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SYSTEM IDENTIFICATION OF A STRUCTURE SUBJECTED TO FREE-, FORCED- VIBRATION AND AMBIENT NOISE EXCITATION

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Abstract

A series of experiments to study soil-structure interaction is performed in the full-scale structure of EuroProteas. EuroProteas is a simple test structure constructed in the experimental facility of Euroseistest in Northern Greece particularly designed to promote soil-structure interaction phenomena as it is a stiff structure founded on soft soil. It consists of two RC slabs representing the superstructure mass supported by four steel columns at a free height of 3.80m. The columns are founded on an identical to the roof RC slab which rests on the ground surface representing the surface foundation. X-braces are connecting the steel columns in both directions ensuring the symmetry of the structure. Its outer dimensions are 3x3x5m and its structural mass and stiffness are reconfigurable, allowing four different model configurations and covering a wide range of resonant frequencies. The foundation soil stratigraphy and dynamic properties are well-documented based on previous extensive geotechnical and geophysical surveys. The experimental campaign included free-vibration tests, forced-vibration tests and ambient noise measurements. A large number of instruments of various types (accelerometers, seismometers, shape-acceleration arrays and laser sensors) have been installed both on the structure and in the surrounding soil in order to obtain a well-instrumented 3D set of recordings to study SSI and wave propagation in soil media. In this paper, we seek to evaluate the dynamic properties and the modal parameters of EuroProteas corresponding to its actual flexible-base response using well-known conventional system identification techniques. The effects of SSI phenomena in the full-scale experiments, such as period elongation and damping increase, are evident in the analysis of the experimental recordings. The estimation of the dynamic characteristics of a system from such experiments may serve as reference for the more accurate calculation of fragility curves and its vulnerability assessment.

Keywords: system identification; experimental soil-structure interaction; field test; large-scale

1. Introduction

Over the last decades, soil-foundation-structure interaction have been widely investigated in small-scale experimental facilities (shaking table or centrifuge apparatuses) [1,2]. However, there are certain limitations existing in small-scale testing, such as the difficulty in reproducing realistic boundary conditions and stress fields in the soil and radiation damping of the wave field emanating from the oscillating structure to infinity.

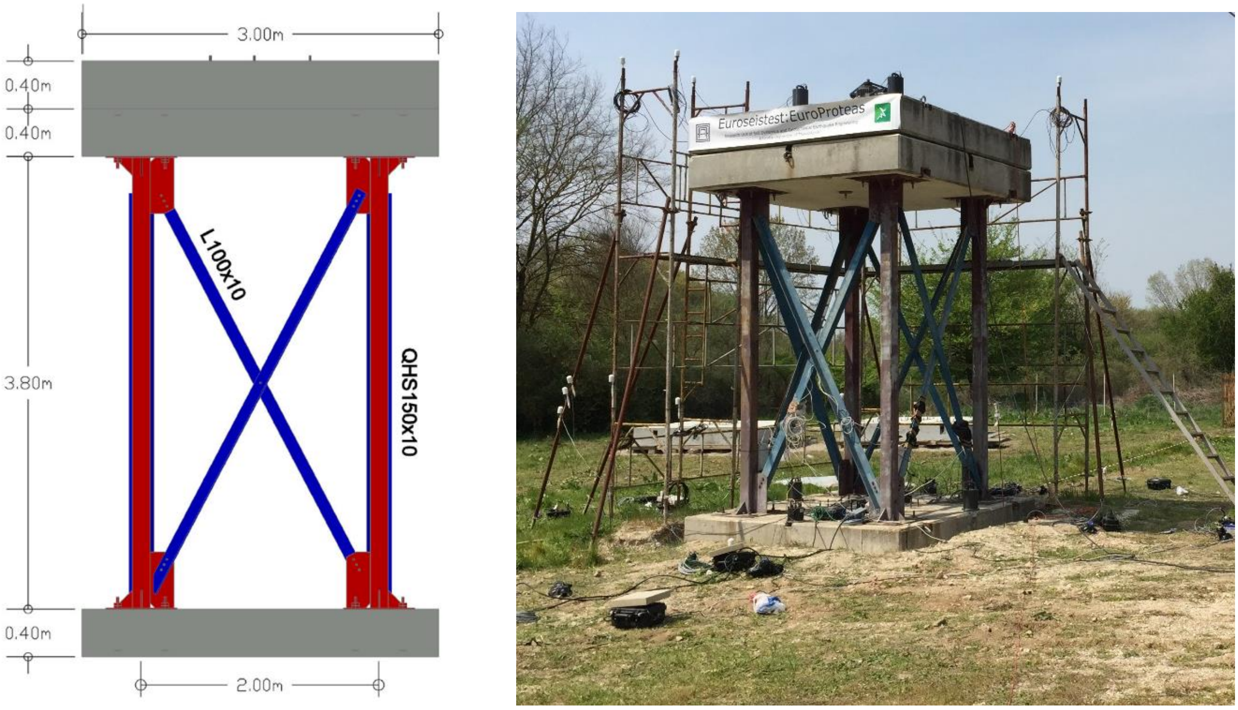
The importance of field testing of full-scale structures in the investigation of soil-structure interaction is associated with those limitations. Additionally, field testing is considered important for the validation of analytical models and their applicability for realistic field conditions, including system identification techniques, estimation of soil properties and nonlinear behavior and calculation of structural and soil damping, which have been developed for idealized conditions [3-10].

