SYSTEM IDENTIFICATION OF SOIL-FOUNDATION STRUCTURE SYSTEMS BY MEANS OF AMBIENT NOISE RECORDS: THE CASE OF EUROPROTEAS MODEL STRUCTURE IN EUROSEISTEST

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ABSTRACT

In this paper we present the system identification of EuroProteas, a real-scale simplified model structure built in Euroseistest site in the framework of the European project "Seismic Engineering Research Infrastructures for European Synergies, SERIES". EuroProteas design and construction involved a particularly stiff structure founded on soft soil, thus mobilization of strong soil-foundation-structure interaction (SFSI) effects is expected during structural oscillations. To this end, system identification is performed using various well-documented parametric and non-parametric techniques, regarding the estimation of the dynamic characteristics of the soil-foundation-structure system. System identification procedures are applied to estimate the modal parameters of the flexible-base structure, while the modal parameters of the fixed-base case are evaluated using a finite element model of the structure. By comparing the results, it is confirmed that the structure under study is subjected to strong SFSI effects.

INTRODUCTION

In order to estimate the dynamic response of a soil-foundation-structure system, its dynamic characteristics are required. The assumption of a fixed-base structure that is usually adopted in practice may be misleading, especially when the foundation soil is soft. There are many well-documented studies in literature for evaluating soil-foundation-structure interaction (SFSI) effects on structures' dynamic response (Gazetas, 1991, Mylonakis et al., 2006). Even though such research efforts are very useful, the corresponding assumptions regarding soil conditions may deviate from those of an actual soil-foundation-structure system. Moreover, estimation of both soil and structural properties contains high uncertainties.

In the last decades, many methods have been developed for evaluating the dynamic characteristics of structures by means of experimental data or real earthquake recordings. These system identification techniques extract the modal characteristics of a system using recorded input and output data. Roughly, these techniques can be categorized in parametric and non-parametric (Stewart and Fenves, 1998), with the parametric ones providing the most rigorous solution in estimating structural modal frequencies and damping ratios. There are many studies in literature describing techniques of system identification or presenting practical applications but only a few of them deal with the investigation of the SFSI effects.

Safak (1995) presented a criterion for detecting the existence of SFSI using earthquake recordings in conjunction with a non-parametric method to identify fundamental frequencies of a fixed-base building and a foundation system when base rocking is negligible and nearby

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free field recordings are not available. Stewart and Fenves (1998) extended Safak's work using parametric system identification procedures for evaluating SFSI effects in structures from strong motion recordings including base rocking. Later, Yun et al. (1999) performed identification of the Hualien soil-structure system, using techniques which correlate an analytical model with a set of forced vibration data. Recently, Chen et al. (2013) presented a parametric system identification method (ARX model) taking into account system nonlinearities for evaluating its modal parameters for various cases of base fixity, which were then applied to centrifuge-based SFSI test data.

The abovementioned studies present system identification methods that require either strong motion or forced vibration data. However, when dealing with real structures it is not always possible to impose artificial excitation without interrupting their operation or taking a significant risk of damaging them. In addition, seismic recordings may not be available as permanent instrumentation of structures is expensive and an earthquake is a random incident.

In this paper, we present the estimation of modal parameters of a real structure prone to SFSI effects using ambient noise measurements. When ambient noise is recorded, the response of the system under study is measured, whereas the excitation remains unknown. In order to identify system's modal parameters, the knowledge of input signal is replaced by the assumption that the response is a realization of a stochastic process with unknown white noise as input. Ambient noise experiments in real structures have the advantage that no artificial excitation is required. We use parametric and non-parametric system identification techniques from recordings derived from ambient noise experiments conducted at the full-scale structure of EuroProteas (Pitilakis et al. 2013), which was constructed at Euroseistest site in Greece (Raptakis et al. 2000) for the investigation of SFSI effects. The modal parameters from system identification techniques are compared with results from the horizontal to vertical spectral ratio technique (Nakamura, 1989).. Finally, model parameters for the flexible soil-foundation-structure system are compared to the fixed-base structure, and SFSI effects are highlighted.

STRUCTURE CONFIGURATION AND INSTRUMENTATION

EuroProteas structure was designed to mobilize interaction with its foundation soil as it is a particularly stiff structure founded on soft soil. As shown in Fig. 1 it consists of a simple steel frame with removable X-bracings on a reinforced concrete slab of 0.40m thickness that corresponds to a shallow foundation. Two similar RC slabs of 9Mg mass each are placed on the top of the structure while the upper one is also removable. Structure's outer dimensions are 3mx3mx5m. EuroProteas is a totally symmetric structure ensuring same bending stiffness in both plane directions. The removable parts of EuroProteas mentioned above (X-bracings, upper slab) allow four different configurations of structure's mass and stiffness, covering a wide range of structural stiffness.

