental frequencies of the soil alone, hence, is a first step to discriminate in a second stage the modes of vibration relevant to the structure.

The modal analysis procedure, available in the adopted commercial software Midas FEA NX, was firstly validated with reference to a simplified soil deposit, characterized by horizontal and parallel layers but modelled by a 3D geometry. Later on, the same procedure has been extended to a more complex subsoil, characterised by stratigraphic and topographic variability.

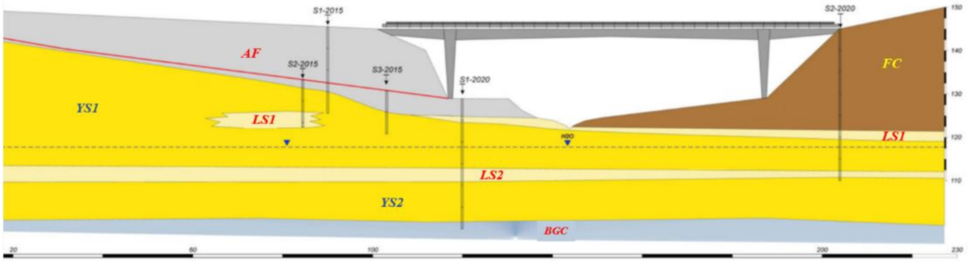

Figure 1. Cross-section of the valley in correspondence of the bridge with location of the available geotechnical boreholes

2 THE CASE STUDY

To properly identify the dynamic and seismic response of bridges and other strategic infrastructures through a direct approach, a suitable portion of the soil interacting with the structure needs to be included in the numerical model, with all morphological and stratigraphic details. It is worth pointing out that in the seismic field the soil volume interacting with the superstructure is much wider than the classical pressure bulb used as reference in the static field and, in principle, should encompass all soil layers found upon the bedrock formation.

In particular for bridges, the subsoil model should be as accurate as possible in order to properly simulate the ground motion at the base of the piers and to account for eventual out-of-phase motion between the bridge supports. The case history considered in this paper is schematically represented in Figure 1. It is an old reinforced concrete bridge located in Southern Italy, founded on a complex alluvial soil deposit. To simulate the valley, the digital elevation model of the area was firstly developed starting from public photogrammetric surveys of the area. Subsequently, the geotechnical model of the subsoil was achieved by collecting the geotechnical data from five boreholes carried out at the bridge site (Figure 1) and from previous geotechnical surveying campaigns. The following soil layers were identified: artificial fill (AF), alluvial deposits consisting of sand and pebbles (YS), fluvial colluvium deposits (FC), alluvial deposits consisting of sandy silt to clayey places (LS), and blue-grey clayey silt (BGC). The rigid bedrock formation, represented by the bottom blue-grey clay layer, was detected at a depth of 65 m starting from the ground level in correspondence of the base of the east pier (borehole S1-2020). In this location, a horizontal-to-vertical spectral ratio (HVSR) test was performed, which delivered peaks of the amplification function at frequencies of 2.07 Hz, 4.5 Hz, 10 Hz and 16 Hz. Table 1 reports the main physical and mechanical properties of the identified soil layers.

Table 1. Physical and mechanical properties of the soil layers

Layer	γ [kN/m^3]	V_s [m/s]	G_0 [MPa]	D_0 [%]
AF	18	370	256	2
FC	18	185 - 225	63 - 94	2
LS 1	18.45	320	198	2
YS 1	21.26	300 - 640	192 - 903	2
LS 2	18.45	660	822	2
YS 2	21.26	680	1004	2
BGC	18.78	650	815	2
Bedrock	18.79	800	1200	2

3 NUMERICAL MODELLING AND ANALYSIS PROCEDURE

The bridge and the subsoil around it were modelled by finite elements through the software Midas, FEA NX. Since in this paper the focus is on the geotechnical aspects of the problem and, in particular, on the identification of the dynamic response of the soil deposit, the structural details will be omitted for sake of brevity. As stated above, the paper tries to shed light on the use of modal analysis for identifying the natural frequencies of 3D soil domains. This procedure could significantly reduce the computational effort of long time-history (TH) analyses and storage of big data. The modal frequencies of the soil deposit will be compared to those provided by TH analysis simulating the propagation of a low-amplitide white-noise signal (total duration of 30s, sampling frequency of 100 Hz and Δt equal to 0.01s).

