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Soil mass participation in soil-structure interaction by field experiments in EuroProteas

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ABSTRACT: A series of experiments to study soil-foundation-structure interaction (SFSI) is performed in the full-scale prototype structure of EuroProteas constructed in the experimental facility of Euroseistest in Northern Greece. Its outer dimensions are 3x3x5m and its structural mass and stiffness are reconfigurable, allowing for four different configurations and covering a wide range of resonant frequencies. A large number of instruments of various types 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 SFSI and wave propagation in soil media. In this paper, we evaluate the effects of SFSI phenomena in the full-scale experiments such as period elongation. Additionally, we examine the extent of participating foundation soil mass in the structure response, based on the waves that are created in the foundation soil because of the vibration of the structure.

1 INTRODUCTION

The effects of soil-foundation-structure interaction (SFSI) have been widely investigated in small-scale experiments (shaking table or centrifuge apparatuses) in the laboratory (Paolucci et al. 2008, Pitilakis et al. 2008). However, there are limitations associated with the boundary conditions, the produced stress fields in the soil and the radiation damping of the wave field emanating from the oscillation of the structure. On the other hand, relatively few large-scale field experiments investigating SFSI effects have been reported so far (Tileylioglu et al. 2011, Star et al. 2015, Pitilakis et al. 2018, Vratsikidis & Pitilakis 2018). The main advantage of the full-scale experiments are the realistic field conditions.

In this paper, we present the results of the forced-vibration experiments performed on the large-scale structure of EuroProteas. We particularly focus on the soil response and we investigate the wave attenuation in soil media.

2 EUROPROTEAS FACILITY

2.1 *EuroProteas structure*

EuroProteas is a perfectly symmetric and reconfigurable structure particularly designed to mobilize strong interaction with its foundation soil 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 a RC slab, identical to the roof slab, which rests on ground surface representing the surface foundation. X-braces are connecting the steel columns in both directions ensuring the symmetry of the structure (Figure 1).

The dimensions of each RC slab are 3x3x0.4m resulting to a total superstructure mass of 18Mg. The total height of EuroProteas structure from the bottom of the foundation slab to the top of the second roof slab is 5m and its total mass (including the foundation slab) is approximately 28.5Mg. Depending on the number of RC roof slabs and the presence of the

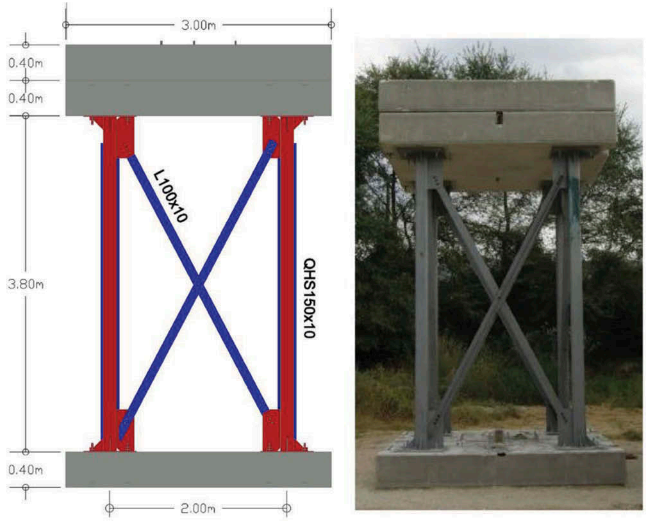

Figure 1. EuroProteas prototype structure sketch and photograph.

X-braces, the fixed-base natural frequency of EuroProteas ranges between 1.78 Hz and 13.06 Hz as derived numerically by means of a 3D Finite Element fixed-base model. A detailed description of the structure can be found in Pitilakis et al. 2013 and Pitilakis et al. 2018.

