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Eccomas Proceedia COMPDYN (2017) 1347-1359

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

LARGE SCALE SOIL-FOUNDATION-STRUCTURE MODEL IN GREECE: DYNAMIC TESTS VS FEM SIMULATION

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Keywords: Soil-structure interaction, soil non-linearity, soil-foundation interface behaviour

Abstract. *This paper provides the results of FEM simulation of dynamic tests recently performed in Thessaloniki on a large-scale single-degree-of-freedom structure resting on a soft soil. The structure (named EuroProteas) was specifically designed to mobilize strong soil-structure interaction (SSI), being a particularly stiff structure founded on soft soil. It consists of a simple steel frame with removable X-bracings founded on a RC slab and supporting the superstructure mass of two RC slabs identical to the foundation slab. It is a totally symmetric structure. Subsoil stratigraphy and dynamic properties of the foundation soil are derived from extended geotechnical and geophysical surveys, including static and dynamic in-situ and laboratory tests. Extensive free- and forced-vibration tests were performed. This paper deals with one set of forced-vibration tests. An eccentric mass shaker was used as a source of harmonic excitation (f_{input} = 3, 4.5, 5, 7 Hz and eccentricity 6.93kg-m) imposed on the roof of the structure. The structural response is recorded by seven accelerometers, five of which are located at the top of the roof slab and two at the top of the foundation slab. Soil response is recorded with seismometers installed on the free soil surface in both horizontal directions. Dynamic FEM modelling of the tests were conducted in the time and frequency domains in order to detect the main aspects of SSI, taking into account soil nonlinearity. Numerical and experimental results were extensively compared. Very interesting results were reached above all in terms of the effects of soil-foundation interface behaviour.*

doi: 10.7712/120117.5497.16830

1 INTRODUCTION

Soil-structure interaction (SSI) has been widely investigated since the 1970s by means of theoretical approaches [1, 2, 3], field and laboratory studies as well as numerical modelling [4, 5, 6, 7, 8, 9, 10, 11, 12, 13].

As for field and laboratory studies, SSI phenomena are commonly studied in small-scale by implementing experiments in shaking-table or centrifuge apparatuses [14, 10, 11, 15, 16]. Laboratory studies are particularly invaluable for the known initial and boundary conditions, and for the large quantity of applied instrumentations. However, very often there are also some disadvantages, such as certain limitations in reproducing actual field conditions (i.e. unbounded subsoil medium, radiation condition to infinity and realistic stress fields in the soil). On the other hand, large-scale field experiments of SSI account for realistic boundary conditions and fulfil the radiation condition to infinity.

Among numerical approaches, finite element (FE) modelling of the whole soil-foundation-superstructure systems is nowadays widely performed. FE modelling allows a realistic evaluation of coupled soil-foundation-superstructure system, in terms of initial and boundary conditions, soil profile, geometry, nonlinearity of soil and/or soil-foundation interface [17]. FEM modelling, combined with field and laboratory tests, is the most useful tools for investigating the complexity of SSI [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30].

In this paper, numerical modelling of a large experimental field campaign to study SSI and wave propagation in the foundation soil due to structural oscillation is presented. The tests were performed in the full-scale experimental facility of EuroProteas in the Euroseistest site, in the north of Thessaloniki, Greece, in the framework of the European project "Seismic Engineering Research Infrastructures for European Synergies, SERIES".

2 EXPERIMENTAL LAYOUT

The EuroProteas structure was specifically designed to mobilize strong interaction with the soil, being a particularly stiff structure founded on soft soil. As shown in Fig. 1.a, it consists of a simple steel frame with reinforced-concrete foundation slab of 3.0x3.0x0.40m, on top of which four steel columns with free height 3.80m are clamped. The steel columns support the superstructure mass of two reinforced-concrete slabs identical to the foundation slab. The four steel columns are connected with steel X-braces in both directions, forming a symmetric structure. The total height from the bottom of the foundation slab to the top of the upper roof slab is 5.0m.

Six experimental campaigns took place, including three sets of free-vibration tests and three forced-vibration tests, performed at different excitation levels. This paper deals with one set of forced-vibration tests. An eccentric mass shaker provided by the Earthquake Planning and Protection Organization EPPO-ITSAK [31] was implemented as a source of harmonic excitation imposed on the roof of the structure. The produced force of the vibrator is governed by the following equation:

$$F = E_C \left(2\pi f_R\right)^2 \tag{1}$$

where F is the shaker output force (in N), E_c is the total eccentricity of the shaker (in kg-m) and f_R is the rotational speed of the shaker (in Hz). The shaker has adjustable eccentricity. For more details, see [32]. The presented forced-vibration tests were performed with eccentricity 6.93kg-m, and input frequencies equal to 3 Hz, 4.5 Hz, 5 Hz and 7 Hz.