Europroteas was instrumented by a large number of instruments (more than 70) of various types both on the foundation-structure and the surrounding soil. The aim was to obtain a well-documented 3D set of recording and monitoring of the wave propagation and SFSI due to the vibration of the structure. The general idea presented in Celebi et al. (2001) was used. Instrumentation included digital broadband seismometers (CMG-6TD and CMG-40T), triaxial accelerometers (CMG-5TD), borehole accelerometers (CMG-5TB) and Shape Accelerations Arrays (SAA). Instrumentation was made available from the laboratory of soil dynamics and geotechnical earthquake engineering of Aristotle University Thessaloniki (LSDGEE-AUTH) and the Institute of Engineering Seismology and Earthquake Engineering, part of the Earthquake Planning and Protection Organisation (EPPO-ITSAK). All the sensors were connected with external GPS receivers and configured on a 200Hz sampling rate of the recording data.

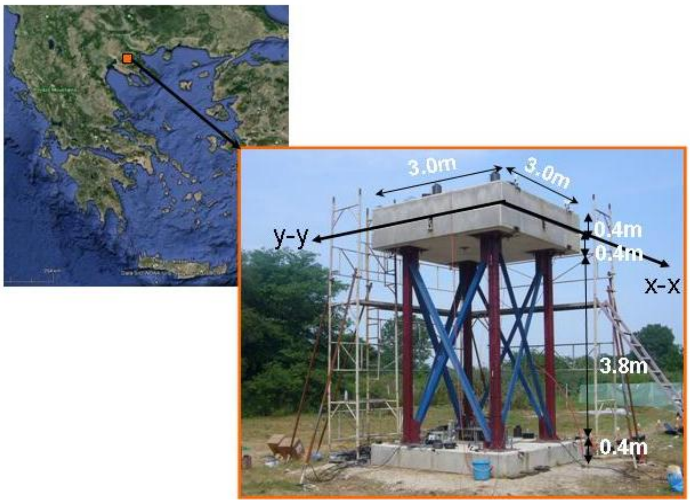


Figure 1. The SFSI full-scale test structure of EuroProteas located in Euroseistest site in Greece (http://euroseisdb.civil.auth.gr/sfsis).

As seen in Fig. 2, seismometers were placed on soil surface every 1.5m, up to a distance of 9m from the foundation, in two directions (approximately north-south and east-west). The intermediate distance of 1.5m was chosen such as to be exactly the half-width of the foundation (3m in width), while the distance of the 9m was chosen such as to be three times the foundation width, after which structural vibration effects on soil response are negligible according to Gazetas (1983). A downhole array was installed in a borehole located in the center of the foundation, with the lower sensor reaching the level of 3m below ground surface (one time the foundation width) and the upper sensor coinciding with the top of the foundation slab. In addition, a 12m-long Shape-Acceleration Array instrument (Measurand Inc.) was placed in the 12m-deep borehole at a distance of 0.5m from the east side of the foundation. In this manner, soil instrumentation covers a volume of 21-by-21-by-12m (due to symmetry) in the NS, EW and vertical directions respectively, around EuroProteas.

The structure was instrumented with 8 accelerometers covering all directions, in both foundation and roof (superstructure) slabs. Five accelerometers were placed on the top of the roof slab; three of them were installed at the middle of the slab parallel to the direction of shaking (in-plane) and other two at opposite corners of the roof slab (Fig. 2), in order to capture possible out-of-plane due to mobilization of torsional modes of vibration.

The full experimental campaign comprised of ambient noise measurements, forced-vibration tests and free-vibration tests. In total, more than 4 hours of ambient noise was recorded in different seasons (winter, summer) and different times in the day (early morning, noon), more than 50 intensity levels (and the corresponding frequencies) were exerted in the forced-vibration tests and 40 intensity levels in the free vibration tests. It is worthy to note that in the forced-vibration tests, the vibrator was placed on the foundation plate as well, in addition to its (typical) placement on the roof slab. This paper deals with system identification from ambient noise measurements, while the processing of the data derived from the other experiments will be reported in forthcoming studies.