After propagating the input signal from the bottom of the model toward the ground surface, top-to-base transfer functions were computed to obtain the fundamental frequencies of the soil at specific locations.

3.1 *Preliminary validation of the numerical procedure on a simplified soil model*

Before modelling the complex valley sketched in Figure 1, a validation test of the overall numerical procedure was performed on a simplified model made of horizontal and parallel soil layers, which has been deliberately modelled in 3D even though the problem geometry is clearly 1D. Table 2 reports the main physical and mechanical parameters assigned to the soil layers for this run. Since the final goal is the identification of the fundamental frequencies of the soil deposit at low strains, a linear visco-elastic behaviour was attributed to all soil layers, considering the initial values of shear stiffness G_0 and damping D_0.

Table 2. Soil properties (De Angelis et al., 2022)

Layer	Depth [m]	γ [kN/m^3]	V_s [m/s]	G_0 [MPa]	D_0 [%]
AF	0 - 3	17	210	76	1
YS	3 - 13	20	540	595	1
CC	13 - 20	23	1340	4212	1

Preliminary, a 1D linear elastic site-response analysis was carried out through the open-source software STRATA (Kottke et al., 2009). The 1D amplification function shown in Figure 3 provides for three peaks at frequencies of 6.9, 14.7 and 24.4 Hz. Subsequently, an eigenvalue analysis was conducted on both a 2D vertical cross section (Figure 2) and on the overall 3D soil domain, sketched in Figure 3. As boundary conditions regard, suitable free-field elements, similar to the infinite elements used to model unbounded domains, were applied along the vertical boundaries of the 2D and 3D f.e. models. The use of nodal springs was avoided since an incorrect calibration of their stiffnesses could significantly alter the frequency response identified through modal analysis. With the use of free-field elements along the vertical boundaries, the participant mass associated to each mode is lower since the total mass matrix also includes the mass of the free-field elements. In addition, this boundary condition may be adopted also for time-history analyses. The obtained results in terms of modal shapes are reported in Figure 2 (a-c) while the corresponding fundamental frequencies and modal participation factors are listed in Table 3. Perfect agreement was obtained between the results of 2D and 3D modal analyses.

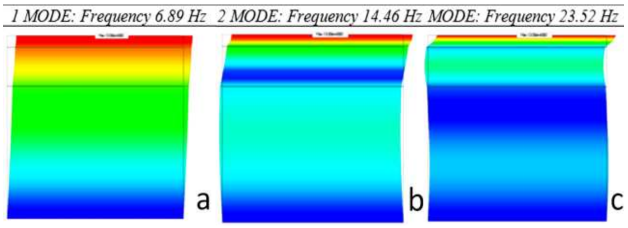

Figure 2. Modal shapes of the 2D model: (a) 1° mode, (b) 2° mode and (c) 3° mode of vibration

Table 3. Fundamental frequencies and participation factors obtained through the 2D modal analysis

Mode	f [Hz]	m_y [%]	m_z[%]	m_{rx} [%]
1	6.9	74.1	0	5.3
2	14.5	11.1	0	5.0
3	23.5	2.5	0	2.2

Table 4. Fundamental frequencies and participation factors obtained through the 3D modal analysis

Mode	f [Hz]	m_x [%]	m_y [%]	m_{rx} [%]	m_{ry} [%]
1	6.9	35.1	2.0	0.2	3.5
1	6.9	2.0	35.1	3.5	0.2
2	14.4	0.1	9.9	7.2	0
2	14.4	9.9	0.1	0	7.2
3	21.4	3.3	2.2	2.0	1.4
3	21.4	2.2	3.3	2.0	1.4
4	23.4	1.2	0.1	0.1	1.4

Once the fundamental frequencies of the simplified soil domain were properly identified by modal analysis (and compared to the values corresponding to the peaks of the 1D amplification function provided by STRATA), also a TH analysis was carried out on the 3D soil domain in MIDAS. The overall results are shown in Figure 3, in which it is evident that all 1D/2D/3D time-history analyses and the modal analyses (single plots in Figure 3) gave the same results, with additional intermediate frequencies provided by the 2D and 3D models.