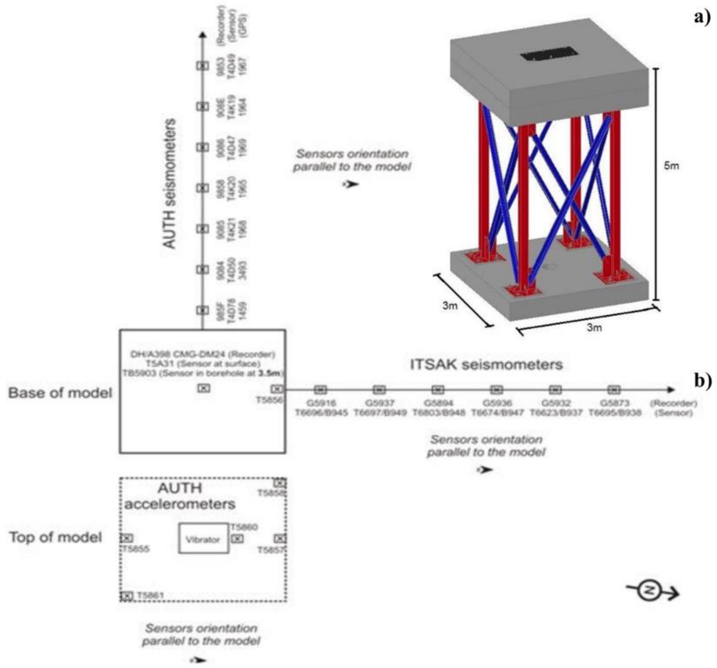

Figure 1: Full-scale experimental facility of EuroProteas in the Euroseistest site established in the Northern Greece: a) the structure; b) the instrumentation layout.

A large number of instruments (more than 80) were installed in every test to monitor structural, foundation and soil response (Fig. 1.b). The structural response was recorded by seven accelerometers, five of which were located at the top of the roof slab and two at the top of the foundation slab. Soil response was recorded by seismometers placed on the soil surface at every 1.5m, up to a distance of 9.0m from the foundation, in two horizontal directions (parallel and perpendicular to the loading direction), so covering an area of 9x9m around the structure. The distance of 1.5m between the sensors was specifically chosen to match half of the foundation width, while the distance of the 9.0m was chosen equal to three times the foundation width, after which structural vibration effects on soil response are negligible according to [2].

As for subsoil stratigraphy and dynamic properties of the foundation soil, they were already documented from extensive geotechnical and geophysical surveys [33]. Nevertheless, in order to define a detailed soil stratigraphy immediately below the prototype structure, additional geotechnical investigations were performed, including static and dynamic in-situ and laboratory tests. Specifically, a 30m deep borehole was drilled in the geometric center of the foundation slab, standard penetration tests were conducted in the 30m deep hole and continuous samples were taken for laboratory tests. The main geotechnical static parameters of four selected samples are shown in Table 1. Fig. 2 shows the soil stratigraphy (on the left) and the V_s profile (on the right), with the corresponding subdivision in 8 layers (A-F). The V_s profile computed from the down-hole array is compared with the results related to another similar site (S1L site) and with those reported in [34]. The latter are considered the most accurate, and therefore they were used in this paper. The average soil shear wave velocity in the uppermost 30m is about 200 m/s. Main dynamic properties of the soil are reported in Table 2. In addition, resonant column (*RCT*) tests were performed on four representative soil specimens, obtaining the $G/G_0(\gamma)$ and $D(\gamma)$ curves shown in Fig. 3.