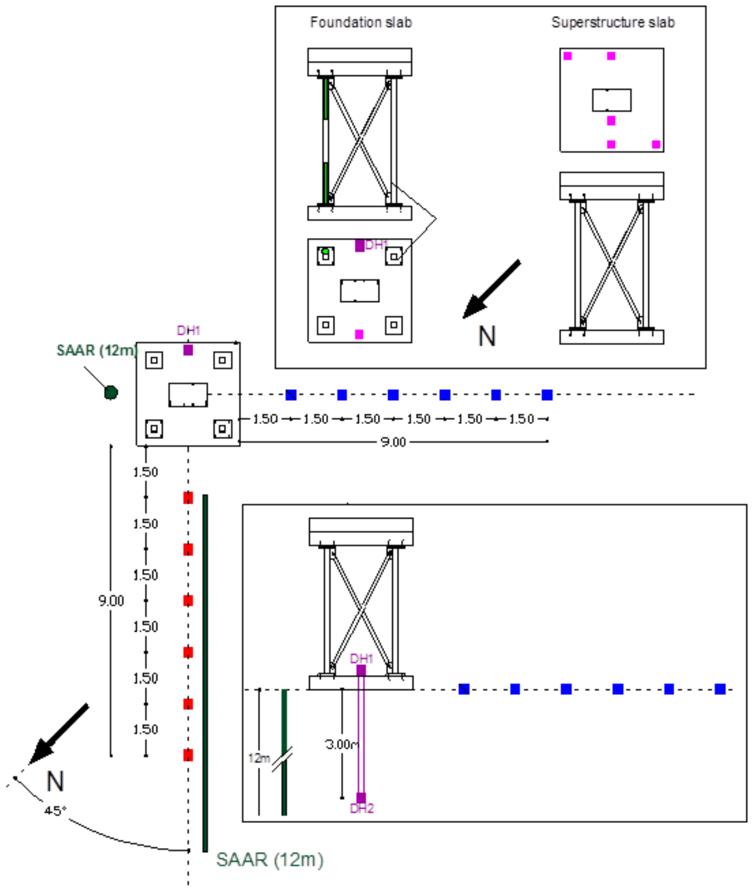


Figure 2. Instrumentation layout of SFSI field tests performed at EuroProteas

SYSTEM IDENTIFICATION TECHNIQUES

System identification of the SSI system was performed using MACEC software (Reynders et al. 2011) which is a Matlab toolbox for operating experimental and operational modal analyses. Since only output data are available in our case, the system identification methods that can be used are output-only or stochastic system identification methods. MACEC includes four of these methods which have each their own advantages and disadvantages:

- Nonparametric positive Power Spectral Density (PSD+) estimation using the correlogram or periodogram approaches
- Reference-based data-driven stochastic subspace identification (SSI-data/ref)
- Reference-based covariance-driven stochastic subspace identification (SSI-cov/ref)
- Operational poly-reference least squares complex frequency domain identification (pLSCF)

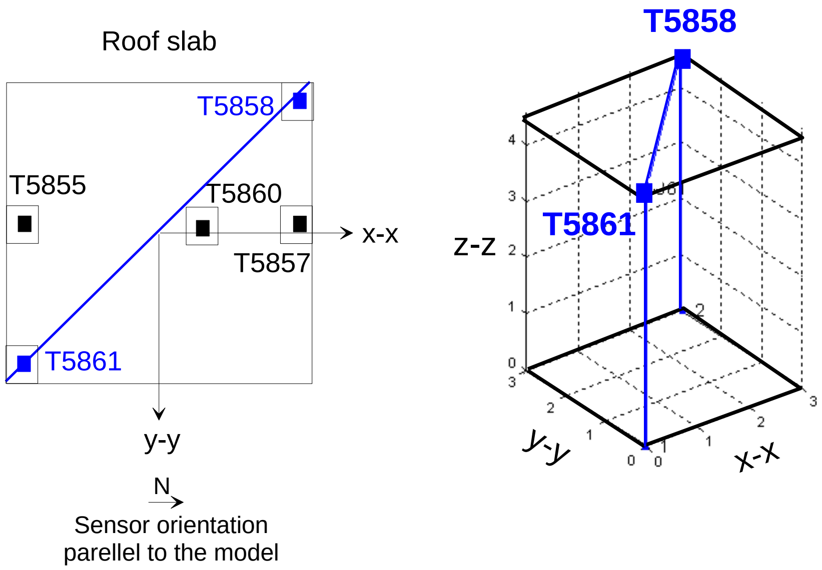


Figure 3: Instrumentation of roof slab of EuroProteas (left) and model configuration in MACEC (right)

In this study two of the above methods were applied, the non-parametric PSD+ estimation using the correlogram approaches and the parametric reference-based covariance-driven stochastic subspace identification. The modal parameters of the structure are estimated by performing a modal analysis of the identified system models. Firstly, the modal parameters were identified in an intuitive, but rather rough way from the series of nonparametric PSD+ models using two different methods, Peak Picking (PP) and Frequency Domain Decomposition (FDD). Secondly, for the series of parametric models, a stabilization diagram was calculated and from this diagram, the stable, physical system modes were extracted.