2.2 *Soil stratigraphy*

EuroProteas structure is located at the center (TST site) of the EuroSeistest experimental array (http://euroseisdb.civil.auth.gr). The stratigraphy and the dynamic properties of the foundation soil are well-documented and defined based on extended geotechnical and geophysical surveys (Pitilakis et al. 1999). Prior to the construction of EuroProteas, a 30m deep borehole was drilled in the geometric center of the foundation slab and a 12m deep borehole was drilled 0.5m away from at the eastern edge of the foundation. The additional geotechnical and geophysical in-situ tests, down-hole measurements and resonant column tests on selected soil samples from the boreholes were performed and described in Pitilakis et al. 2018.

The resulting soil stratigraphy and Vs profile below EuroProteas is presented in Figure 2 compared with the profiles derived by Pitilakis et al. (1999) and with results related to another similar site. Discrepancies are noticed in the comparison of the uppermost 7 meters, however the Vs profile proposed by Pitilakis et al. 1999 was used as it is considered more accurate. Close to the surface of the soil profile (3 to 8m depth) the shear wave velocity is estimated approximately from 100m/s to 130m/s.

2.3 *Instrumentation layout*

The structure and the surrounding soil were instrumented according to a particularly dense three-dimensional instrumentation scheme specifically designed to record structural response and wave propagation in the soil media. More than 80 instruments of various types were installed to monitor structural, foundation and soil response including digital broadband seismometers, triaxial accelerometers, borehole accelerometers and Shape Acceleration Arrays.

We updated the instrumentation layout described in Pitilakis et al. (2018) by adding more instruments on new locations on the soil surface and on the foundation of the structure. More seismometers were placed close to the structure along the direction of excitation to measure the soil response in greater detail. Furthermore, additional accelerometers were placed on the

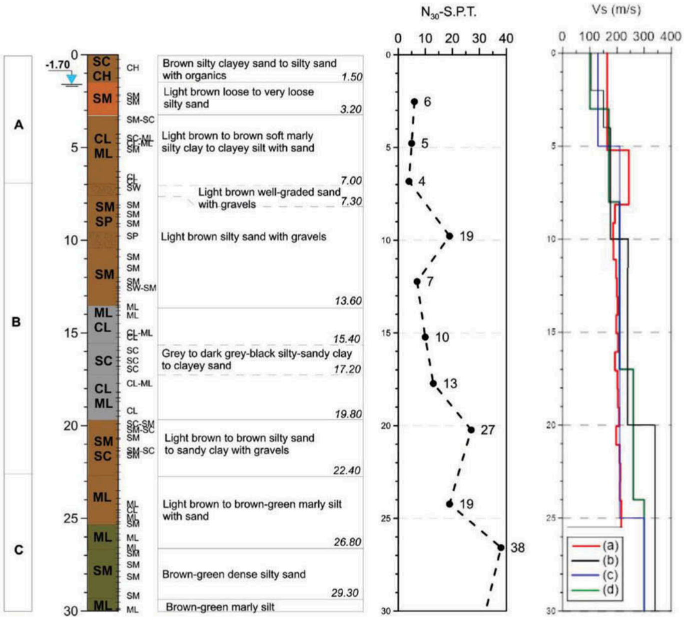

Figure 2. Soil stratigraphy of the 30m deep borehole (left) and Vs profile from (a) down-hole tests compared with (b) Vs profile at a site approximately 50m south of EuroProteas, (c) reference model of the valley cross-section and (d) Pitilakis et al 1999 proposed Vs profile.

foundation slab to capture its motion in both in-plane and out-of-plane directions. The final instrumentation scheme is shown in Figure 3.

3 EXPERIMENTS

We performed forced vibration experiments on EuroProteas structure using the MK-500U (ANCO Engineers Inc) eccentric mass vibrator system, owned by the Earthquake Planning and Protection Organization EPPO-ITSAK, as a source of harmonic excitation. The shaker was placed both on the foundation and on the roof slab to increase rocking of the structure, exciting the structure along its main axes. Excitation force amplitude varied between 0.07kN and 28.58kN at frequencies that range from 1Hz to 10Hz (Figure 4).

The amplitude of the harmonic forces is modified according to the eccentricity of the shaker. In Experiment A the lowest available eccentricity is used, gradually increasing in Experiments B and C, reaching the largest value in Experiment D. 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. The produced force of the shaker can be calculated as follows

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

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 according to the number of pairs of plates used is presented in Figure 4.