In this paper, we present a series of free- and forced-vibration experiments and ambient noise measurements performed in the prototype structure of EuroProteas. Applying different methods of data interpretation, we estimate the flexible-base period and damping of the system and we investigate its nonlinear dynamic behavior. It is shown that the flexible-base frequency of the system is highly influenced by the soil-foundation-structure interaction effects and the damping is increased as anticipated.

Until now, only a few studies have demonstrated the significance of soil-foundation structure interaction in the vulnerability assessment of structures [11]. The findings of the experiments presented herein emphasize the importance of considering soil-foundation-structure interaction effects and the nonlinear behavior of the soil-foundation interface in the vulnerability assessment of structures and the calculation of fragility curves.

2. EuroProteas Experimental Facility

2.1 EuroProteas structure



(a) (b)

Fig. 1 – (a) A 2D sketch and (b) a photo of EuroProteas.

EuroProteas is a perfectly symmetric and reconfigurable structure particularly designed to mobilize strong interaction with its foundation soil (Fig.1). The large superstructure mass in combination with the soft foundation soil ensure the demonstration of soil-foundation-structure interaction effects and the nonlinear behavior of the soil-foundation interface.

EuroProteas prototype structure is founded on a square reinforced concrete slab (C20/25) with dimensions 3.0m x 3.0m x 0.4m resting on the ground surface. The superstructure mass consists of two identical to the foundation reinforced concrete slabs that are supported by four square hollow steel columns (QHS 150 x 150 x 10mm) clamped on the foundation. L-shaped (100 x100 x 10mm) X-braces are connecting the steel columns in all the sides of the structure ensuring its total symmetry. Assuming a uniform unit weight of 25kN/m^3 for the concrete, the total mass of each slab is estimated at 9.16Mg, while the total mass of the structure is calculated approximately at 28.5Mg. Its outer dimensions are 3.0m x 3.0m x 5.0m.

The X-braces and the upper roof slab of the structure are removable allowing the modification of the mass and the stiffness and consequently, the adjustment of structure to soil ratio. Depending on the number of the roof slabs and the arrangement of the X-bracing system the fixed-base frequency of EuroProteas covers a range between 1.78Hz and 13.06Hz as calculated numerically using the finite element software SAP2000 [12].

2.2 Foundation Soil

EuroProteas is located at the Euroseistest experimental array (http://euroseisdb.civil.auth.gr). The foundation soil stratigraphy and its dynamic properties are defined based on extended geophysical and geotechnical in-situ and laboratory surveys reported in earlier studies [13,14]. Additionally, prior to the construction of the prototype structure a series of geotechnical and geophysical tests was performed including drilling boreholes, down-hole measurements, resonant column and cyclic triaxial tests on undisturbed soil specimens [9,15].