MACEC requires a model composed of the measurement nodes connected for visualization purposes with beams to be constructed in order to perform the system identification and the modal analysis. For the system identification procedure only the data of two out of the five available accelometers were used, as this choice provided the best visualization of the identified mode shapes. More specifically, the used recordings were derived from the accelometers placed on the edges of the diagonal of the structure. It should be noted that the number of the instruments used for the system identification procedure does not affect the identified modal frequencies. The model was constructed as shown in Fig 3, where the nodes at the roof slab (at height 4.6m from the base slab) are the points of instruments 5858, and 5861, where recordings were available.

Besides the system identification procedures using the MACEC software, the ambient noise recordings were further analyzed in the frequency domain using the spectral ratios of horizontal to vertical Fourier amplitude spectra method (HVSR) (Nakamura, 1989).

Finally, a 3D finite element model of EuroProteas considering rigid fixity at the base was constructed using the software SAP2000 v.14 (Computers and Structures Inc., 2004) and subsequently a modal analysis was performed in order to estimate its dynamic parameters. As EuroProteas is a simplified model without any complication in its construction, and every structural characteristic including dimensions and material properties is well known, the finite element model is very accurate. This is an important advantage of EuroProteas, compared to real structures where many uncertainties arise during their numerical simulations (Karapetrou et al., 2014).

The 3D finite element model of EuroProteas was attempted to be as close as possible to the real structure. The steel frame and the X-bracings were simulated using linear elastic finite elements, while the slabs and the connecting plates at the edges of each X-bracing were simulated by surface finite elements (Fig. 4).

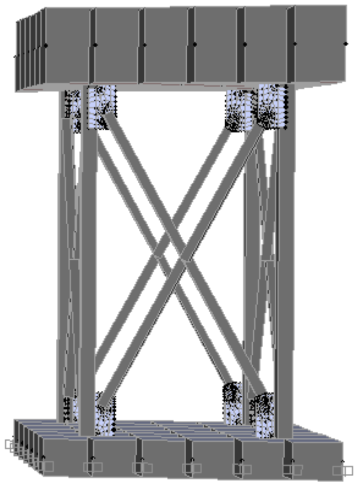


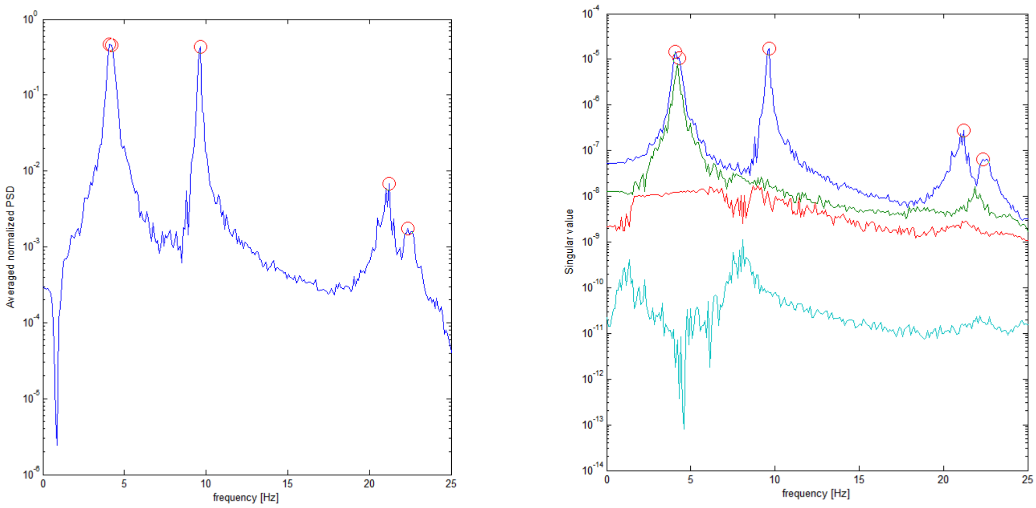
Figure 4: Model configuration in SAP2000

SYSTEM IDENTIFICATION

The determination of the modal parameters of the non-parametric identified system using the peak picking method consists of choosing the peaks of the plotted averaged normalized Power Spectral Density (Fig. 5a). Five modes were identified: two swaying modes at 4.102Hz and 4.199Hz .one torsional mode at 9.668 Hz and two coupled translational torsional modes at 21.191Hz and 22.363 Hz.

In the Frequency Domain Decomposition (FDD) method the singular values are obtained from the decomposition of the PSD matrix and the modal parameters are estimated by picking the peaks of the first singular value (Fig. 5b). Five modes were identified: two swaying modes at 4.102Hz and 4.297Hz .one torsional mode at 9.668 Hz and two coupled translational torsional modes at 21.191Hz and 22.363 Hz. Apart from the second horizontal mode at 4.297Hz, the rest of the modal frequencies are equal between the two methods.