The unified database containing all the available data files of the experiments performed has been presented in Pitilakis et al. 2018, and Vratsikidis and Pitilakis 2018.

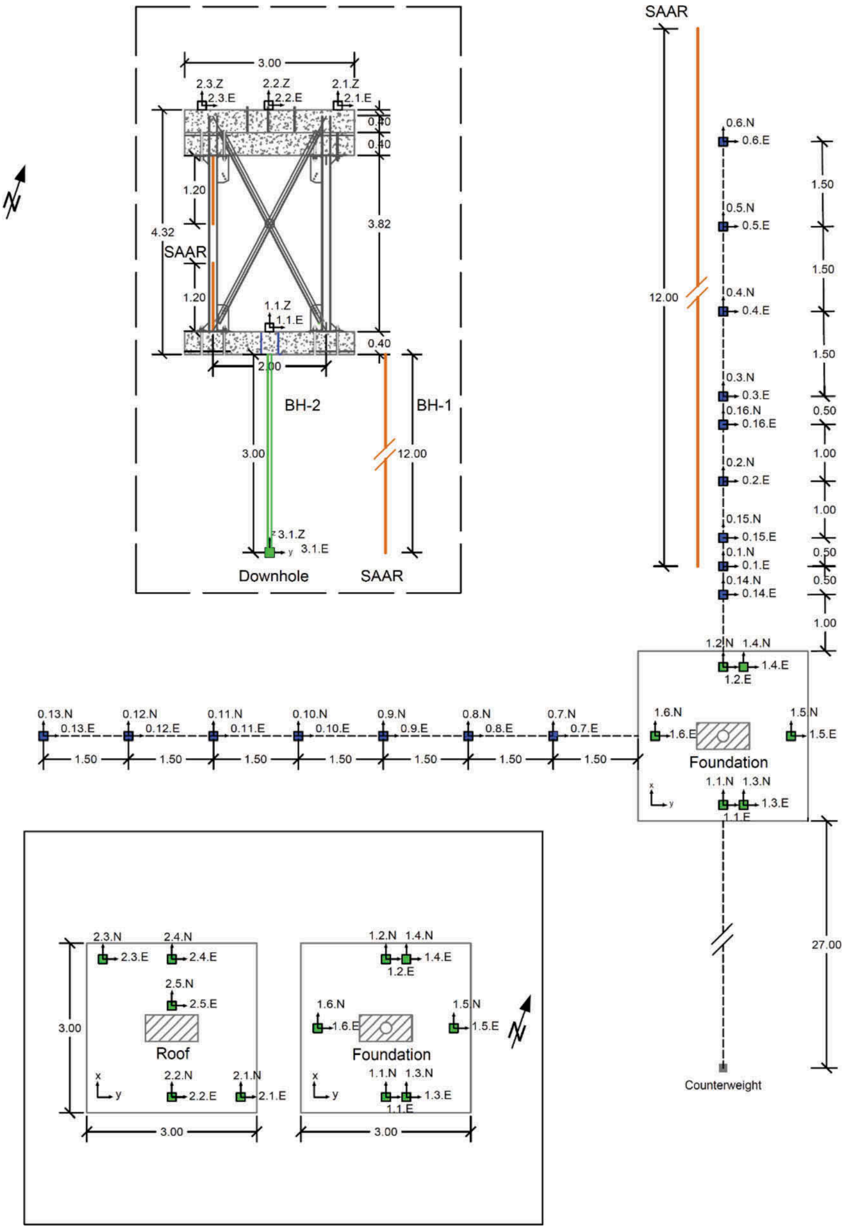

Figure 3. Instrumentation layout of EuroProteas experimental campaign.