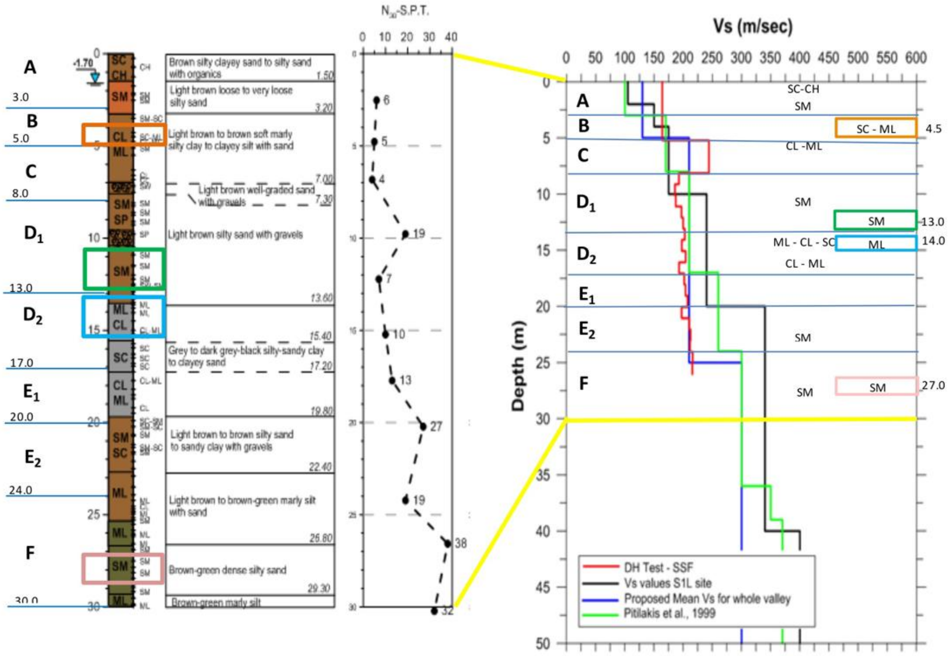

Figure 2: Geotechnical characterization of the foundation soil: soil stratigraphy and N_{SPT} profile (on the left); shear wavevelocity profile from down-hole tests, compared with literature profiles (on the right).

Table 1: Main physical properties of tested soils.

Boring	Sample	Depth (m)	AUSCS	w_w (%)	e
BH1	35	12.45-13.00	SM	27.6	0.485
BH2	8	4.00-4.55	SC-ML	28.9	0.537
BH2	23	13.60-14.00	ML	36.6	0.738
BH2	47	26.80-27.00	SM	27.5	0.677

Table 2: Main dynamic properties for the investigated stratigraphy.

Layer	z (m)	V_s (m/s)	G_0 (kPa)	D_0 (%)	$V_{s,\ av}$ (m/s)	f (Hz)
A	0-3	100	21407	2.5	204.38	0.59
B	3-5	125	32652	3.0	204.38	0.59
C	5-8	170	58919	3.0	204.38	0.59
D1	8-13	210	89908	2.5	204.38	0.59
D2	13-17	210	89908	2.5	204.38	0.59
E1	17-20	260	137819	2.5	204.38	0.59
E2	20-24	260	137819	2.5	204.38	0.59
F	24-30	300	183486	1.75	204.38	0.59

3 NUMERICAL MODELLING

The forced-vibration tests described in the previous section have been simulated by a 2D finite element model (Fig. 4) by means of the ADINA code [35, 36]. The soil, the foundation slab and the roof slabs have been modelled using 9-node 2D solid elements, the steel columns and the X-braces has been modelled using 2-node Hermitian beam elements.