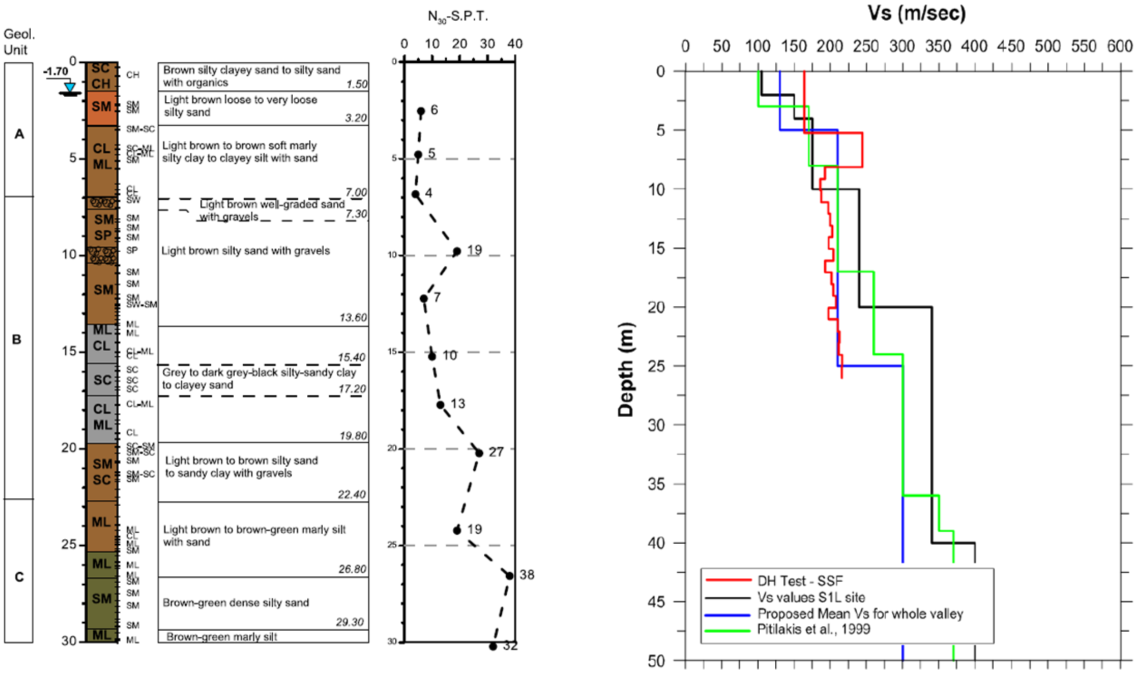


Fig. 2 – Soil stratigraphy of the 30m deep borehole at the geometrical center of the foundation (left) and Vs profile from down-hole tests compared with Vs profile at S1L site approximately 50m south of EuroProteas, a reference mean Vs model of the valley cross-section and proposed Vs profile in [13] (right).

The foundation soil stratigraphy as defined based on the acquired data is presented in Fig. 2. The small stiffness of the top soil layer is pronounced by the low recorded N_{SPT} values down to a depth equal to two times the foundation width. Moreover, the shear wave velocity profile derived from the down-hole measurements is compared with the profiles proposed in previous studies. Close to the soil surface the shear wave velocity is estimated approximately at 100m/s.

3. Experimental Program

3.1 Instrumentation

A dense instrumentation scheme was designed to record the structural and soil response. A large number of instruments of various types was installed including digital broadband seismometers, triaxial accelerometers, borehole accelerometers and Shape Acceleration Arrays. Instruments and equipment for the experiments were provided by the Research Unit of Soil Dynamics and Geotechnical Earthquake Engineering (SDGEE-AUTH, http://sdgee.civil.auth.gr/) and the Institute of Engineering Seismology and Earthquake Engineering, part of the Earthquake Planning and Protection Organization (EPPO-ITSAK, http://www.itsak.gr/) (Fig. 3).

