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FULL-SCALE TESTING OF A MODEL STRUCTURE IN EUROSEISTEST TO STUDY SOIL-FOUNDATION-STRUCTURE INTERACTION

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Abstract. *A large experimental campaign to study soil-foundation-structure interaction and wave propagation in soil media due to structural oscillation is presented in the large-scale experimental facility of EuroSeistest in Greece, where a real-scale model structure (EuroProteas) was recently constructed. The structure was especially designed to promote soil-foundation-structure interaction taking into account the well-known foundation soil at site. Six experimental campaigns were performed: three pull-out (free-vibration) and three forced-vibration sets of tests. Pull-out was performed with a counterweight and the total pull-out force exceeded 15kN. Forced-vibration sine sweep tests were performed using an eccentric mass vibrator and total force exceeded 20kN. The vibrator was placed both on the foundation and the top of the structure. Response was recorded by a dense 3D array composed of more than 80 recording devices (accelerometers, seismometers, shape acceleration arrays). In this paper we present the recorded response from selected tests, highlighting soil-foundation-structure effects in the structure and in the soil.*

1 INTRODUCTION

Experimental investigation of soil-foundation-structure interaction is nowadays regularly investigated in small-scale by implementing experiments in shaking-table or centrifuge apparatuses. The increasing number of such experimental facilities worldwide has lead to a significant number of scientific publications [1, 2]. Nevertheless, laboratory tests present limited ability to reproduce certain field conditions, such as boundary conditions.

On the other hand, large-scale field experiments of SFSI involve inherently realistic boundary conditions that are necessary for model calibrations. Among the first SFSI field studies, Lin and Jennings (1984) [3] and Luco et al. (1988) [4] derived foundation impedance functions based on forced-vibration field tests, while de Barros and Luco (1995) [5] performed forced-vibration tests on a reduced-scale model of a nuclear reactor. Recently, Tileylioglu et al. (2011) [6] realized forced-vibration SFSI experiments on a large-scale model test structure in Garner Valley, California, focusing on dynamic impedance functions.

In this study, we present a large experimental campaign to study soil-foundation-structure interaction and wave propagation in soil media due to structural oscillation, in the full-scale experimental facility of *EuroProteas* in Greece. The tests series were performed in the framework of the on-going European project "Seismic Engineering Research Infrastructures for European Synergies, SERIES" by means of a large-scale simplified prototype structure built in *EuroSeistest* site, in the north of Thessaloniki, Greece.

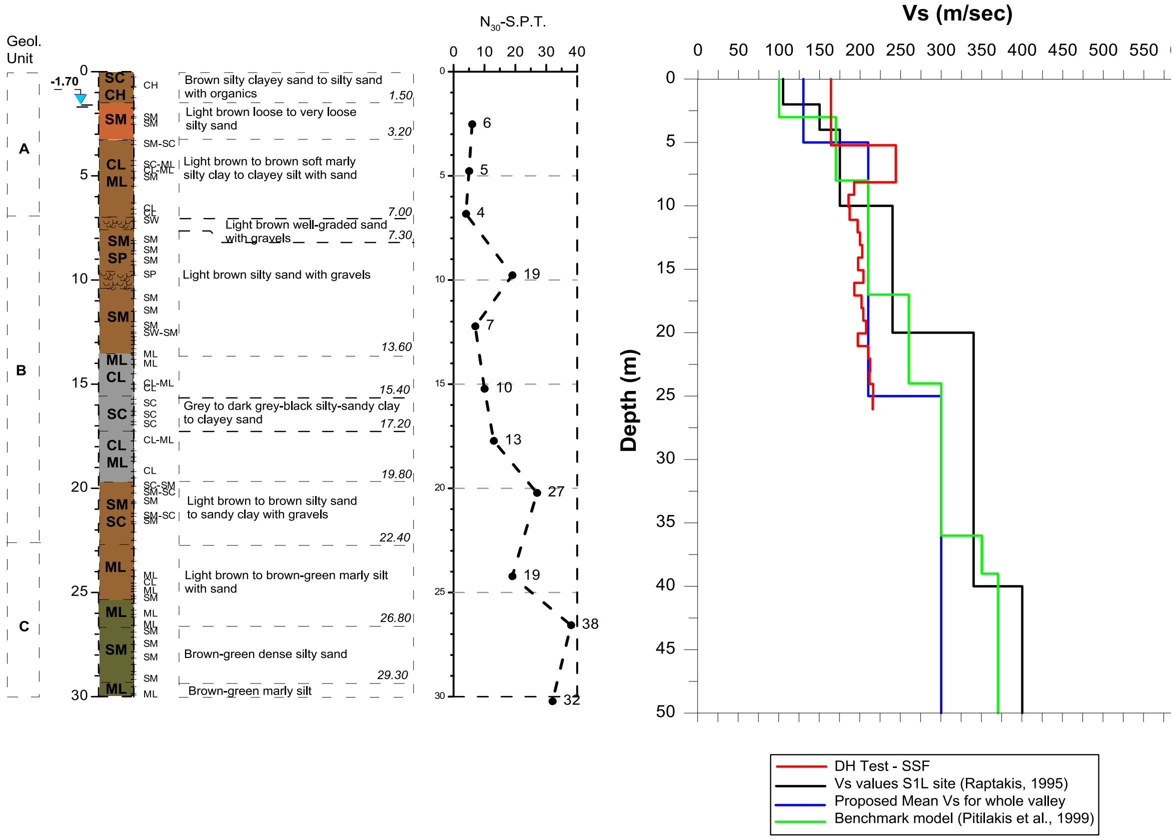
2 DESCRIPTION OF EUROPROTEAS FACILITY

2.1 Foundation soil conditions

Subsoil stratigraphy and dynamic properties of the foundation soil at *EuroProteas* site are already well-documented from extended geotechnical and geophysical surveys [7, 8, 9]. However, in order to define the detailed soil stratigraphy immediately below the prototype structure, additional geotechnical and geophysical surveys were performed to measure the exact soil properties at site. The abovementioned investigation comprised of drilling boreholes, geophysical down-hole measurements and laboratory tests on selected soil samples.