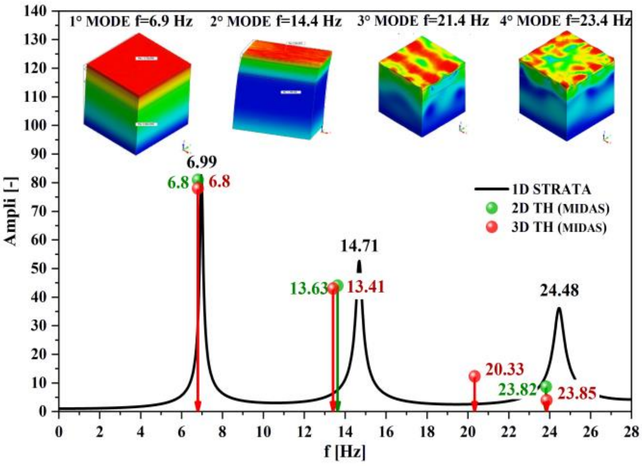

Figure 3. Comparison of 1D, 2D and 3D analysis results for the simplified soil model

3.2 *Analysis of the selected case study*

After validating the overall numerical procedure on the simplified soil configuration illustrated above, the same procedure was carried out for the case study of the bridge valley in Figure 1.

The generated 3D model (Figure 4) has extension in plan of 250m x 200m and a maximum depth of 65m, corresponding to the bedrock roof in the middle of the valley.

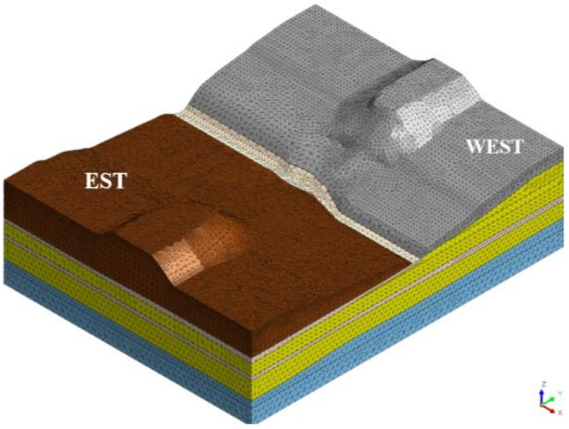

Figure 4. 3D Numerical model of the case study

Fifteen vertical lines have been identified within the 3D soil domain (Figure 5), in order to perform 1D linear analyses with the software STRATA.

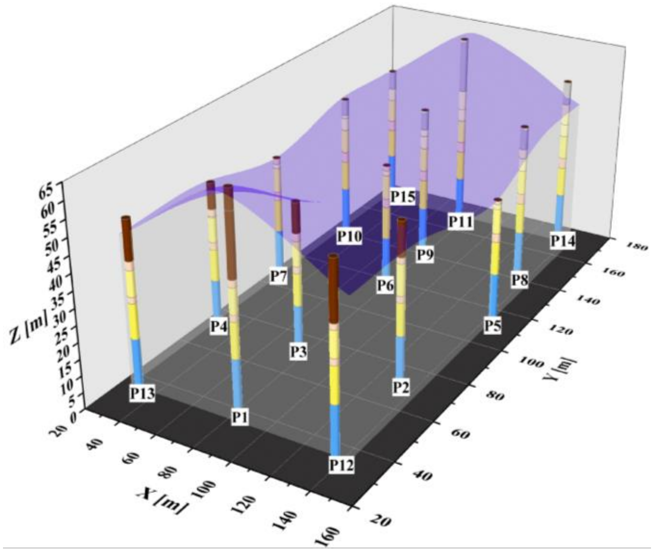

Figure 5. Reference verticals selected in the 3D model for comparing with 1D site response analysis

In addition, eight vertical cross sections (Figure 6), which englobe the vertical lines used for the 1D site response analyses, were selected to perform 2D TH analysis with the white-noise signal as input.