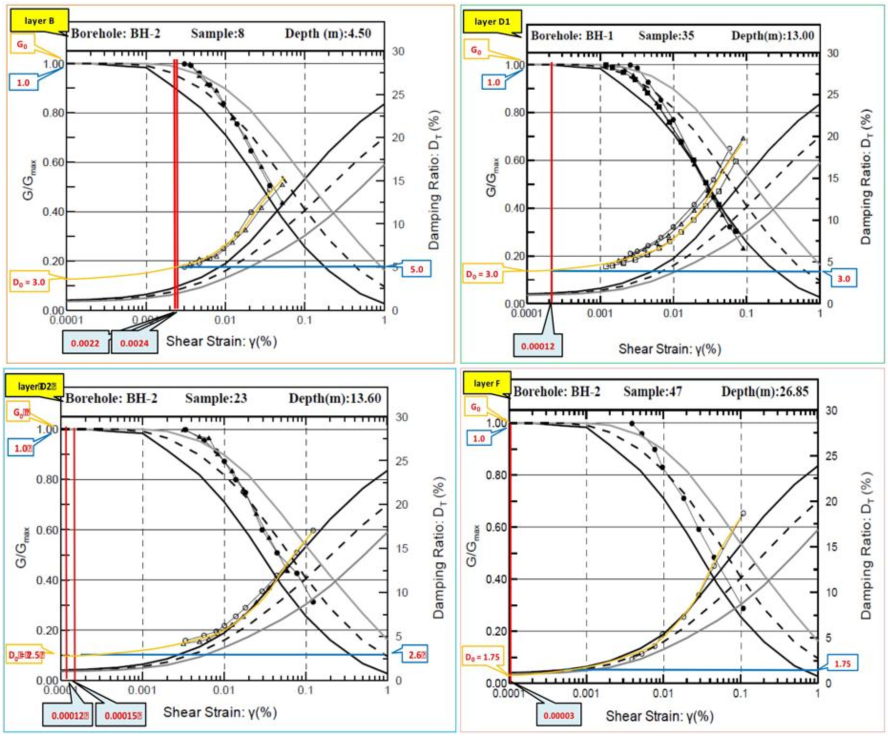

Figure 3: Curves G/G_0 vs γ and D vs γ obtained by RCT tests for the four selected samples (corresponding to four different layers), showing the updating of G and D with the achieved shear strain level, for the f $_{input}$ = 3 Hz.

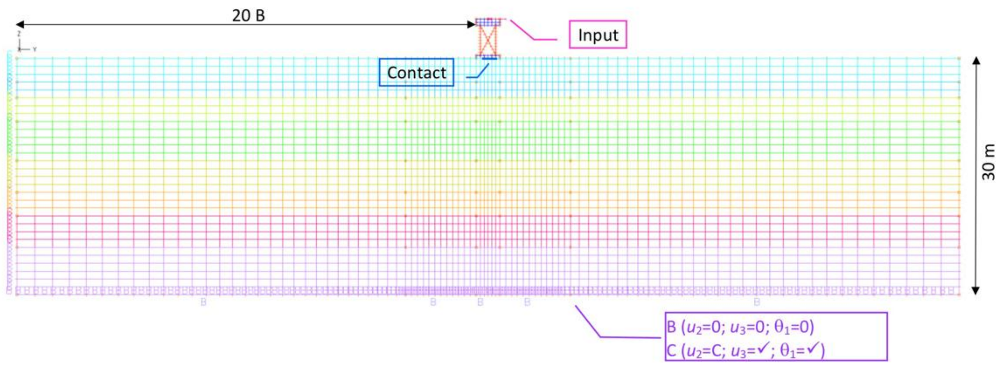

Figure 4: FEM model; showing geometry, loading and boundary conditions.

The horizontal bottom boundary has been fixed 30.00 m from the structure, according to the soil stratigraphy discussed in Section 2; the two lateral boundaries have been chosen considering a distance equal to 20 B from the structure, where B is the dimension of the foundation slab (3m), in order to minimize as much as possible boundary effects. For the horizontal bottom boundary all the displacements and the rotations were fixed; for the lateral boundaries the vertical displacements were free, the rotations were fixed while the horizontal displacements were linked by "constrain equations" that imposed the same horizontal *y*-translation.

The FE model allows foundation-soil sliding and foundation up-lifting phenomena by means of contact laws between the structure and the soil. The soil has been modelled combining the data get by the in-situ tests and the *RCT* tests: the 8 layers (A-F) shown in Figure 2 have been considered, as shown by the different colours of Fig. 4. Both the soil and the structure have been modelled by means of linear visco-elastic constitutive models. But, in order to take into account the soil non-linearity, the shear strain level in the soil has been estimated for each input frequency, and thus the values of G and D have been updated according to the achieved shear strain level considering the D-γ and G-γ curves of Fig. 3 (the updating is shown just for one input frequency, i.e. f = 3Hz). As for the constitutive parameters adopted for the structure, typical values of reinforced concrete and steel have been considered, i.e. for the slabs (reinforced concrete): E = 31500 MPa; ν = 0.2 and ρ = 2.55 kNs^2/m^4; for the steel columns and the steel X-braces: E = 210000 MPa, ν = 0.3 and ρ = 7.5 kNs^2/m^4.

Two loading conditions have been applied: i) a "mass proportional" load has been applied to the whole system, in order to take into account the unit weight of the soil, the concrete and the steel elements; ii) the acceleration time-histories recorded by the T5860 accelerometer (Fig. 1.b) has been applied in the "loading direction" at the center of the roof to simulate the applied excitation.