Specifically, a 30m deep borehole was drilled in the geometric center of the foundation slab of the model and a 15m deep borehole was drilled at the edge of model. Standard penetration tests (S.P.T.) were conducted in the 30m deep hole and continuous samples were taken according to Eurocode 7 [10] regulations for undisturbed sampling. Split-spoon and undisturbed samples were retrieved for laboratory index testing and soil classification to establish strength and compressibility soil characteristics. In addition, resonant column tests were performed at representative soil specimens. The boreholes were cased for the execution of down-hole tests, for the installation of a down-hole accelerograph in the geometrical center of *EuroProteas'* foundation and for the installation of shape-acceleration-arrays (SAAR, Measurand, Inc.) sensors at the edge of the model. Figure 1 shows soil stratigraphy and shear wave velocity profile, as estimated from geotechnical and geophysical tests from the borehole in the geometrical center of the foundation, prior to the construction of the structure.

Soil consists of silty clay in the uppermost 15m, to silty sand at depth of 30m. In the upper 5m, shear wave velocity is estimated approximately at 130m/s, while it increases to more than 300m/s at 50m depth. The detailed sedimentary structure and the full geometry of all soil deposits, as well as, the Vs structure, of the test site is very well defined to a depth of 200 m, where the more significant impedance contrast lies between the gneissic bedrock soil and sediments [7,8,9].



a) b)

Figure 1: a) Soil stratigraphy from borehole TST-1DSM-BH-02 in the center of the foundation and b) shear wave velocity profile from down-hole tests, compared with literature

2.2 Structure

The design concept of *EuroProteas* prototype structure in *EuroSeistest* site involved a stiff, simplified structure, with reconfigurable mass and stiffness, aiming to mobilize strong SFSI. In this manner, salient effects of SFSI mechanism can be clearly attested on the superstructure and soil response. More specifically, the following requirements were envisaged during the design of the *EuroProteas*:

- Fixed-base natural frequency of the prototype adjusted with stiffness and mass modification.
- Large superstructure mass to ensure notable SFSI response, in conjunction with the soft foundation soil.
- Steel moment frame to allow flexibility and easy construction.
- Reconfigurable bracing system to allow stiffness and damping modification.
- Strong rigid reinforced concrete (RC) roof slab to allow for mass addition and eccentric mass shaker mounting.
- 50% of superstructure mass in RC foundation slab to accommodate for stability, dynamic footing response and eccentric mass shaker mounting.

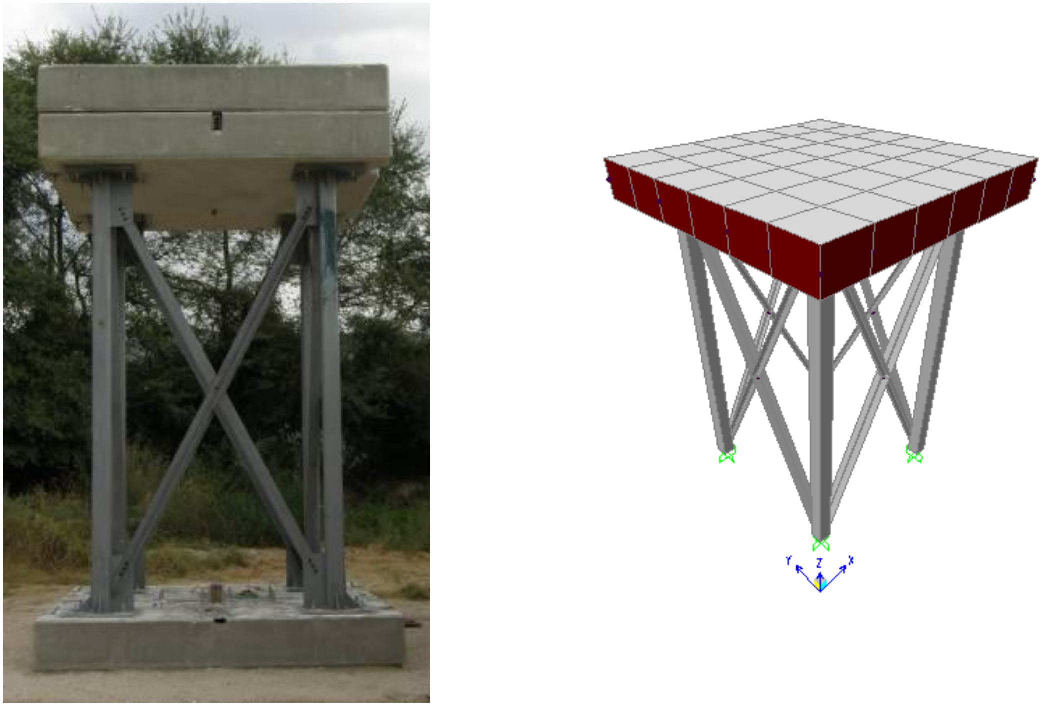
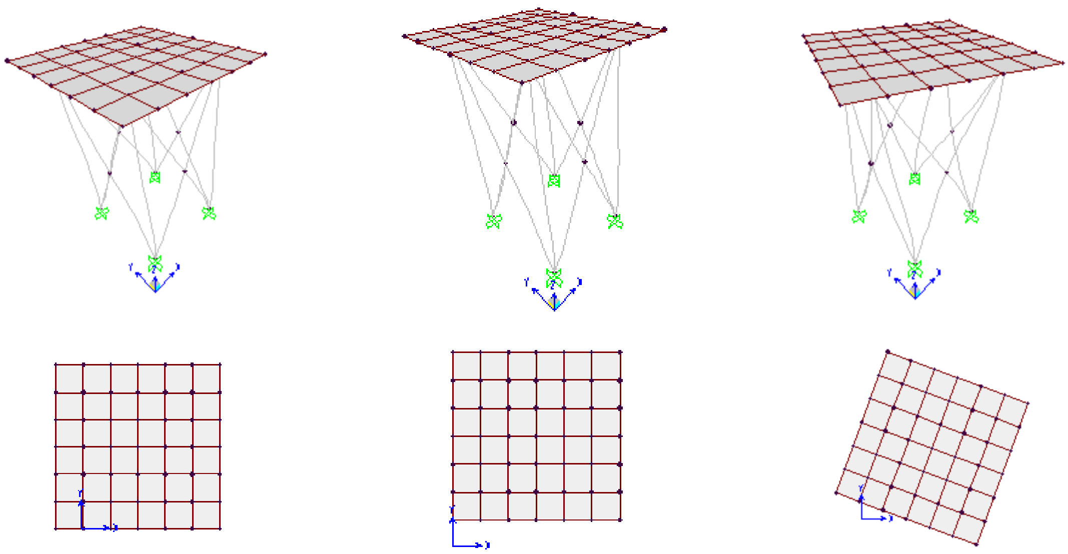