4 DATA PROCESSING

4.1 *Period elongation*

We estimated the flexible base frequency of the SFSI system using the data acquired from the forced vibration experiments. In Figure 5 we present time sections of the recorded response of the roof of the structure along the direction of loading for three different excitation frequencies. The time interval is taken when the system reached the steady state in each excitation in three different experiments. In this case the eccentric mass shaker is placed at the top of the

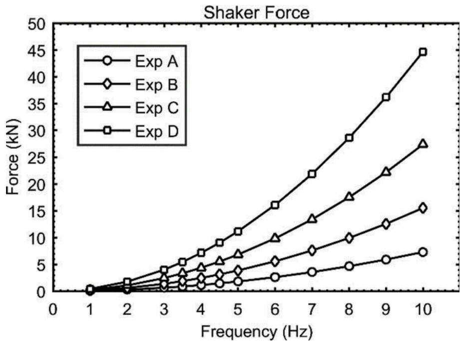

Figure 4. Frequency-force relationship of the MK-500U eccentric mass shaker (ANCO Engineers Inc.).

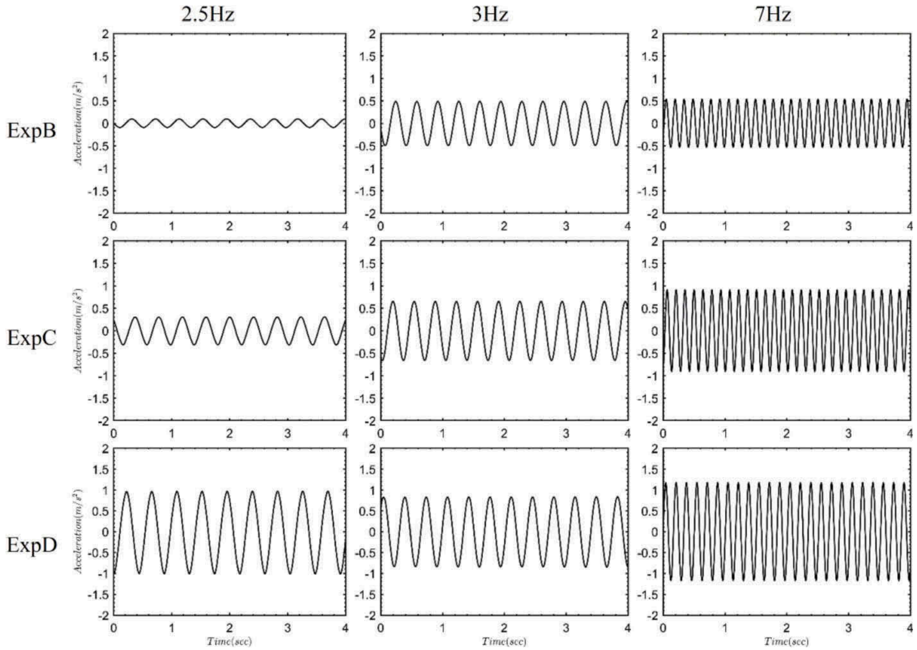

Figure 5. Structural response in a time window of 4 seconds recorded at the roof during Experiments B, C and D for excitation frequency of 2.5Hz, 3Hz and 7Hz (acceleration units in m/s^2).

structure producing larger forces with increasing number of pairs of mass plates used and increasing excitation frequency.

As seen in Figure 5, the response of the structure when the excitation frequency of the shaker is 3Hz is almost equal in amplitude with the response for excitation frequency of 7Hz in Experiments B and C. One should consider that when the excitation frequency is 3Hz the amplitude of the loading force is 1.4kN in Experiment B and 2.5kN in Experiment C, while for the excitation frequency of 7Hz the amplitudes are 7.6kN and 13.4kN, respectively. Moreover, the amplitude of the response for the 3Hz excitation is much greater than the one for the 2.5Hz excitation which produces a loading force of the same order in both experiments (0.97kN and 1.71kN respectively). These results indicate that the resonance frequency of the SFSI system is close to 3Hz. Furthermore, in Experiment D, in which the forces produced are much larger as shown in Figure 4, we notice a shift in resonance to the excitation frequency of

2.5Hz, possibly due to nonlinearities introduced in the SFSI system because of the larger loading forces.