Finally, in line with the Rayleigh damping approach, the damping matrix has been assumed proportional to the mass and stiffness matrices through the well-known factors α_r and β_r, evaluated as $\alpha_r = D \cdot \omega$ and $\beta_r = D/\omega$, being D the damping ratio of the different involved materials and ω the angular frequency of the involved system [37, 38, 39], considering for the soil an average frequency equal to $V_{s,av}/4h_d$ (Table 2) and for the structure the expression suggested by [40]: $T = C_1 \cdot H^{3/4}$, with $C_1 = 0.075$.

4 COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

The response of the above described system has been analysed in the time and frequency domains in order to detect the main aspects of SSI. In particular, the following physical quantities were studied and compared: recorded acceleration amplification ratio along the ground surface, from the foundation until the distance from it equal to 9.0 m (Fig. 5); experimental and numerical maxima accelerations and also acceleration time-histories for a significant time interval concerning the structure and the soil response (Figs. 6-9); experimental and numerical Fourier spectra in the structure and in the soil surface (Fig. 10).

More precisely, Fig. 5 shows the acceleration amplification ratio measured during the tests along the ground surface, every 1.5m from the structure. It is very important to stress the de-amplification that occurs moving from the foundation to the soil, due to foundation up-lifting, that represents a natural isolation system. This result has been well captured by FEM simulation, as shown in Figs. 6-9. An acceleration decrease of one order of magnitude along the structure, from the top to the base, and along the ground surface, from the accelerometer placed on the foundation and the accelerometer placed at a distance of 9m, can be observed generally for all the input frequencies. The FE modelling satisfactorily captures these experimental results. Some discrepancies exist for f_{input} = 3 Hz, where the numerical acceleration does not decrease along the ground surface moving away from the foundation, in contrast with the experimental accelerations. In finite-element modelling of unbounded media a cut-off frequency exists, below which no radiation damping occurs when the soil properties increase with the depth [41]. For the analysed soil stratigraphy, this cut-off frequency is approximately equal to 4.5 Hz. The analyses in the frequency domain (Fig. 10) confirmed the above-described results.

The careful in situ and laboratory dynamic soil characterization, including soil nonlinearity evaluation, certainly contributed to the overall good agreement between experimental and numerical results for both the structure and soil response. This underlines, once more, the fundamental role played by soil characterization and modelling for the realistic prevision of the seismic behaviour of soil-structure systems and in turn for the safety seismic design and/or retrofitting of structures.

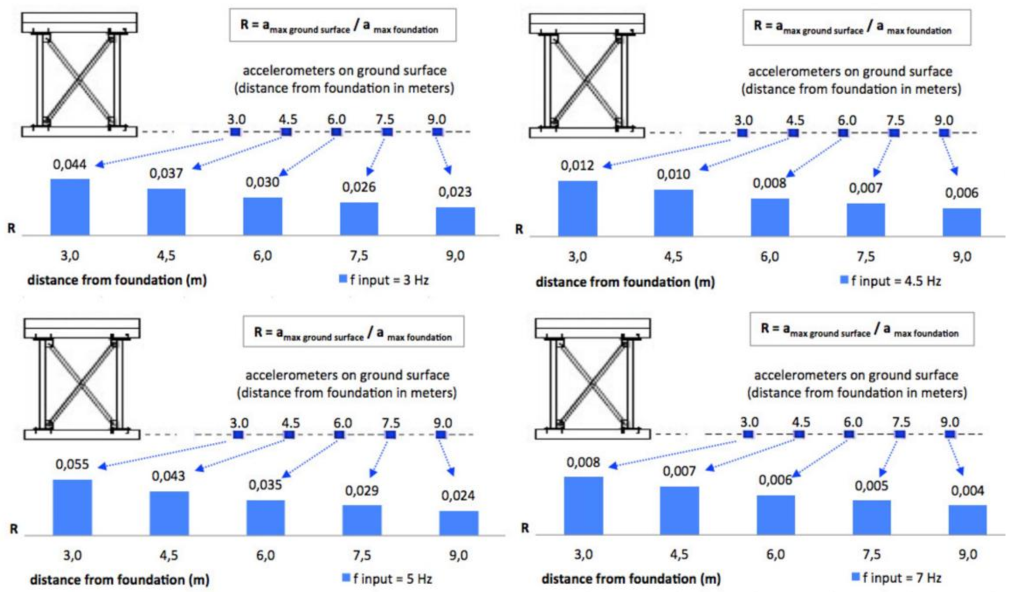

Figure 5: Recorded acceleration amplification ratio along the soil surface, from the foundation until the distance equal to 9.0 m.