Figure 2: (a) Prototype structure (*EuroProteas*) constructed at *EuroSeistest* site (b) FE model of the structure under fixed-base conditions



(a) (b) (c)

Figure 3: Modal analysis of the model structure (a) 1st uncoupled transverse mode (T_1=0.12sec) (b) 2nd uncoupled transverse mode (T_2=0.12sec) (c) 3rd torsional mode (T_3=0.093sec)

The structural design conformed to the provisions of modern codes and regulations (i.e. Eurocode 3 [11] for the design of steel members and connections, Eurocode 7 [10] and Eurocode 2 [12] for the design of the foundation, and Eurocode 8 [13] for seismic design).

Based on the above requirements, the prototype was designed to comprise of one RC foundation slab 3x3x0.4m, on top of which four steel columns with free height 3.80m are clamped, supporting the superstructure mass of one (or two, depending on the configuration) RC slabs identical to the foundation slab. The four steel columns are connected with X-braces in both directions, forming a totally symmetric structure (Figure 2). The mass of each RC slab is 9.16Mg, assuming uniform concrete weight 25kN/m^3. The total height from the bottom of the foundation slab to the top of the upper roof slab is 5.0m. Fixed-base natural frequency can be configured between 2.1Hz and 11.5Hz, depending of the number of roof slabs and the bracing system. For the experimental campaign that will be presented herein, the natural fixed-base frequency of *EuroProteas* is configured at 8.32Hz along the horizontal axes, based on modal analysis of the test structure FE model (Figure 2b) performed by means of SAP2000 [14]. The corresponding modes of vibrations under fixed-base conditions are shown in Figure 3 revealing two uncoupled swaying modes (Figure 3a and 3b) along the horizontal axes and one torsional mode (Figure 3c) due to the symmetrical distribution of the structural stiffness.

3 EXPERIMENTAL CAMPAIGN

In the framework of the European project SERIES, six experimental campaigns took place in the *EuroProteas* test site, including three sets of free-vibration tests and three forced-vibration tests, performed at different excitation levels. Experiments are described in detail in the ensuing.

3.1 Instrumentation

A large number (more than 80) of various types of instruments were installed in every test to monitor structural, foundation and soil response. In this manner, a particularly dense three dimensional instrumentation scheme was set, recording wave propagation and SFSI due to the vibration of the structure. Instrumentation included digital broadband seismometers (CMG-6TD and CMG-40T), triaxial accelerometers (CMG-5TD), borehole accelerometers (CMG-5TB) and Shape Accelerations Arrays (SAAR). Instrumentation was made available from the Research Unit of Soil Dynamics and Geotechnical Earthquake Engineering of Aristotle University of Thessaloniki (SDGEE-AUTH) and the Earthquake Planning and Protection Organization (EPPO-ITSAK).

Figure 4 shows a typical instrumentation layout of the experiments at *EuroProteas*. 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. Superstructure instrumentation was mostly in line with the direction of loading, whereas accelerometers were also installed at the two opposite corners of the roof slab to capture possible transverse and torsion response. Furthermore, two 1.2m-long shape-acceleration-arrays SAAR arrays are attached to a steel column of the structure to measure possible deviation of structural response along the column length.

Soil response is recorded with seismometers installed on the free soil surface in both directions, covering an area of 9x9m around the structure, as seen in Figure 4. In the direction of loading, a 12m-long shape-acceleration-array (SAAR) is placed on the soil surface. This instrument consists of an array of MEM sensors every 0.5m, making a total of 25 acceleration recording instruments. In the borehole in the center of the foundation is placed an accelerometer at depth equal to one time the foundation width. In the borehole at 0.5m from the side of the foundation is placed a second 12m-long SAAR, providing recordings every 0.5m to a depth of 12m.