Using the parametric system identification technique (Reynders et al, 2011), the stabilization diagram in Fig. 6 shows the identified stable modes for system order 114. Five modes were identified: two swaying modes at 4.107 Hz and 4.286 Hz one torsional mode at 9.603 Hz and two coupled translational torsional modes at 21.131Hz and 22.419 Hz. Apart from the eigenfrequencies and the mode shapes, parametric stochastic subspace identification also provides a direct estimation of modal damping. The corresponding values of damping ratios to each mode are 3.04% for the first, 3.42% for the second, 0.8% for the third, 1.35% for the fourth and 1.47% for the fifth.



(a) (b)

Figure 5. The eigenfrequencies of the non-parametric identified system of EuroProteas using a) the Peak Picking method (1st mode: 4.102Hz, 2nd mode: 4.199 Hz, 3rd mode: 9.668 Hz, 4th mode: 21.191 Hz and 5th mode: 22.363 Hz and b) the FDD method (1st mode: 4.102Hz, 2nd mode: 4.297 Hz, 3rd mode: 9.668 Hz, 4th mode: 21.191 Hz and 5th mode: 22.363 Hz).

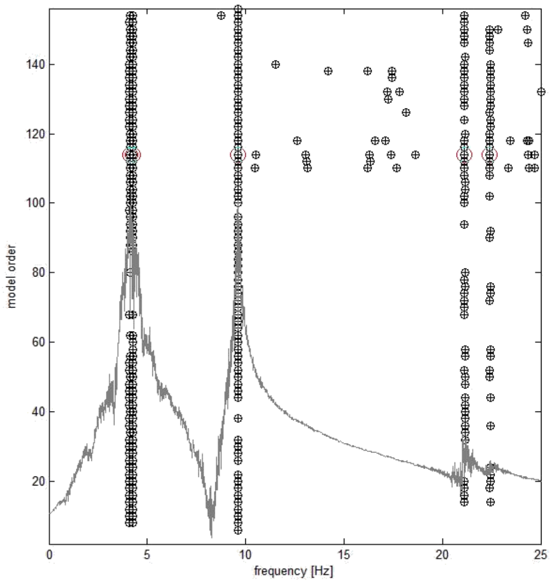


Figure 6. Stabilization diagram of the identified modes of EuroProteas using parametric system identification. The identified modes are 1st mode: 4.107Hz, 2nd mode: 4.286Hz, 3rd mode: 9.603Hz, 4th mode: 21.131 Hz and 5th mode: 22.419Hz.

Apart from the system identification, ambient noise was processed in frequency domain using the horizontal to vertical spectral ratio, H/V method (Nakamura, 1989). The procedure to compute H/V spectral ratios was the following: noise windows of 400sec duration were selected and divided into smaller windows of 20sec duration with 50% overlapping between the adjacent windows. Each window (total number 39) was 10% cosine-tapered and Fourier transformed, and their amplitude spectra smoothed using a Hanning filter. The transfer function of each window was calculated, as well as their average. The coordinates of the first maximum peak of the average ratios, correspond to frequency and amplification of resonance.