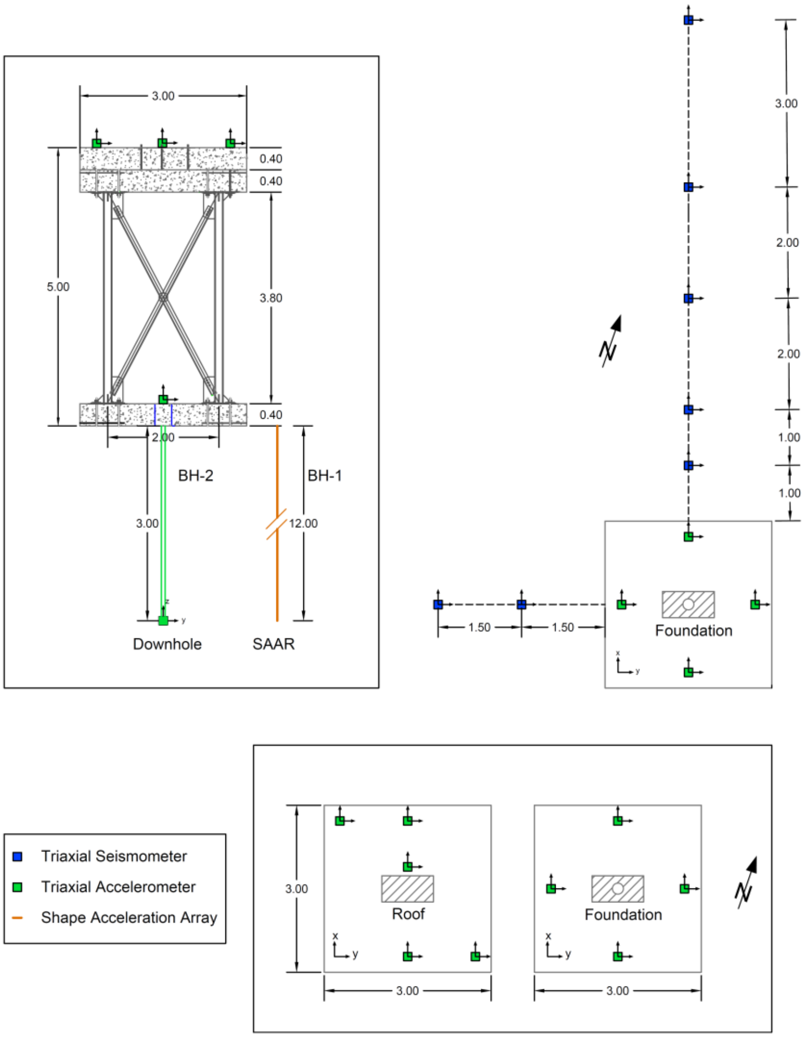


Fig. 3 – Instrumentation layout.

Five triaxial accelerometers were installed on the roof slab, three of them were installed along the axis of shaking (in-plane) and the other two at the opposite corners of the slab to capture possible out-of-plane vibration due to the mobilization of the torsional or transverse modes of the structural response. Additionally, four accelerometers were mounted at the middle of the edges of the foundation slab, two along the axis of shaking and the other two perpendicular to it to capture possible translational, rocking and out-of-plane response. One accelerometer was clamped inside the borehole BH-2 located at the geometrical centre of the foundation at the depth of 3m.

Soil response was recorded with seven digital broadband seismometers placed on the soil surface and aligned to the principal axes of the structure. Five of them were installed along the direction of loading. This array, which is denser close to the foundation, was able to record the soil response and wave emanation due to the oscillation of the structure. Additionally, two seismometers were placed on the soil surface in the out-of-plane direction. Finally, one shape acceleration array was installed in the borehole BH-1 adjacent to the foundation.

Due to the symmetry of the structure, this dense instrumentation scheme allowed the recording of the structural and soil response in three directions. All the instruments were connected to external global positioning system (GPS) antennas and their sampling frequency was set to 200 Hz.

3.2 Experimental procedure

Pull-out forces were applied to the roof slab by a wire rope of 14mm diameter clamped at a reinforced concrete counterweight buried in the soil 27m away from EuroProteas. The tension was applied to the wire rope by a pulling hoist and when the desired level of force was reached, the wire rope was cut loose and the structure oscillated freely until rest. The applied tension force was measured by a load cell attached to the roof slab and to the one end of the wire rope (Fig. 4).

In total, five pull-out forces were applied having amplitudes that varied between 2-16kN (Table 1).

Table 1 – Summary of the free-vibration experiments.

Experiment ID	**Force Amplitude (kN)**
A	2
B	2.5
C	5
D	10.5
E	16

Fig. 4 –The one end of the wire rope and the load cell attached to the roof slab.

Four series of forced-vibration tests were performed. The eccentric mass shaker MK-500U owned by the Institute of Engineering Seismology and Earthquake Engineering (ITSAK) was implemented as a source of harmonic excitation. It is a portable uniaxial dual counter-rotating shaker that can produce a maximum force amplitude of 5tons in a frequency range between 0.1-20Hz (Fig. 5a). Eight mass plates in four different sizes (A, B, C and D) can be used in pairs to adjust the eccentricity of the shaker and hence the output force. The amplitude of the output force of the shaker is given by the Eq. (1)