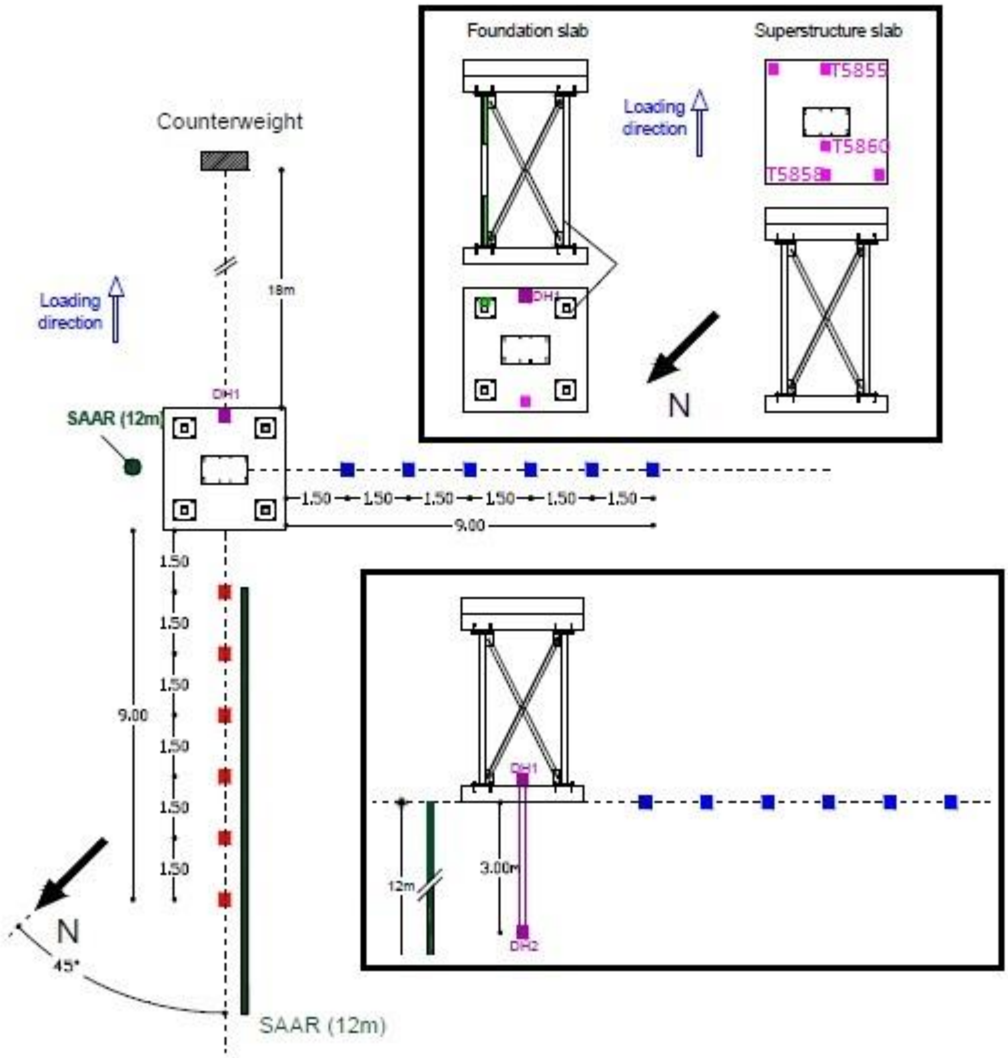


Figure 4: Instrumentation layout of the experimental campaign at *EuroProteas*

From the above, it is obvious that response due to vibration of the structure is recorded in three directions in the soil, providing a uniquely dense instrumentation scheme to study SFSI and wave propagation effects due to structural oscillation.

3.2 Free-vibration testing

In the free-vibration test series, pull-out forces were applied to the roof slab by a wire rope, clamped at a RC counterweight of 1.5t buried in the soil at 28m away from the structure. Tension was applied to the wire rope by mechanical means, and then the wire rope was cut loose to cause free oscillation of the structure until rest. Tension force was measured on the wire rope using an electronic load cell. In total, more than 25 pull-out experiments were performed on the *EuroProteas* structure, with the pull-out force varying between 2.5kN and 15kN.

Figure 5 shows indicative the recorded acceleration response at instruments T5858, T5855 and T5856 (Figure 4), all located on the roof slab along the excitation axis, T5858 and T5856 fixed close to the slab edge and T5855 close to the geometric center.

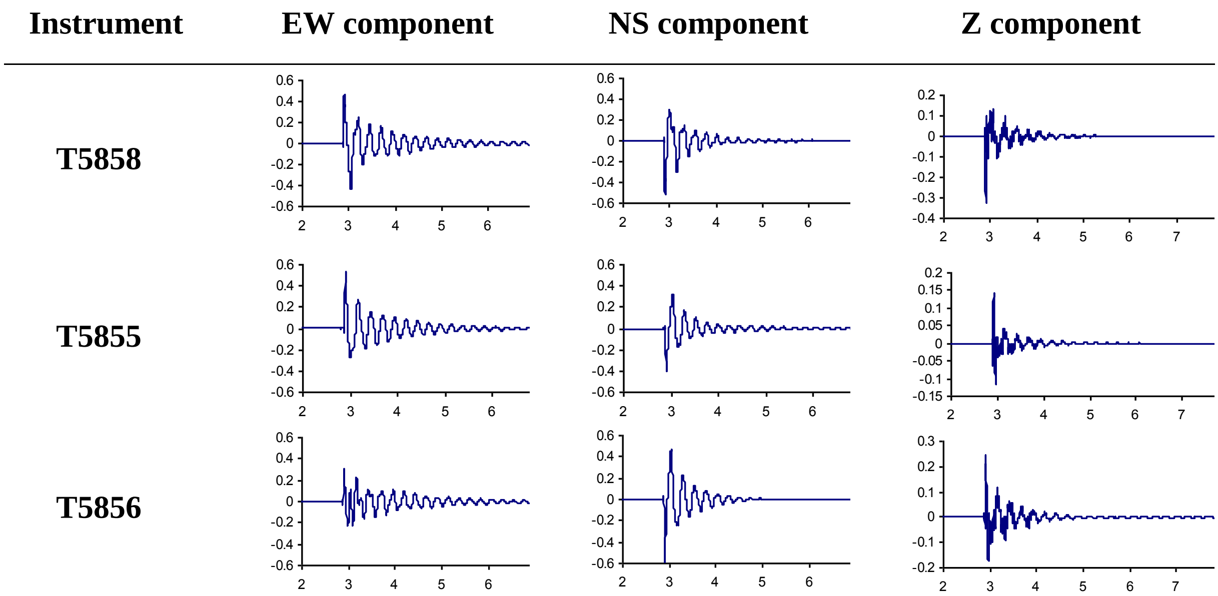


Figure 5: Free-vibration acceleration response (measured in m/s^2) at the top of the structure test at pull-out force 10.3kN

The viscously damped vibration of the structure is clear in Figure 5, caused by the pull-out force. Almost constant structural damping may be attested by the form of the recorded motion in time.