4.2 *Soil mass participating in the response*

In Figure 6 we shown the decay of the maximum values of the amplitude of the vertical component of the soil surface response as the distance from the foundation increases, for different excitation frequencies. It can be noticed that up to 1m away from the structure the amplitude of the response is greater when the structure is excited close to its resonant frequencies, indicating that the soil around the foundation and the structure respond to the loading as a whole system. However, for these excitation frequencies the decay of the response is faster in the next few meters compared to the soil response for greater excitation frequency. For larger excitation force at 7Hz, the decay with distance is slower. In general, it can be seen that there is a reduction in the amplitude of the soil response by more than 50% at a distance equal to the foundation width B = 3m for all the excitation frequencies and that at a distance equal to 2B = 6m the maximum values of the response are almost negligible. This participating soil mass, where the shear modulus should be evaluated for the calculation of the impedance functions, is a bit larger than the one described in NIST (2012) (equal to 0.75B/4), but lower than the one described in Gazetas (1983) and Mylonakis et al. (2006), which equals to 2 to 4 times the foundation width.

Another interesting aspect of the soil response is the fact that the north component is much lower than the vertical component, even close to the structure (Figure 7), probably because of the rocking of the structure close to its resonant frequencies, which results in the production of Rayleigh waves which are predominant in the foundation and the surrounding soil.

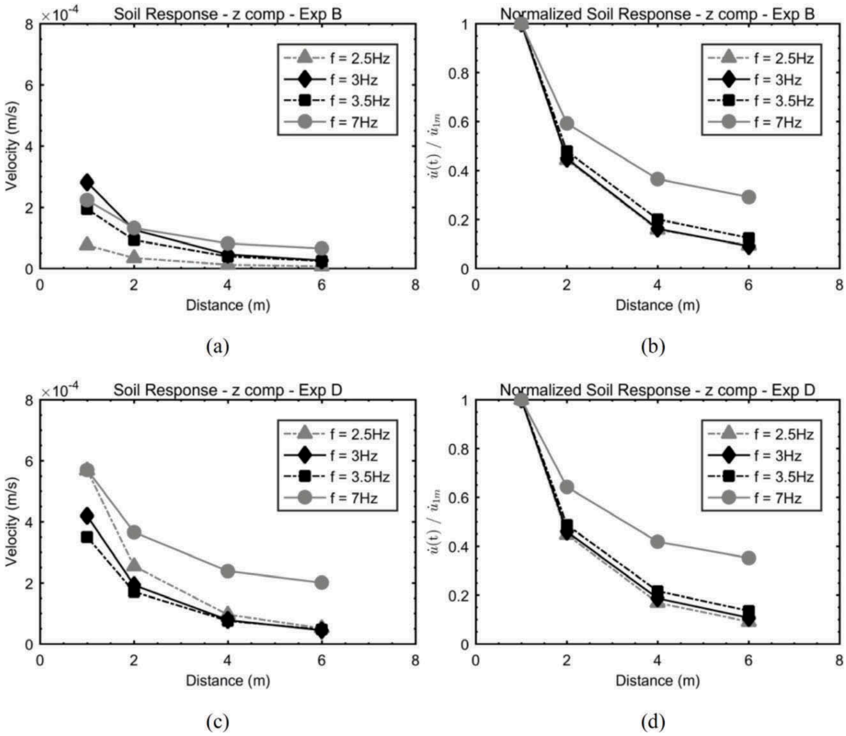

Figure 6. Decay of the vertical component of the recorded soil surface response with distance in Experiment B (a, b) and in Experiment D (c, d).

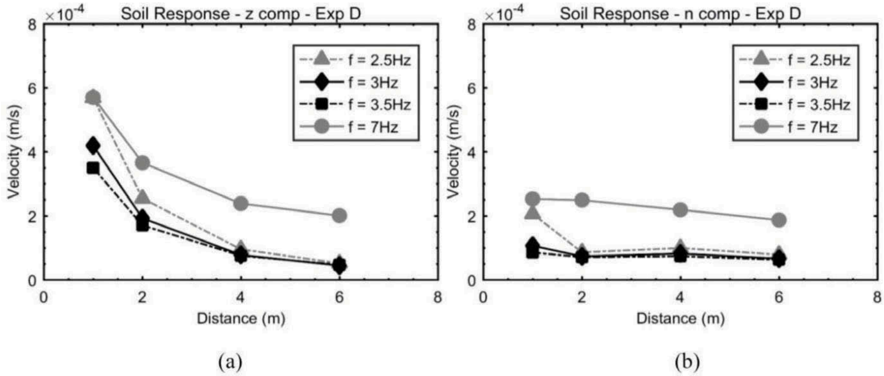

Figure 7. Decay of (a) the vertical and (b) the north component of the recorded soil surface response with distance in Experiment D.