$$F = E(2\pi f)^2 \tag{1}$$

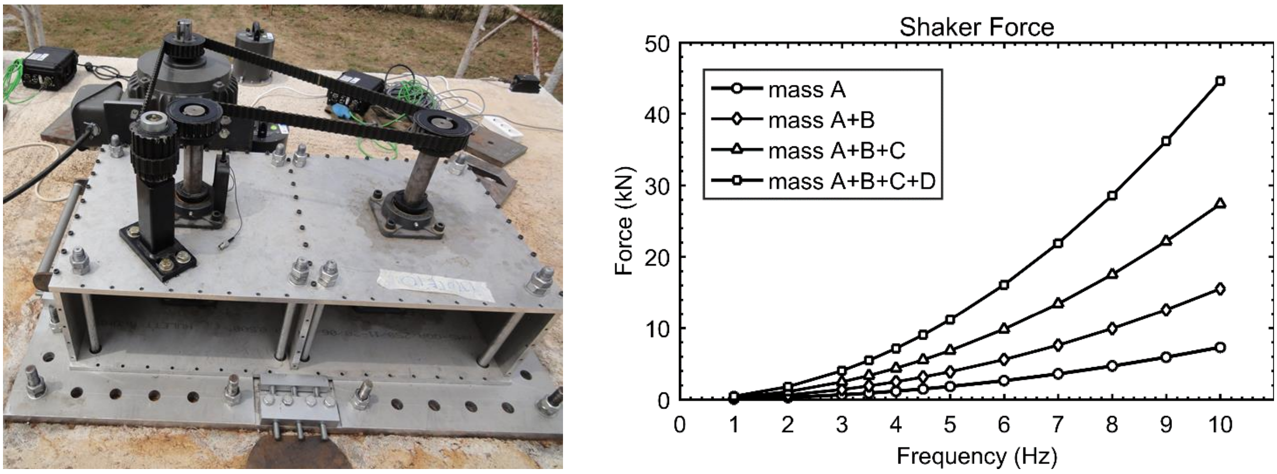
where F is the shaker output force (in N), E is the total eccentricity of the shaker (in kg-m) and f stands for the rotational speed of the shaker (in Hz). The frequency – force relationship is given in Fig. 5b.

In the experiments described herein, the eccentric mass shaker was placed at the geometrical centre of the top roof slab of the structure and it was orientated to produce a force having a direction perpendicular to the one side of the structure and parallel to the North-South recording direction of the installed instruments. Excitation force amplitude varied between 0.07kN and 28.5kN at frequencies that ranged from 1Hz to 10Hz including the fixed- and flexible-base fundamental frequency of the EuroProteas soil-structure system (Table 2). In all tests and for each excitation frequency the shaker force was held constant for a sufficient time window until the system reached steady state.

At the beginning and at the end of each experiment ambient noise was recorded for several minutes simultaneously by the structure and soil stations at 200 Hz sampling rate. In total more than 30 minutes of ambient noise were recorded.

Table 2 – Summary of the forced-vibration experiments.

Experiment ID	**Mass / Plate**	**Total Eccentricity (kg-m)**	**Frequency Range (Hz)**	**Force Amplitude (kN)**
A	A	1.85	1-10	0.07 – 7.3
B	A + B	3.93	1-10	0.15 – 15.5
C	A + B + C	6.93	1-8	0.3 – 17.5
D	A + B + C + D	11.31	1-8	0.5 – 28.5



(a) (b)

Fig. 5 – (a) Eccentric Mass Shaker MK-500U and (b) its frequency – force relationship.

4. Test Results

4.1 System identification

System Identification of EuroProteas was conducted using the MACEC software [16], a Matlab toolbox for operating experimental and operational modal analysis. The methods used were output-only or stochastic system identification methods. Specifically, the Peak Picking method (PP), the Frequency Domain Decomposition (FDD) method and the parametric stochastic subspace identification (SSI) technique were applied on ambient noise recordings.

Five modes were identified, two swaying modes, one torsional mode and two coupled translational-torsional modes as summarized in Table 3.

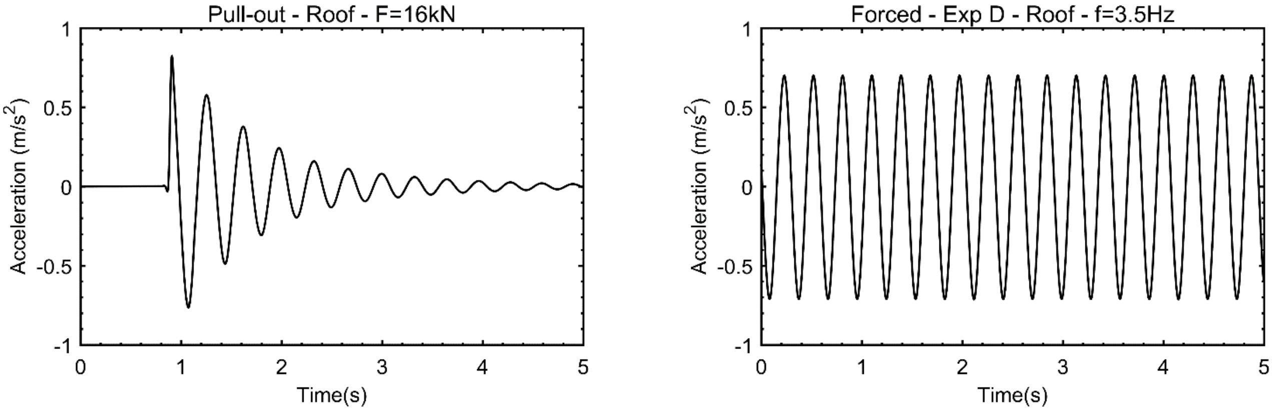
Table 3 – Resonant Frequencies estimated by the system identification analysis methods.