In a similar way, the recorded velocity response on the free soil surface in the direction of shaking is shown in Figure 6. Similar form of the response is apparent in the soil, due to the unit pulse excitation of the structure. Because of soil damping, the oscillation fades out after approximately two seconds. Moreover, the decay of maximum amplitude is obvious with increasing distance from the structure.

Looking at the Fourier spectra (Figure 7) of the recordings on the structure and on the soil surface, the resonant soil-foundation-structure system frequency can be estimated approximately at 4Hz.

Regarding the recordings from the shape-acceleration-arrays (SAAR) due to structural oscillation, unfortunately the pull-out force amplitude and the consequent vibration amplitude were low, within the instrument noise levels (displacement in the order of 10^{-4}m), making conclusions rather obscure even for forces around 15kN.

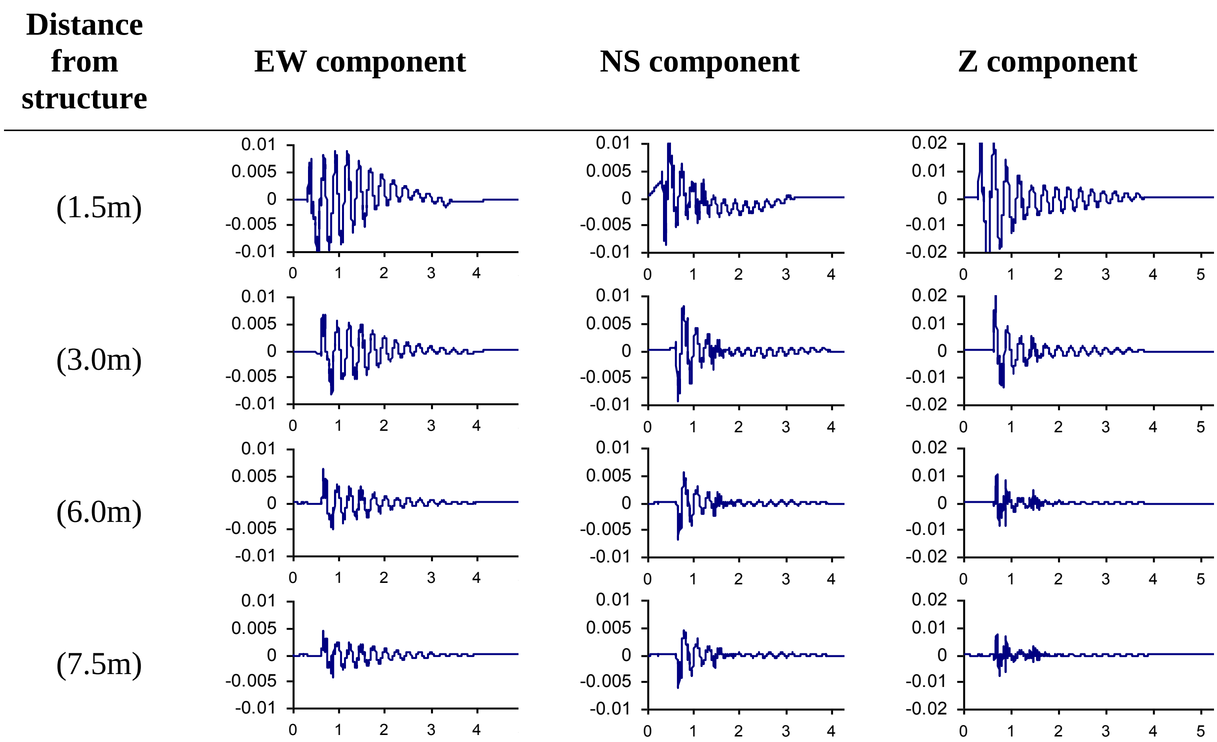


Figure 6: Velocity time histories (measured in m/s) recorded on the soil surface with increasing distance from the foundation due to pull-out force of 8.89kN.