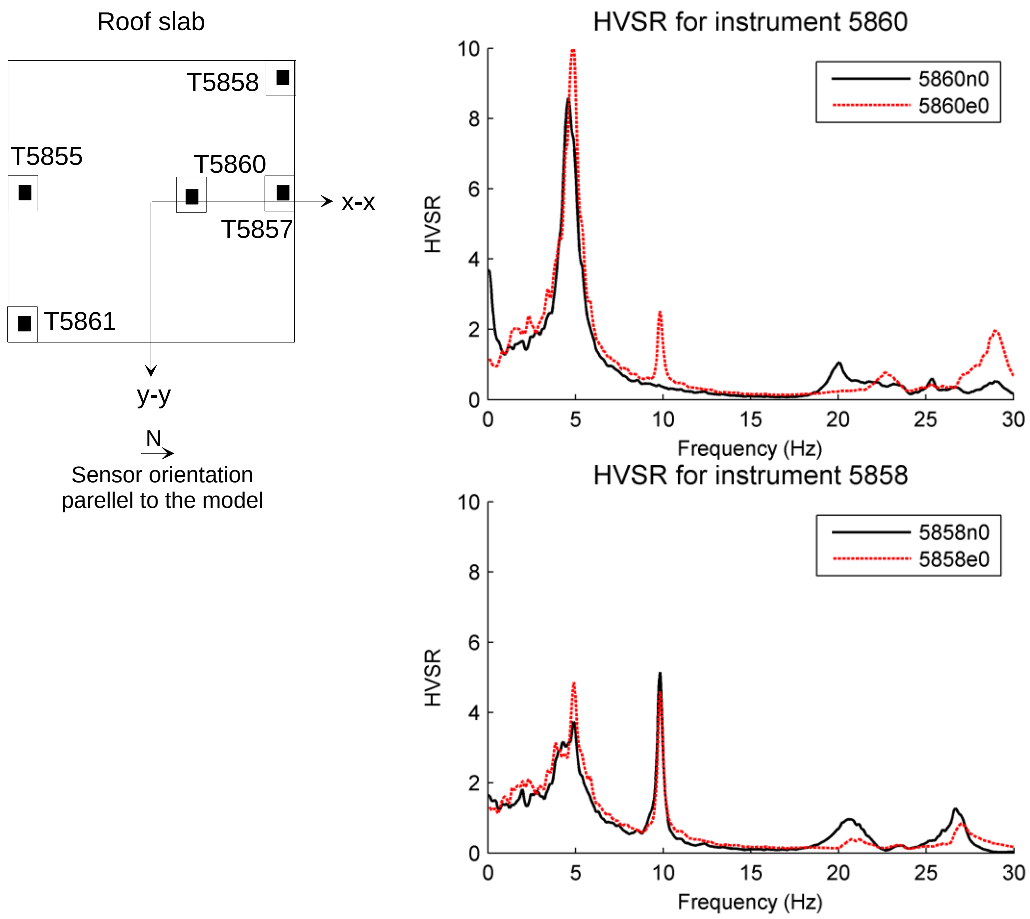


Figure 7. H/V ratios for the instruments T5860 & T5858 on the roof slab.

H/V ratios were calculated for all the instruments installed on the roof slab and the soil. Fig. 7 shows the H/V ratios for the instrument T5860, at central axis of the roof slab for the two directions (in-plane "n0", x-x and out-of-plane "e0", y-y). It can be seen that the soil-foundation-structure system resonates at 4.6-4.9Hz, while there is a second peak at 9.8Hz and another two in 20 to 30Hz frequency range. The first peak is attributed to the soil-foundation-structure system fundamental frequency, representing an uncoupled translational vibration mode, while the second one corresponds to a torsional mode. The H/V ratios calculated for the instrument T5858, which located at the corner of the roof slab (Fig. 7), shows the first peak at about 4.9Hz, whereas the second peak at 9.8Hz is larger in amplitude than at the central instrument T5860, suggesting that the mode at 9.8Hz is torsional. Two more modes are apparent around 21Hz and 27Hz. In both cases, the first modes that were identified by system identification (two horizontal modes at around 4.1 to 4.2Hz and one torsional at 9.5Hz) are adequately captured by the HVSR method as well. The coupled translational torsional around 21Hz is also apparent in the HVSR method, whereas there is a clear peak between 25-30Hz which is not identified in the parametric and non-parametric system identification techniques.

Regarding the dynamic characteristics of the soil, the HVSR method produces resonant peaks at approximately 0.72Hz, which coincides with the reported resonant frequency of the soil profile at Euroseistest site (Raptakis et al. 2000). In the instruments at distance larger than 6m from the foundation (or two times the foundation width), the resonant frequency is closer to 0.72Hz, which is the resonant frequency of the soil profile at Euroseistest (Fig. 8).