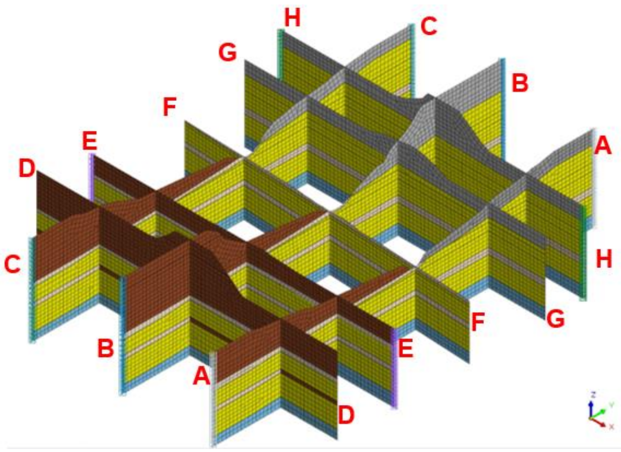

Figure 6. Vertical cross sections selected in the 3D model for performing 2D TH analyses

For the sake of brevity, the fundamental frequencies and amplification functions will be provided only for the most important locations, i.e. in correspondence of the central longitudinal section of the valley (sect. B-B) and the bridge piers (sect.s E-E and H-H) (Figure 6).

In Figure 7, the amplification functions obtained by 2D TH analyses and the frequencies (single bar) provided by STRATA have been compared. Likewise the simplified soil model discussed in the previous section, the 2D models provide for additional frequencies compared to the 1D simulation, especially in the zones where strong topographic irregularity exists.

Finally, both TH and modal analyses were carried out on the overall 3D model (Figure 4) with the software MIDAS FEA NX. For the entire surface corresponding to the ground level, the fundamental frequencies identified from the peaks of the amplification function provided by the TH analysis are shown in Figure 8, together with the frequencies obtained from the 1D analyses (single points). It can be observed that in correspondence of verticals P1, P3, P6 and P11, where the topographic effects play a predominant role, the 3D model gives significantly different frequencies compared to both 1D and 2D models. In these sites, the highest amplifications occur at higher frequencies. On the other hand, where the irregularities are less pronounced the amplification peaks for the different models (1D, 2D and 3D) occur amost at approximately the same values.

Figure 9 shows the results obtained from a 3D modal analysis. Eight vibration modes with the highest values of participating mass have been identified. The response of the valley covers the frequency range from 2 Hz (1 mode) to 10 Hz (8 mode). Due to the geometry complexity, there are both local modes of vibration affecting individual zones of the slope, and global modes regarding the whole domain.

Comparing the results of the 3D TH analysis with the results of the 3D modal analysis, it emerges that there is a satisfactory correspondence between the first mode of vibration, which involves only the EAST side of the slope, and the second mode of vibration, which involves the WEST side of the valley. Actually, the fundamental frequencies associated to the first two oscillation modes correspond to those obtained by the the 3D TH analysis (Figure 8 a-b).

Figure 10 shows the percentage error between the fundamental frequencies provided by modal and TH analyses for the first two modes of vibration of the 3D model. A global mode of vibration is activated around 5Hz, corresponding to the frequency found for most of the valley in Figure 8(a). A second global mode provided by modal analysis may be found close to 7 Hz, corresponding to the dominant value computed by TH analysis in Figure 8(b).