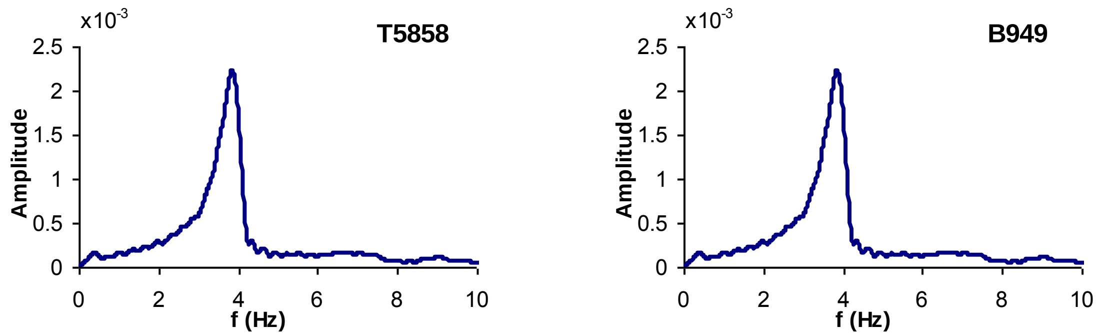
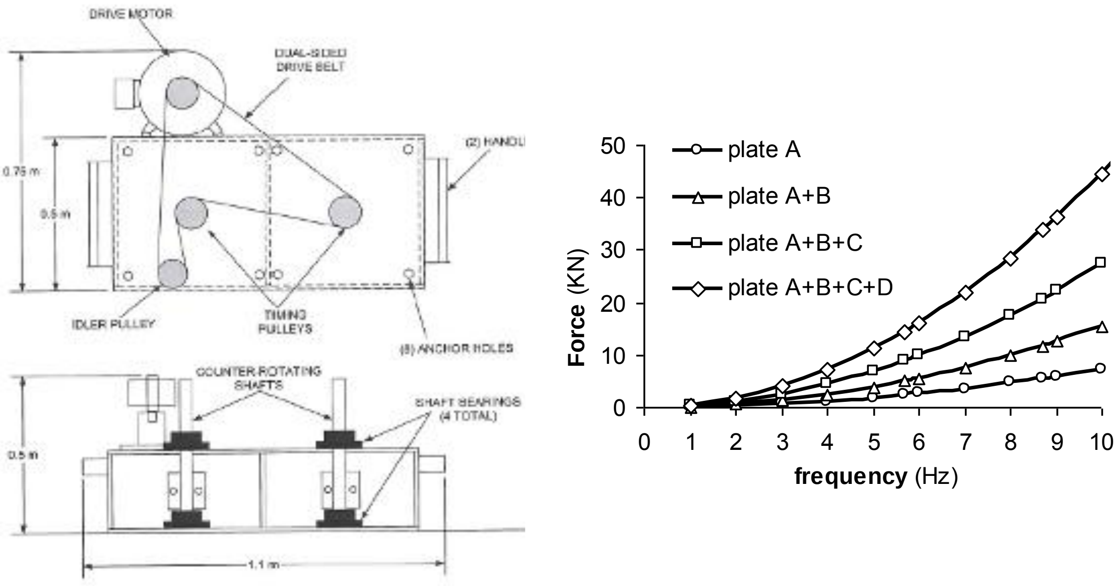


Figure 7: Fourier spectra of recording a) on the roof slab and b) on the soil surface at distance 1.5m from the foundation

3.3 Forced-vibration tests

For the forced-vibration tests, the MK-500U eccentric mass vibrator system owned by the Earthquake Planning and Protection Organization EPPO-ITSAK [15] was implemented as a source of harmonic excitation imposed on the model structure. The particular mass vibrator system is a portable, unidirectional dual counter-rotating shaker that can produce a maximum sinusoidal horizontal force of 5 tons and can be operated from 0.1 to 20Hz. The shaker's eccentricity can be varied between 0.15kgm and 11.3kgm in various increments to produce maximum horizontal force from 10.5Hz to 20Hz. The shaker is powered by a 2.2kW,



a) b)

Figure 8: (a) MK-500U schematic (b) frequency-force relationship of the MK-500U shaker [ANCO Engineers, Inc]

1200rpm electric drive motor (Figure 8) controlled by a Toshiba VF-S9 adjustable speed drive. During the forced-vibration tests at *EuroProteas*, the motor drive was operated manually adjusting the operating speed of the shaker to the desired excitation frequency.

The produced force of the vibrator is governed by the following equation:

$$F = E\ (2\pi f)^2 \qquad (1)$$

where F is the shaker output force (in N), E is the total eccentricity of the shaker (in kg-m) and f stands for the rotational speed of the shaker (in Hz). The MK-500U shaker has a total of eight mass plates in four different sizes (A, B, C and D) that can be used to adjust the vibrator's eccentricity. One plate of each size is to be mounted to the hub on each rotating shaft in specific order and orientation. These plates allow the shaker eccentricity to be adjusted as mentioned above. Depending on the number of plates and the operating frequency, output force can be adjusted, as seen in Figure 8b.

Three series of forced-vibration tests were performed on *EuroProteas*. In the first series of tests, the eccentric mass vibrator system was clamped on the specially designed metal plate at the geometrical center of the foundation. Moreover, it was orientated so that the produced force would be on the same direction as the applied pull-out forced at the free-vibration tests. In the second and third series of forced-vibration at *EuroProteas*, the vibrator was placed both on the foundation and on the top roof slab, in order to increase rocking of the structure.

As mentioned before, the produced force of the vibrator can be adjusted by the mass of the plates and the output frequency. In all three forced-vibration experimental campaigns, the total force varies between 0.07kN and 21kN, at frequencies that range from 1Hz to 10Hz, depending on the mass shaker configuration.

Forced-vibration Series No. / Mass plate	**2 / A+B**
Instrument Series No	**T5856**
Recorded motion	**Structural response / Acc. (m/sec^2)**