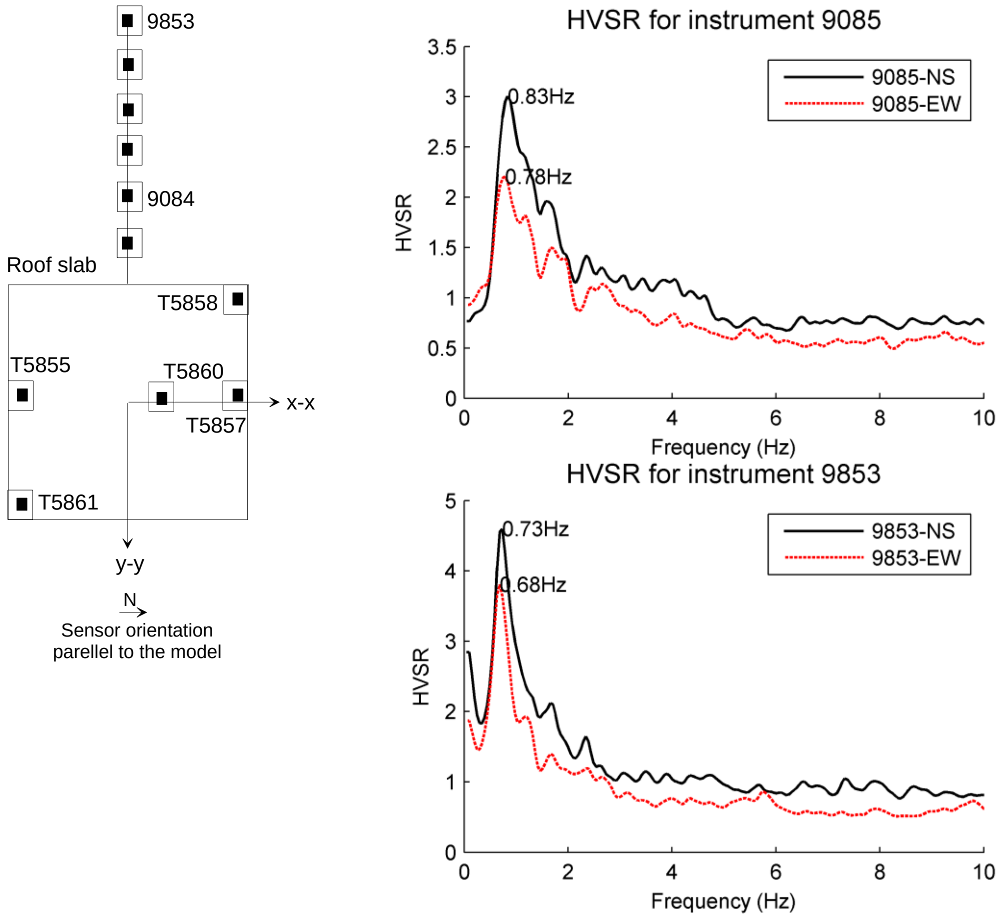


Figure 8. Response at 4.5m distance from foundation (left) and at 9m from the foundation (right)

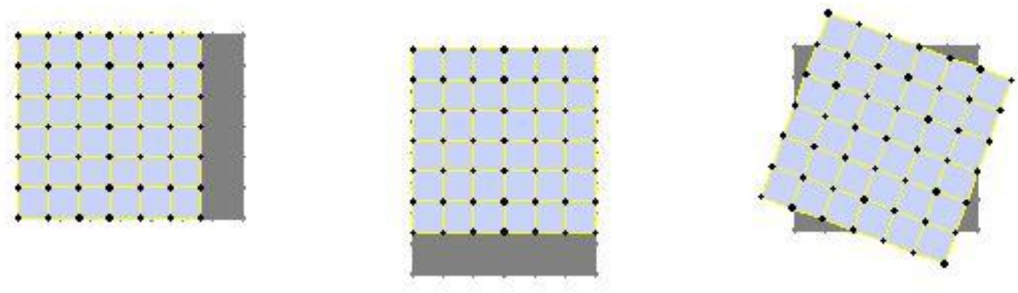


Figure 9: The mode shapes of the fixed base system using a finite element model corresponding to the three uncoupled modes of it. The first two uncoupled translational modes are at 9.13Hz and the third uncoupled torsional mode is at 11.87Hz

As regards to the fixed-base structure, EuroProteas was modeled using finite elements. Fig. 9 presents the results derived from the modal analysis of the fixed base system using SAP2000. As it was expected from theory, due to the totally symmetry of EuroProteas three uncoupled modes were determined. Two uncoupled translational modes at 9.13 Hz and one uncoupled torsional mode at 11.87 Hz. It is worthy to note that the fundamental frequency of the fixed-base structure according to the material and geometrical properties of EuroProteas was determined at 8.32Hz.

Table 1. Comparison of the results obtained within this framework (Trans = translational mode and Tors= torsional mode)

	Flexible system								**Fixed system**	
	Peak Picking		**FDD**		**SSI**		**HVSR**			
Mode	Freq (Hz)	Shape	Freq (Hz)	Shape	Freq (Hz)	Shape	Freq (Hz)	Shape	Freq(Hz)	Shape
1	4.102	Trans	4.102	Trans	4.107	Trans	4.6-4.9	Trans	9.13	Trans
2	4.199	Trans	4.297	Trans	4.286	Trans	-	-	9.13	trans
3	9.668	Tors	9.668	Tors	9.603	Tors	9.8	Tors	11.87	Tors
4	21.191	Coupled trans-tors	21.191	Coupled trans-tors	21.131	Coupled trans-tors	21	Coupled trans-tors	-	-
5	22.363	Coupled trans-tors	22.363	Coupled trans-tors	22.419	Coupled trans-tors	25-30	Coupled trans-tors	-	-

Finally, a comparison between the results of both flexible and fixed base conditions of the structure is presented in Table 1. It is worthy to note that the identified eigenfrequencies for the flexible system are almost the same for the three different applied methods. For this structural configuration, the resonant frequency referring to the translational mode of the structure shifts from 9.13Hz down to 4.10Hz, due to soil-foundation-structure interaction. Another interesting conclusion is that SFSI effects are stronger in the translational mode of vibration compared to the torsional mode as reflected in the comparison of the corresponding resonant frequencies.