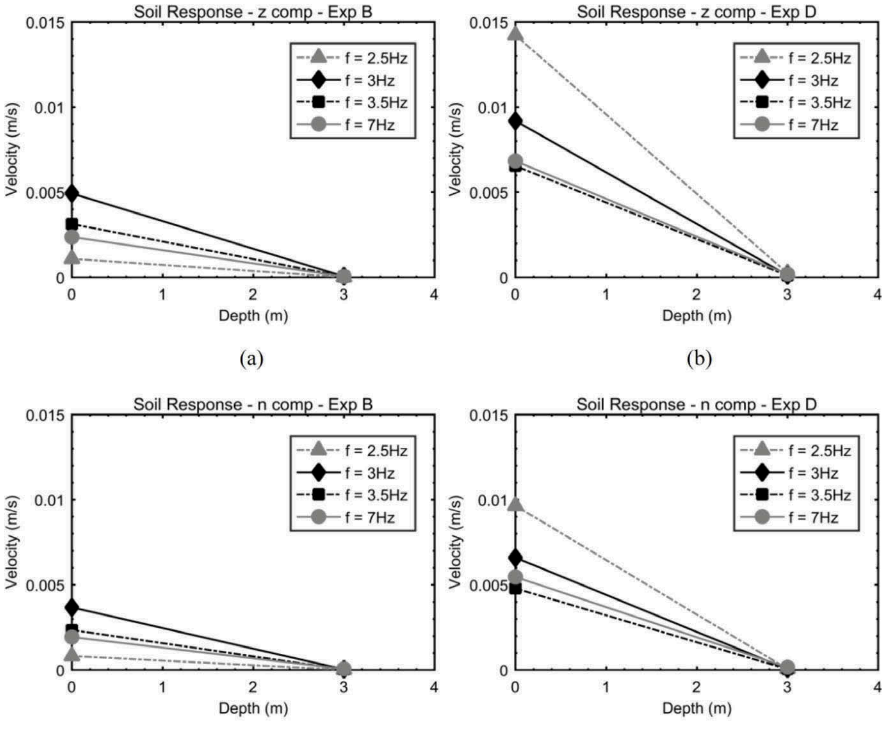

Figure 8. Decay of the vertical component of the recorded soil surface response up to a depth of 3m in (a) Experiment B and in (b) Experiment D and of the north component of the recorded soil surface response up to a depth of 3m in (c) Experiment B and in (d) Experiment D.

Concerning the wave propagation in the foundation soil immediately below the structure, we show in Figure 8 the maximum amplitude of the north (horizontal) velocity response at a depth of B = 3m, where the down-hole accelerometer is installed, and we compare it with the velocity recorded at the top of the foundation. We notice that the response at this depth can be considered negligible as it has values of approximately 0.0001m/s, which are similar to the values of the soil surface recorded at a distance of 4m away from the foundation during the same experiments. However, further investigation of the foundation soil response at depths closer to the surface is required.

5 CONCLUSIONS

The results of forced-vibration experiments performed in the prototype structure of EuroProteas were used to evaluate SFSI effects and investigate wave propagation due to the oscillation of the structure in the foundation soil. The resonant frequency of the structure was estimated close to 3Hz; however, as the loading increased, a shift in lower values was noticed possibly due to soil nonlinearities introduced to the system. Concerning the wave propagation in the surrounding participating soil, it is clearly shown that there is a decrease of more than 50% in the amplitude of the response at a distance equal to the foundation width in both the horizontal and vertical direction away from the foundation.

ACKNOWLEDGEMENTS

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