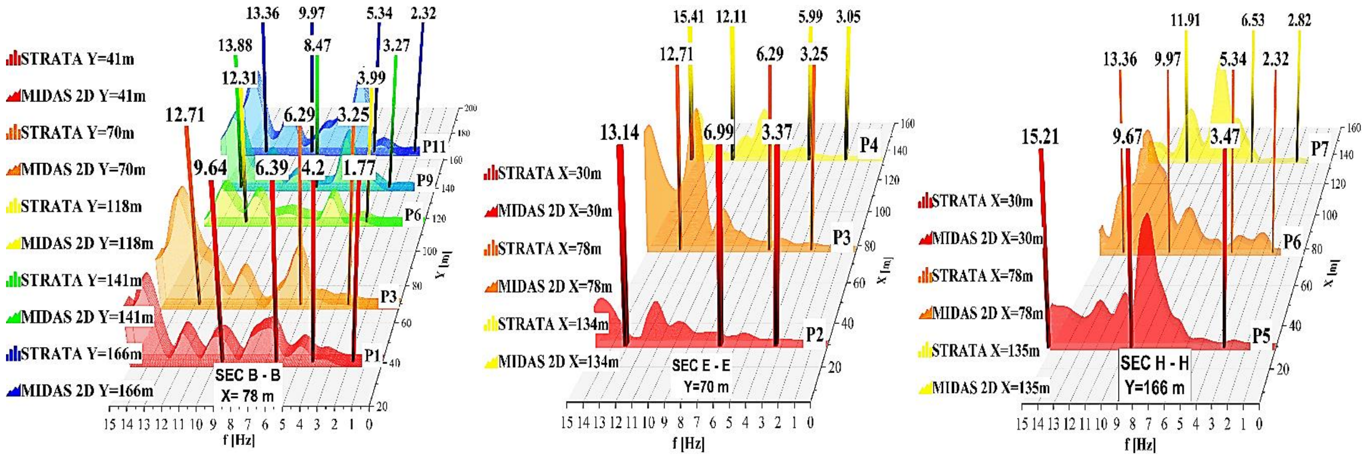

Figure 7. Amplification function at fixed locations (P_i) provided by 2D TH analyses and fundamental frequencies (single bars) provided by 1D site response analysis

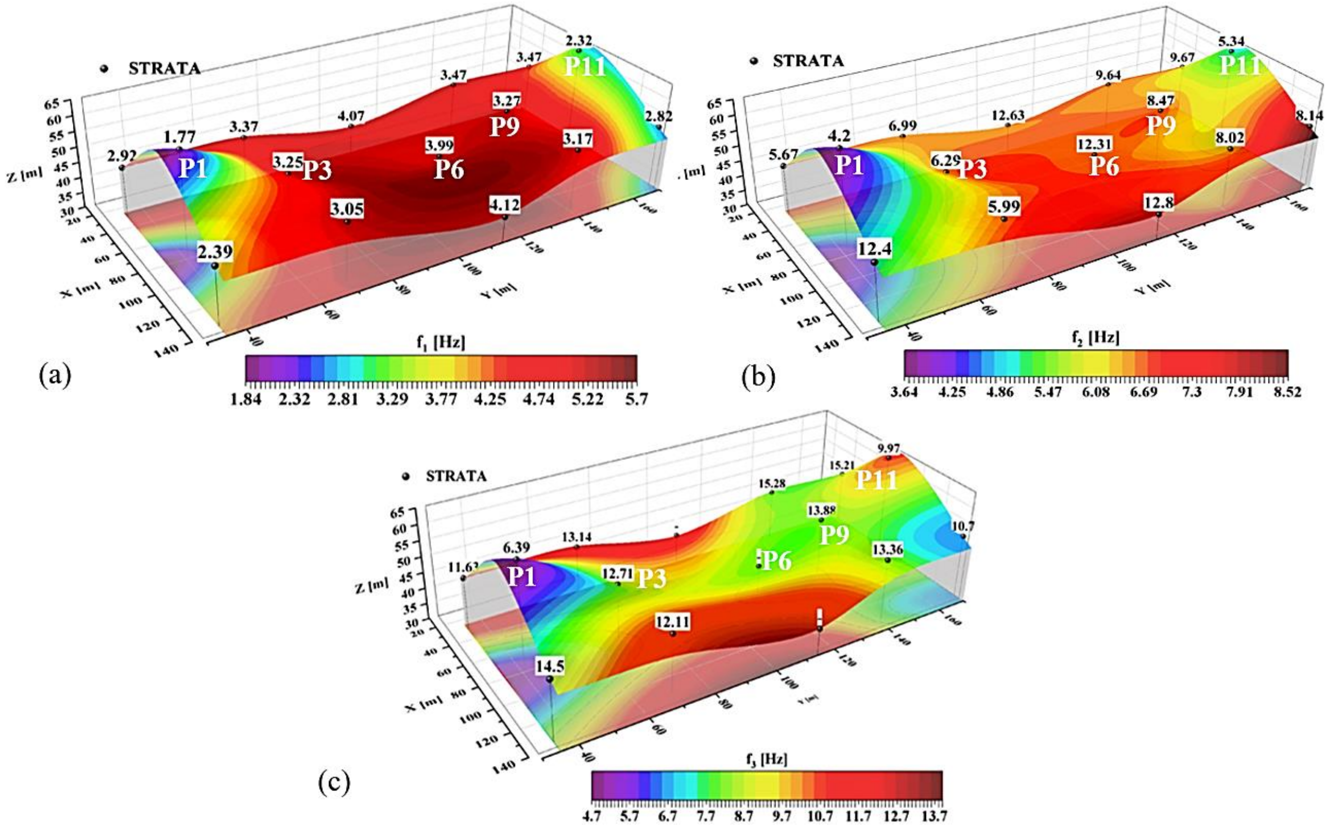

Figure 8. Spatial variability of the first (a), second (b) and third (c) fundamental frequency obtained by a 3D time-history analysis of the valley