CONCLUSIONS

This study presents the system identification of the full-scale soil-foundation-structure system of EuroProteas located at Euroseistest site in Greece. Ambient noise measurements were employed to estimate modal frequencies and damping ratios from (a) parametric and non-parametric identification techniques and (b) horizontal to vertical spectral ratio. By comparing the results of the system identification procedures to those of a modal analysis performed using a finite element model of the fixed-base structure it is revealed that EuroProteas is prone to strong SFSI effects. The resonant frequency of the structure shifts from 9.13Hz down to 4.10Hz, due to soil-foundation-structure interaction. More important is the shifting for the translational mode of vibration, rather than for the torsional mode.

The basic advantage of this framework is that the presented procedure for identifying the modal parameters of the SFSI system can be applied easily to every structure, providing accurate knowledge of its dynamic behavior including its interaction with the surrounding soil, without the need for available earthquake or other forced-vibration recordings. The identified dynamic characteristics can be used for further analysis and design of the system.

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REFERENCES

Bard P. and Roeck G. (1999) “Reference-Based Stochastic Subspace System Identification for Output-Only Modal Analysis”, *Mechanical Systems and Signal Processing*, 13(6), 855-878

Celebi, M., & Crouse, C. B. (2001). *Recommendations for soil structure interaction (SSI) instrumentation*. Citeseer.

Chen Z., Trombetta N. W., Hutchinson T. C., Mason H. B., Bray J. D. and Kutter B. L. (2013) “Seismic System Identification Using Centrifuge-based Soil-Structure-Interaction Data”, *Journal of Earthquake Engineering*, 17:4, April 14 469-496

Computers and Structures Inc. (2004). “SAP 2000-Structural Analysis Program: Linear and Nonlinear Static and Design of Three-dimensional structures”, Berkeley, California, USA

Clotaire M., Gueguen P. and Bard P. (2007) “Dynamic Parameters of Structures extracted from Ambient Vibration Measurements: An Aid for the Seismic Vulnerability Assessment of Existing Buildings in Moderate Seismic Hazard Regions”, *Soil Dynamics and Earthquake Engineering*, 28, 593-604

Gazetas G. (1983) “Analysis of machine foundation vibrations: state of the art”, *Soil Dynamics and Earthquake Engineering*, Vol. 2, No 1

Gazetas G. (1991) “Formulas and Charts for Impedances of Surface and Embedded Foundations”, *Journal of Geotechnical Engineering*, Vol. 117, No 9

Karapetrou S., Manakou M., Lamprou D., Kotsiri S. and Pitilakis K. (2014) “Real-Time Seismic Vulnerability Assessment of a High-Rise RC Building Using Field Monitoring Data”, *In: Proceedings of the Second European Conference on Earthquake Engineering and Seismology*, Instabul

Mylonakis G., Nikolaou S. and Gazetas G. (2006) “Footings under seismic loading: Analysis and design issues with emphasis on bridge foundations”, *Soil Dynamics and Earthquake Engineering*, 26, 824-853

Nakamura Y. (1989) A method for dynamic characteristics estimation of subsurface using microtremors on the ground surface, QR Railway Tech. Res. Inst. 30, 1

Pitilakis, K., Anastasiadis, A., Pitilakis, D., & Rovithis, E. (2013). Full-scale testing of a model structure in Euroseistest to study soil-foundation-structure interaction. In V. P. (eds. . M. Papadrakakis, V. Papadopoulos (Ed.), *Proceedings of the 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering* (pp. 12–14). Kos, Greece.

Raptakis D., Chavez-Garcia F.J., Makra K. and Pitilakis K. (2000), “Site effects at Euroseistest Part I. Determination of the valley structure and confrontation of observations with 1D analysis”, *Soil Dynamics and Engineering*, Vol.19, 1-22

Reynders E., Schevenels M. and Roeck G. (2011) “Macec 3.2: A Matlab Toolbox for Experimental and Operational Modal Analysis – User’s Manual”, Katholieke Universiteit, Leuven

Safak E. (1995) “Detection and Identification of Soil-Structure Interaction in Buildings from Vibration Recordings”, *Journal of structural engineering*, Vol. 121, No 5, 899-906

Stewart P. J. and Fenves L. J. (1998) “System Identification for Evaluating Soil-Structure Interaction Effects in Buildings from Strong Motion Recordings”, *Earthquake engineering and structural dynamics*, 27, 869-885

Tileylioglu S., Stewart P. J and Nigbor L. R. (2011) “Dynamic Stiffness and Damping of a Shallow Foundation from Forced Vibration of a Field Test Structure”, *Journal of geotechnical and geoenvironmental engineering, ASCE* Vol. 137, No 4, April 1, 344-353

Yun C.-B., Choi J.-S. and Kim J.-M. (1999) “Identification of the Hualien soil-structure interaction system”, *Soil Dynamics and Earthquake Engineering*, 18, 395-408