f(Hz)/ force(kN) — EW component — NS component — Z component

5 / 3.88

5.7 / 5.04

6 / 5.59

8 / 9.93

9 / 12.57

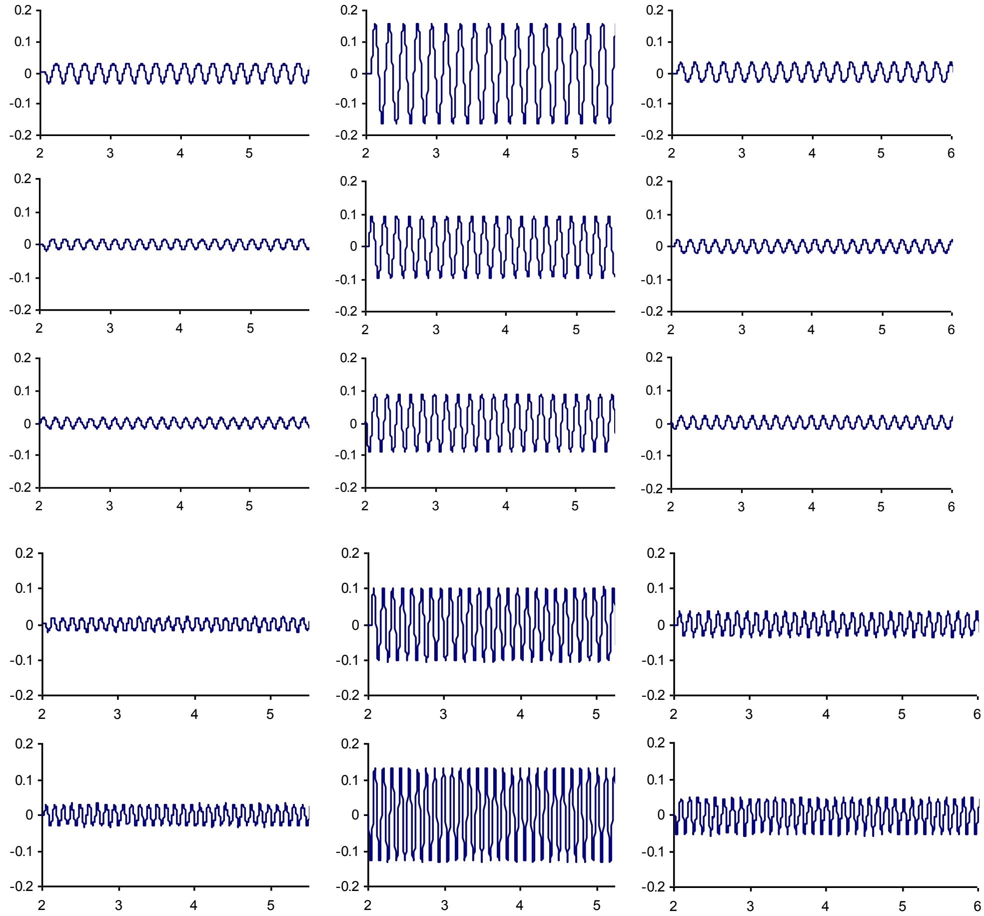


Figure 9: Acceleration time histories (measured in m/s^2) from forced-vibration tests recorded at the top of the roof slab, for different excitation frequencies and forced amplitudes

As in the case of the free-vibration tests, selected recordings at the soil and the structure are presented in the ensuing. Similarly, the three components of the recorded motion are shown for each instrument. Structural response was recorded by accelerometers and SAARs, while soil response was recorded by seismometers and SAARs.

In Figure 9, structural accelerations records from instrument T5856 located close to the edge of the roof slab are depicted along the direction of shaking. The recorded acceleration response is presented for a series of tests, according to the output frequency and the output force of the vibrator system.

As the eccentric mass vibrator is able to produce larger forces, and thus vibration amplitudes on the structure, response in the soil was also recorded in the vertical direction by the SAAR. Figure 10 presents acceleration recordings in three directions (horizontal x-x and y-y, x-x being the direction of shaking, and vertical z-z) in the soil in a vertical array up to 5m depth. Recorded motion in both in-plane (x-x) and out-of-plane (y-y) directions seems to fade out after a depth equal to one time the foundation width (3m) for horizontal shaking, something in accordance with the literature [16].

Mass plates	**A+B+C**
Output frequency (Hz) / Output force (kN)	**8 / 17.51**
Recorded motion	**Soil response (in vertical direction)**
Type of recorded motion	**Acceleration (g)**