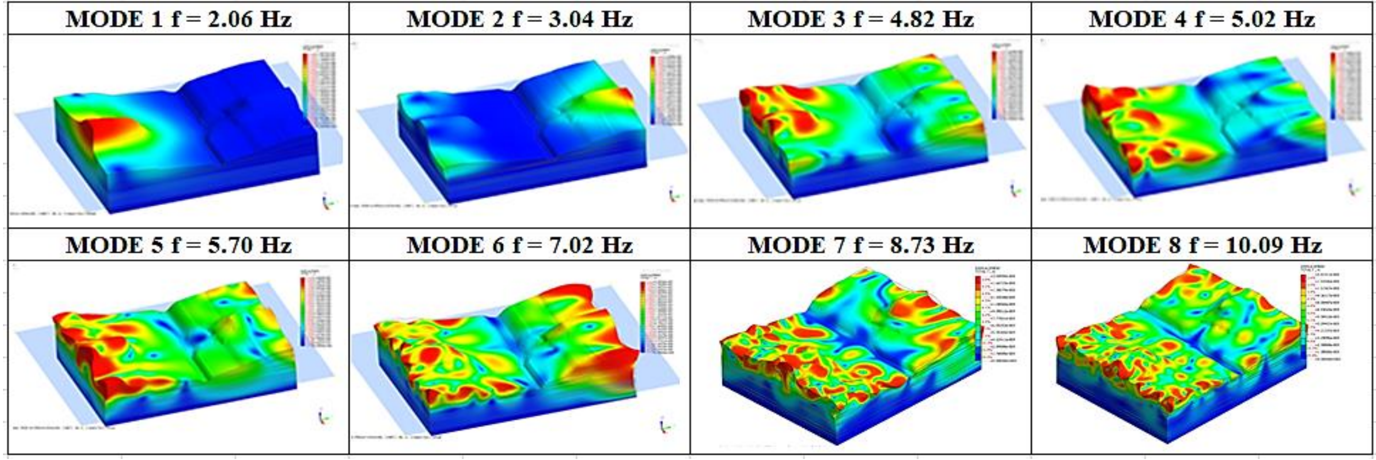

Figure 9. Frequency and mode shapes of the eight oscillation modes of the valley

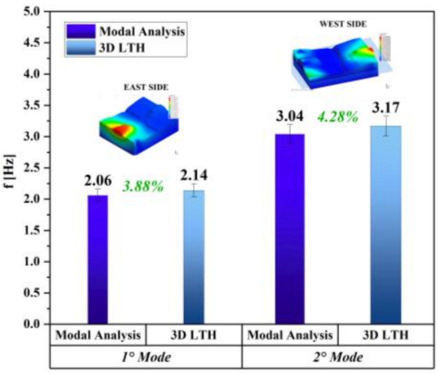

Figure 10. Comparison between 3D modal and TH analyses for the first two modes of vibrations

4 CONCLUSION

The paper tried to shed light on the potentiality of modal analysis for identifying the dynamic response of a complex subsoil, characterized by strong topographic and stratigraphical variability. Reference was made to a valley crossed by a bridge with a quite refined geotechnical investigation.

Both modal and time-history (white noise) analyses have been perfomend with the same finite element software, Midas FEA NX. The numerical procedure was prelininarly validated on a simplified 3D soil domain. From the numerical study it emerged that the dynamic response of the valley in the linear regime was not reproduced neither by 1D or 2D models. Converseley, 3D modal and time-history analyses allowed to identify all possible modes of vibration of the subsoil. The identification of the vibration modes of the soil domain without the structure was a crucial step in the overall computational process, which allow us to distinguish the vibration modes of the soil from those of the structure when the coupled system will then be solved. The numerical study was limited to the hypothesis of linear elastic behaviour of the soil. As future perspective, soil nonlinearity will be accounted for and the seismic analysis of the complete system, made of bridge and soil, will be carried out.

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