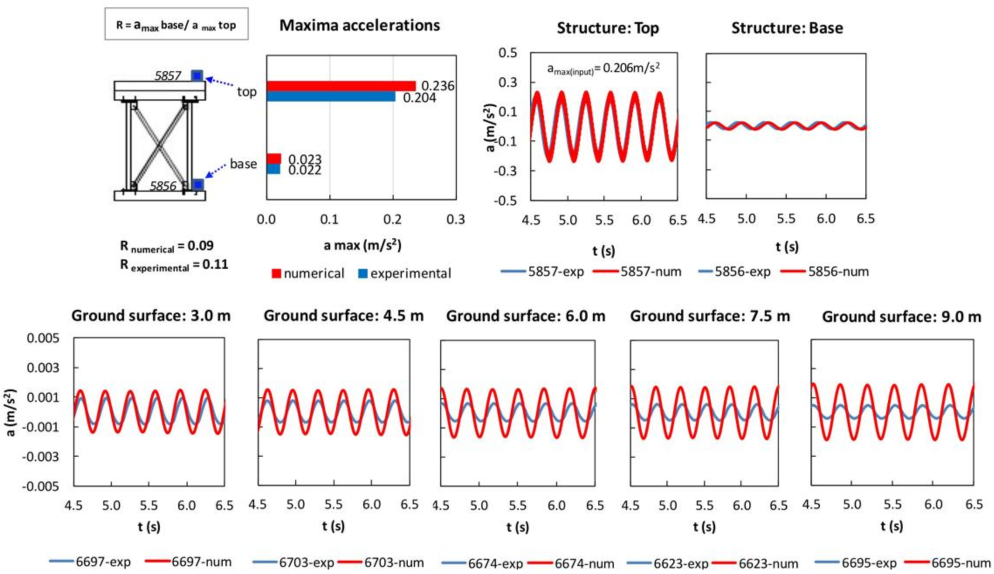

Figure 6: Comparison between experimental (in blue) and numerical (in red) results in terms of maxima accelerations and acceleration time-histories, concerning the structure response (the upper row) and the soil response (the lower row), for f_{input} = 3 Hz.

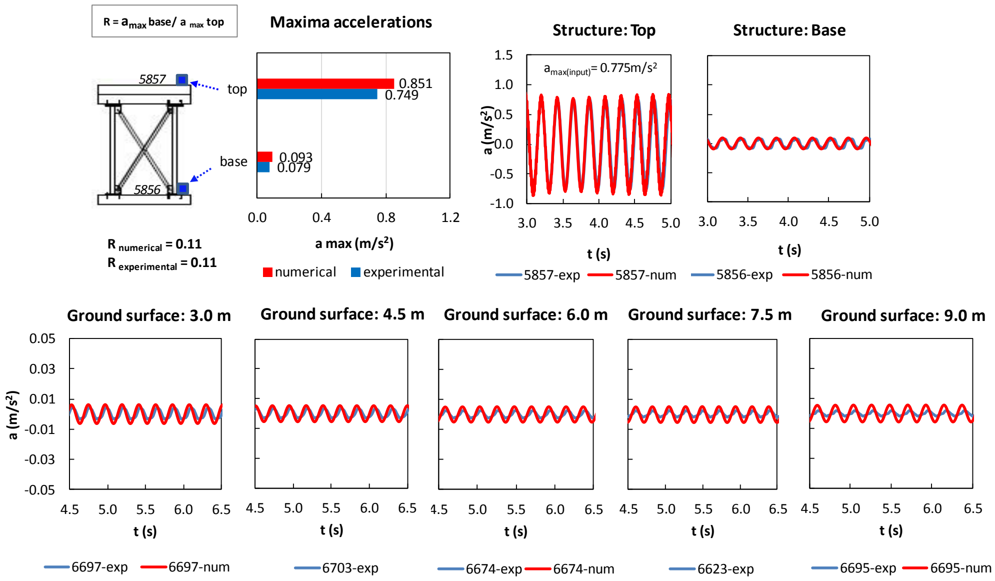

Figure 7: Comparison between experimental (in blue) and numerical (in red) results in terms of maxima accelerations and acceleration time-histories, concerning the structure response (the upper row) and the soil response (the lower row), for f_{input} = 4.5 Hz.