Mode	**PP (Hz)**	**FDD (Hz)**	**SSI (Hz)**	**Mode Shape**
1	3.51	3.51	3.48	Translational
2	3.52	3.52	3.58	Translational
3	8.98	8.98	8.98	Torsional
4	20.51	20.51	20.61	Coupled Translational-Torsional
5	21.1	20.6	20.65	Coupled Translational-Torsional

The identified resonant frequencies of the system estimated by the different system identification techniques are very similar. Compared to the numerically calculated fixed-base frequencies [9], the resonant frequency referring to the translational mode of the structure shifts from 9.13Hz to approximately 3.5Hz. This result pronounces the soil-foundation-structure interaction effects on the system. Additionally, the corresponding damping ratio is estimated at 5% for the first mode and 3.6% for the second mode.

4.2 Structural Response

In Fig. 6a we present the recording of the roof acceleration along the direction of loading for a free-vibration test with applying pull-out force of 16kN. Additionally, in Fig. 6b a time window of the roof response during the forced-vibration experiment D and for an excitation frequency of 3.50Hz is shown.



(a) (b)

Fig. 6 – Acceleration response recorded at the roof for (a) a free-vibration experiment and (b) a forced-vibration experiment.

4.3 Damping

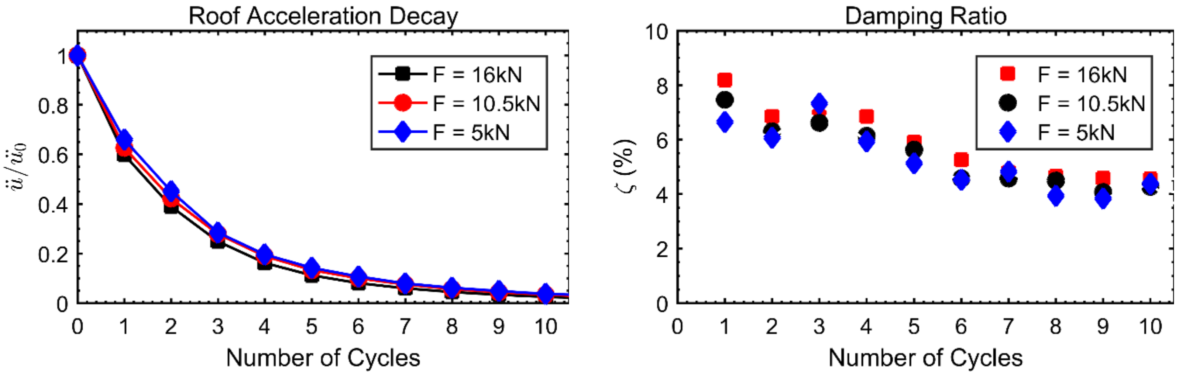
In Fig. 7a we show the amplitude of the acceleration motion recorded at the roof of EuroProteas normalized by the maximum acceleration recorded for three free-vibration tests with increasing applied pull-out forces. A decrease of more than 70% in the amplitude is noticed after three cycles of oscillation in all the tests. This pronounces the large amount of energy dissipated in only the first few cycles of oscillation. The rate of decrease shown is almost similar in all the tests irrespectively of the amplitude of the applied pull-out force.

Furthermore, we calculated the system damping ratio from the free-vibration experiments using the logarithmic decrement method [17] as in Eq. 2

$$\zeta = \frac{1}{2\pi} ln \left(\frac{u_i}{u_{i+1}}\right) \quad (2)$$

where ζ is the damping ratio and u_i and u_{i+1} are the values of the amplitude of two adjacent cycles of motion.

In Fig. 7b the calculated damping ratios for three free-vibration experiments are presented. During the first three to four cycles the value of the damping ratio is estimated between 6% and 9%, while it is decreased to approximately 4-5% afterwards. This decrease indicates a nonlinear behavior of the soil-structure system in the first cycles of oscillation. Additionally, it is seen that the value of the damping ratio increases significantly in the first cycles of oscillation with increasing pull-out force. However, this trend is not so important in the rest of the motion. It is interesting to note that the system damping ratio measured in the field is slightly greater than the one calculated as ζ=4.4% according to [7] and [18] and the one estimated from the system identification techniques at approximately 5%.