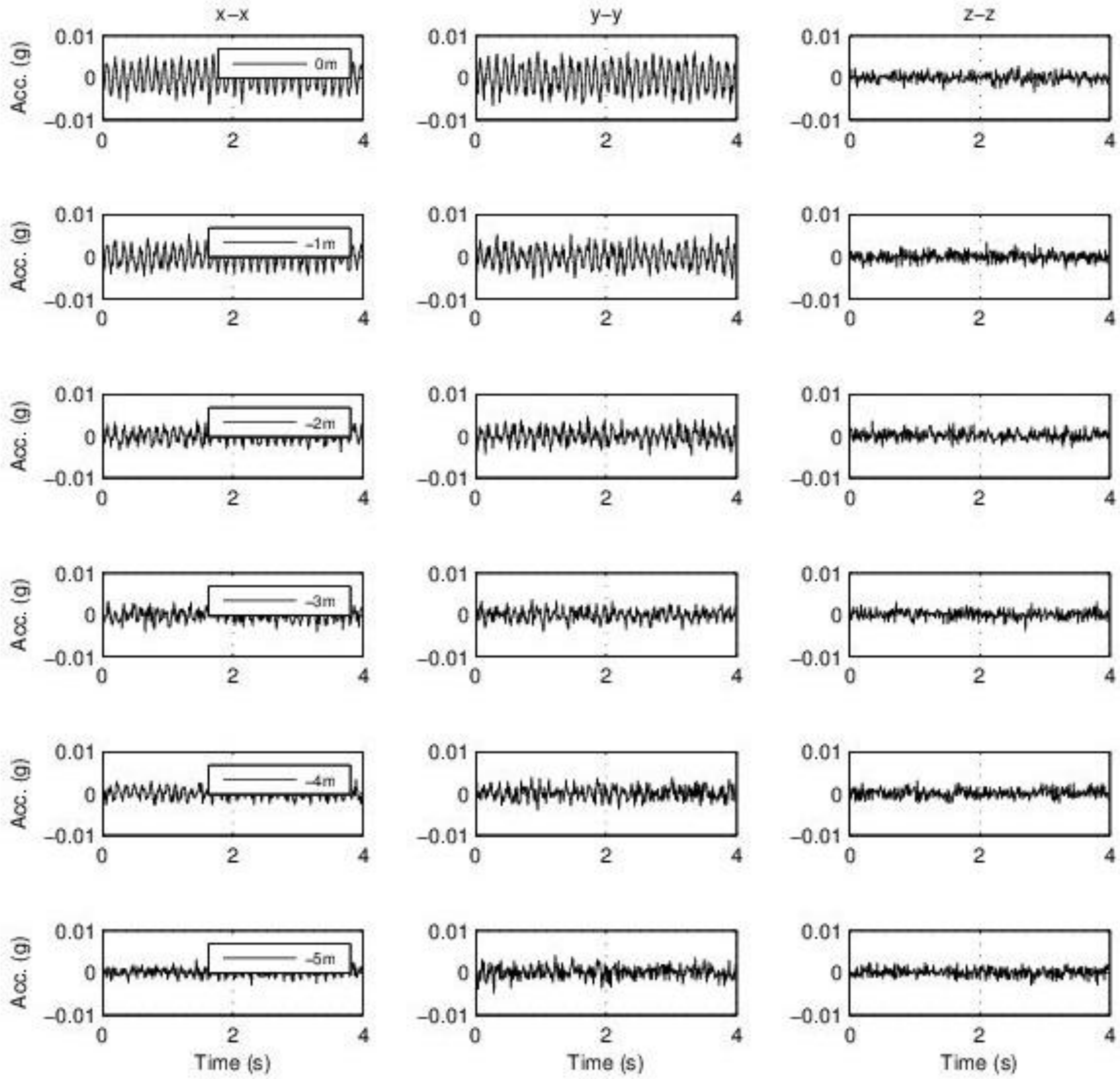
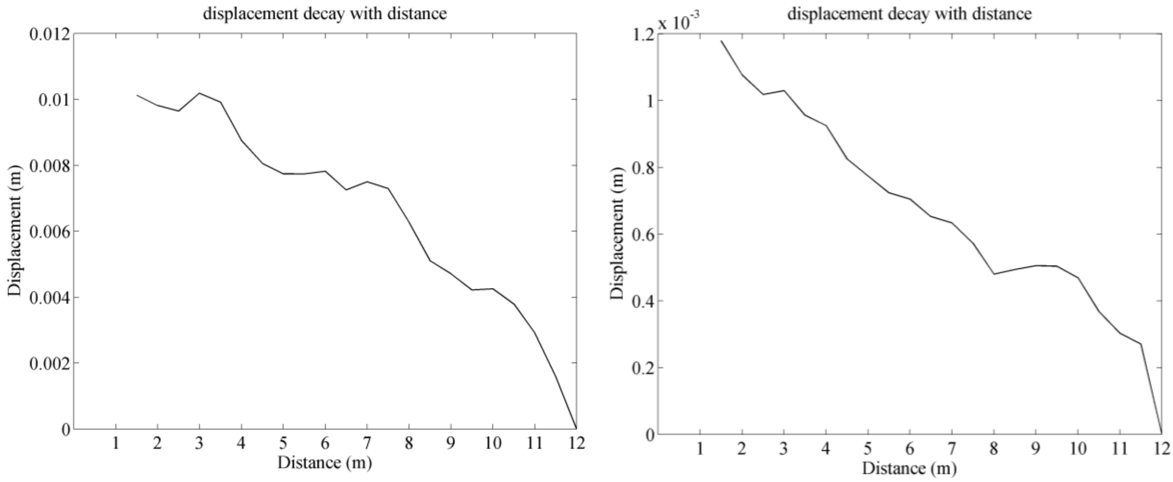


Figure 10: Recorded acceleration in the soil in the vertical array for output frequency 8Hz and output force 17.51kN of the eccentric mass vibrator. Acceleration is presented with depth, from soil surface to 5m depth

Figure 11 presents the decay of acceleration with distance from structure for forced-vibration shaking at 8Hz and output force 17.51kN. It can be seen that in the vertical array (Figure 11a), the decay of displacement response amplitude decreases at almost instant rate from distance larger than one time the foundation width (3m), while in the horizontal array (Figure 11b) the decrease of displacement amplitude is constant with distance.



a) b)

Figure 11: Decay with distance of the recorded displacement from the vertical (a) and horizontal (b) SAARs for output frequency 8Hz, and output force 17.51kN

4 DISCUSSION

A model structure (*EuroProteas*) was constructed in the *EuroSeistest* site array in order to study soil-foundation-structure interaction in large-scale. Free-vibration and forced-vibration tests were performed on the soil-foundation-structure system, using pull-out forces by a wire rope and an eccentric mass vibrator respectively. Aim of the study is to better understand and identify SFSI mechanism, as well as wave propagation effects in the coupled soil-foundation-structure system, induced by free and forced structural oscillation. In large-scale experiments we avoid all disadvantages arising from reduced-scale modeling, typically met in shaking table or centrifuge experiments.

Basic novelties of the study are:

- The very dense instrumentation of the SFS system, including more than 80 accelerometers and seismometers deployed in three directions, covering a volume of 9x9x12m around and beneath the structure. Such an instrumentation is able to capture wave propagation effects in the soil mobilized by structural oscillation, in addition to soil-foundation-structure interaction phenomenon identification.
- The easily reconfigurable mass and stiffness of *EuroProteas* structure in conjunction with the very well-known soil properties, are such to promote strong SFSI effects.
- The large number of pull-out tests performed to elucidate the so-called soil-foundation-structure system natural frequency.
- The large number of forced-vibration tests performed in the range of 1Hz to 10Hz, with exciting force amplitudes up to 20kN. The eccentric mass shaker was mounted on the foundation and on the roof slab of *EuroProteas*, enabling for different approximations of structural oscillation and foundation vibration analyses.
- The development of a *EuroSeistest* database portal (www.euroseisdb.civil.auth.gr) where all the recordings will be made available.

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