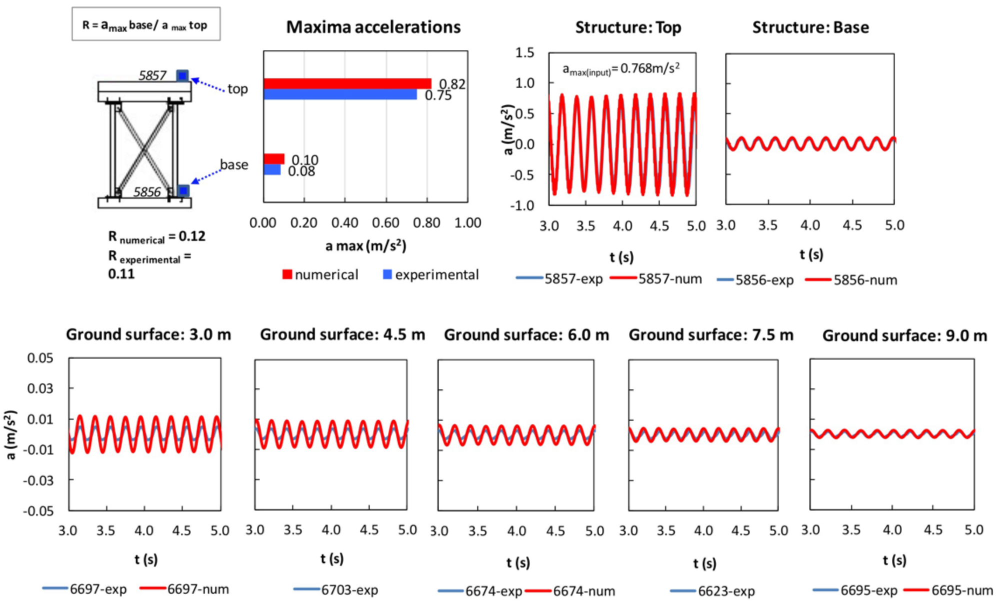

Figure 8: Comparison between experimental (in blue) and numerical (in red) results in terms of maxima accelerations and acceleration time-histories, concerning the structure response (the upper row) and the soil response (the lower row), for f_{input} = 5 Hz.

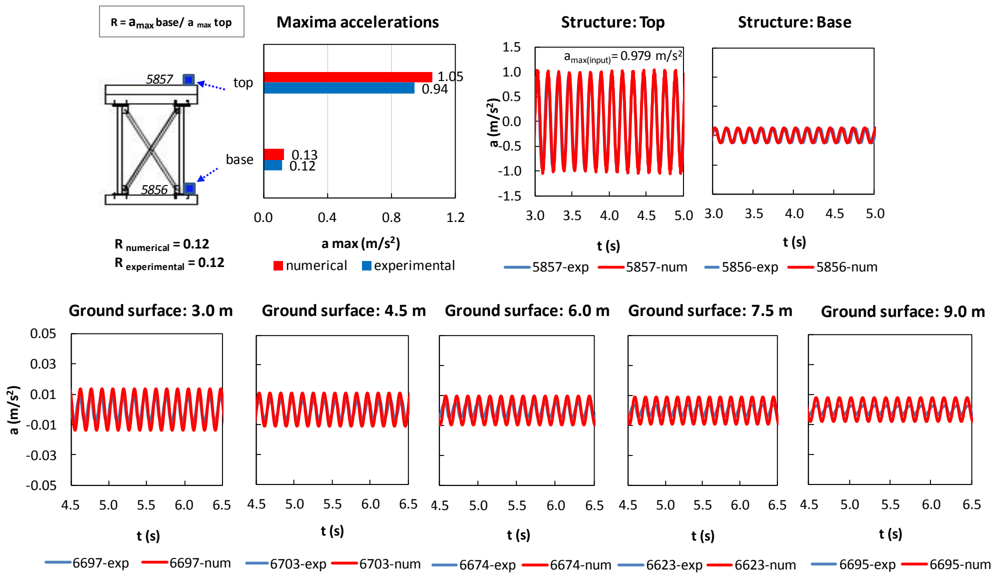

Figure 9: Comparison between experimental (in blue) and numerical (in red) results in terms of maxima accelerations and acceleration time-histories, concerning the structure response (the upper row) and the soil response (the lower row), for f_{input} = 7 Hz.