(a) (b)

Fig. 7 – (a) The normalized decay of the recorded acceleration at the top of EuroProteas and (b) the calculated damping ratio.

4.4 Period elongation

The maximum amplitude of the acceleration recorded at the roof versus the period of the input signal with respect to the eccentric mass shaker’s eccentricity during the forced-vibration experiments is reported in Fig. 8. It is noticed that for the smaller eccentricities of 1.85kg-m and 3.93kg-m, the peak response is shown at a period of 0.28sec or at the frequency of 3.50Hz, being in a good agreement with the flexible-base resonant frequency predicted by system identification at 3.48Hz. This period is shifted to approximately 0.33sec (or 3Hz) in the case of the largest eccentricity implying strong nonlinear behavior possibly because of the larger excitation force.

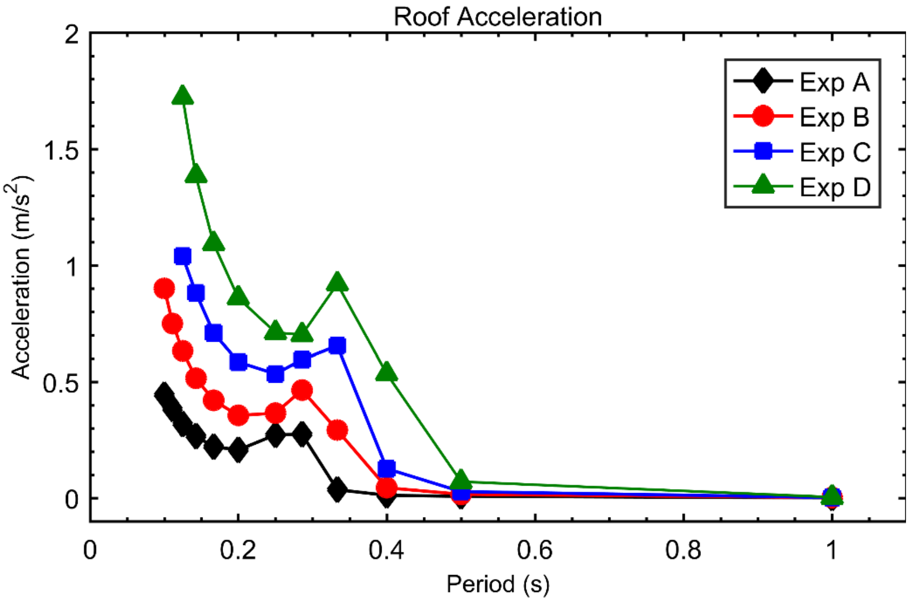


Fig. 8 – Maximum amplitude of the acceleration recorded during the forced-vibration experiments at the roof at different excitation frequencies.

Similar conclusion can be drawn by looking at the transmissibility functions calculated according to [17] for each experiment and presented in Fig. 9. The acceleration response factor is calculated as the ratio of the acceleration recorded at the roof to the shaker force normalized by the superstructure mass. Additionally, the acceleration response function is decreased for large amplitude forces such as experiments C and D indicating an increase in the value of damping possibly due to nonlinearities introduced in the soil-foundation interface and the foundation soil.