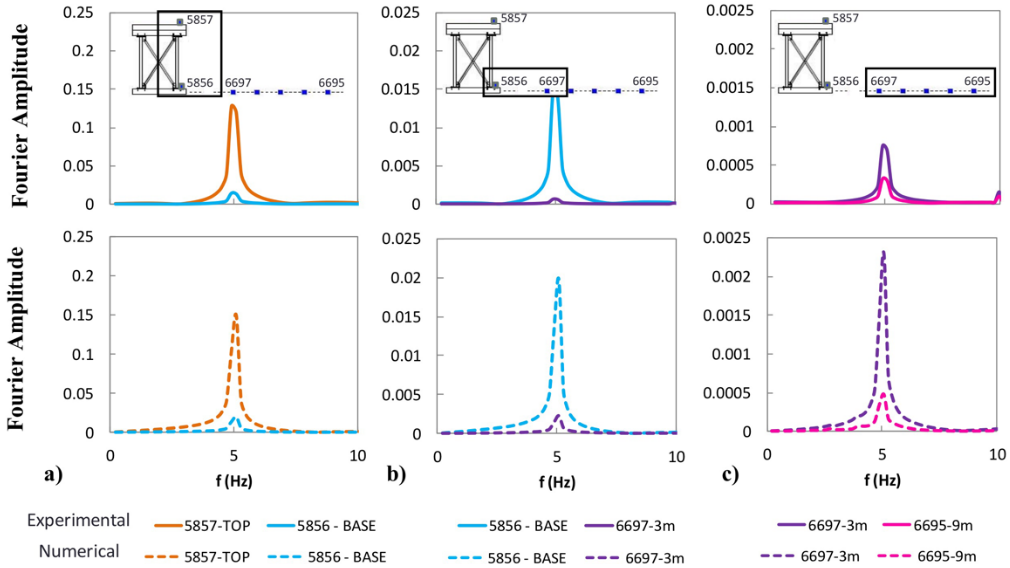

Figure 10: Comparison between experimental (continuous lines) and numerical (dashed lines) acceleration Fourier spectra, just for f_{input} = 5 Hz: a) in the structure (base-top); b) in the foundation - soil surface (foundation-3m distance); c) in the soil surface (3m-9m distance).

5 CONCLUSIONS

The present paper deals with the dynamic response of a soil-foundation-superstructure system involving a large-scale single-degree-of-freedom structure resting on a soft soil, subjected to forced-vibration tests. The structure consists of a simple steel frame with removable X-bracings founded on a reinforced concrete slab of 3x3x0.40m, whereas the soil has an average soil shear wave velocity in the uppermost 30m of about 200 m/s. EuroProteas was instrumented by a large number of instruments of various types, placed both on the structure and in the soil, with the aim to obtain a well-instrumented 3D set of recordings in order to investigate wave propagation and SSI due to the vibration of the structure.

We present the results of the numerical simulation of one set of forced-vibration tests, characterised by a source of harmonic excitation (f_{input} = 3, 4.5, 5, 7 Hz and eccentricity 6.93kg-m) imposed on the roof of the structure. The results are investigated in the time and frequency domains, evaluating the effects of soil nonlinearity and soil-foundation interface behaviour on SSI. The experimental vs numerical results allows us to observe that:

- Soil properties can vary greatly from site to site, differently from structure material properties, thus it is fundamental to perform a careful geotechnical investigation of these properties by means of both in-situ and laboratory tests for the realistic prevision of the seismic behaviour of soil-structure systems, and in turn for the safe seismic design and/or retrofitting of structures. This is especially true in the dynamic field.
- In the investigated tests, across the soil-foundation interface the seismic waves did not pass completely, due to observed and well numerically simulated foundation uplifting. This constitutes a natural isolation, which in turn contributes to reduce the vibrations in the soil if the input comes from the structure (as in the present case) or to reduce the stress-strain level in the structure if the input comes from the soil (i.e. earthquakes, pile drillings, etc.).
- Numerical modelling of the fully-coupled soil-structure system captures well the dynamic response of the system, nowadays with a definitely reasonable time effort, taking into account the real soil stratigraphy, the fundamental soil nonlinearity, the complex interaction between soil and structure, as well as the other initial and boundary conditions.

ACKNOWLEDGEMENTS

The Authors would like to thank Dr. Emmanouil Rovithis for providing us with data recordings from the experiments, as well as all members of the Research Unit of Soil Dynamics and Geotechnical Earthquake Engineering of AUTH and of EPPO-ITSAK that contributed in the experimental campaign.

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