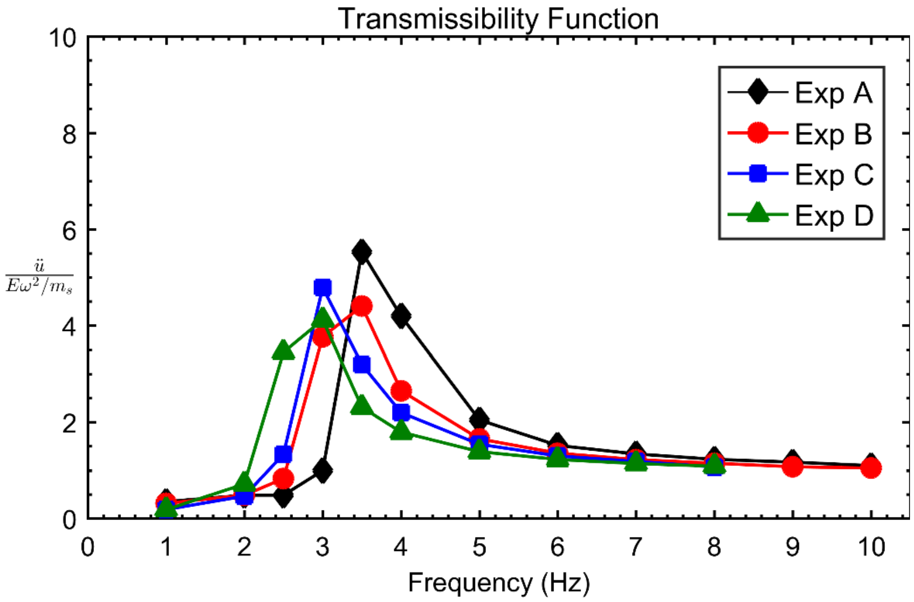
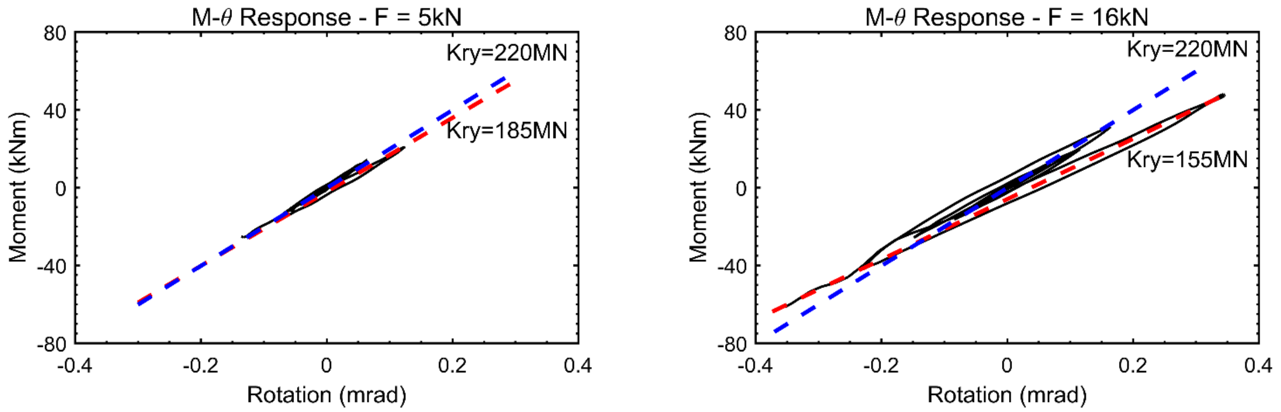


Fig. 9 – Transmissibility functions for the forced-vibration experiments.

4.5 Moment – Rotation

In Fig. 10 we present the moment-rotation response of the soil-structure system for the applied pull-out forces of 5kN and 16kN. The moment at the base was calculated as the product of the acceleration, the superstructure mass and the height of the structure, whereas the rotation θ is calculated as the ratio of the horizontal roof displacement over the height of the structure.



(a) (b)

Fig. 10 – Moment-rotation response of the system for the applied pull-out forces of (a) 5kN and (b) 16kN.

The slope of a typical moment rotation response corresponds to the rocking stiffness of the system. An initial slope corresponding to a low value of stiffness, approximately 185MN for the force of 5kN and 155kN for the force of 16kN, is noticed indicating a nonlinear response in the first couple of cycles of oscillation. Then, the rocking stiffness increases and is estimated around 220MN. This value is very close to the rocking stiffness K_{ry} = 270MN calculated using the empirical equation proposed by [19]. The difference in the initial slope is attributed to the higher level of nonlinear effects that take place for greater applied forces. Additionally, a larger energy dissipation is noticed in the first couple of cycles for the force of 16kN confirming the increased damping ratio noticed in the decay of the acceleration recordings.

5. Conclusions

The results of an extensive sequence of experiments performed in the prototype structure of EuroProteas, located in Northern Greece, were used to identify the dynamic properties of the system and the soil-foundation-structure interaction effects. The experiments included ambient noise measurements, free- and forced-vibration tests.

Ambient noise measurements were employed to estimate modal frequencies and damping ratios applying parametric and non-parametric identification techniques. The effects of soil-foundation-structure interaction, such as period lengthening and damping increase were pronounced. Similar findings were observed from the free- and forced vibration tests. The resonant frequency of the system was shifted to lower values compared to the numerically calculated fixed-base resonant frequency. The damping ratio observed during the free-vibration tests increased in the first cycles of oscillation. Moreover, an increased value of the damping ratio was also reported in the forced-vibration experiments for the large amplitude excitation forces.

6. Acknowledgements

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