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Numerical Simulation of Large-Scale Soil-Foundation-Structure Interaction Experiments In The EuroProteas Facility

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ABSTRACT

In this study we present preliminary numerical modeling of forced-vibration full-scale soil-foundation-structure experiments performed in the facility of EuroProteas; a particularly stiff model structure founded on soft soil, mobilizing strong soil-foundation-structure interaction (SFSI) effects during structural oscillation. EuroProteas' outer dimensions are 3x3m in plan view and 5m high. Various model configurations are possible by reconfiguring structural mass and stiffness. Forced-vibration tests were performed by means of an eccentric mass vibrator referring to sine sweeps tests with loading frequency varying between 1Hz and 10Hz and a total harmonic force up to 20kN. The vibrator was mounted both on the foundation and the superstructure slab of the model. We present preliminary 3D numerical simulation of the forced-vibration field experiments with emphasis on the recorded soil response. Discussion follows upon the adequacy of 2D and 3D modelling of the experiments.

Introduction

Experimental soil-foundation-structure interaction (SFSI) is commonly addressed in small-scale by implementing experiments in shaking-table or centrifuge apparatuses, as presented in indicative publications (Maugeri et al., 2000, Massimino, 2005, Paolucci et al., 2008, Pitilakis et al., 2008, Pitilakis and Clouteau, 2010). Nevertheless, laboratory tests present certain limitations in reproducing actual field conditions, especially to account for realistic stress fields in the soil. On the other hand, large-scale field experiments account for realistic boundary conditions. In their early studies, Luco et al. (1988) derived foundation impedance functions from forced-vibration field tests, while de Barros and Luco (1995) performed forced-vibration tests on a reduced-scale model of a nuclear reactor. Tileylioglu et al. (2011) reported forced-vibration experiments on a large-scale structure in Garner Valley, California, focusing on dynamic impedance functions.

In this study, we present a numerical assessment of a large experimental field campaign to study SFSI and wave propagation in the foundation soil due to structural oscillation. The tests were performed in the full-scale experimental facility of EuroProteas in the Euroseistest site established in the Mygdonian valley in Northern Greece (http://euroseisdb.civil.auth.gr/). The

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construction and experiments were conducted in the framework of the European project SERIES.

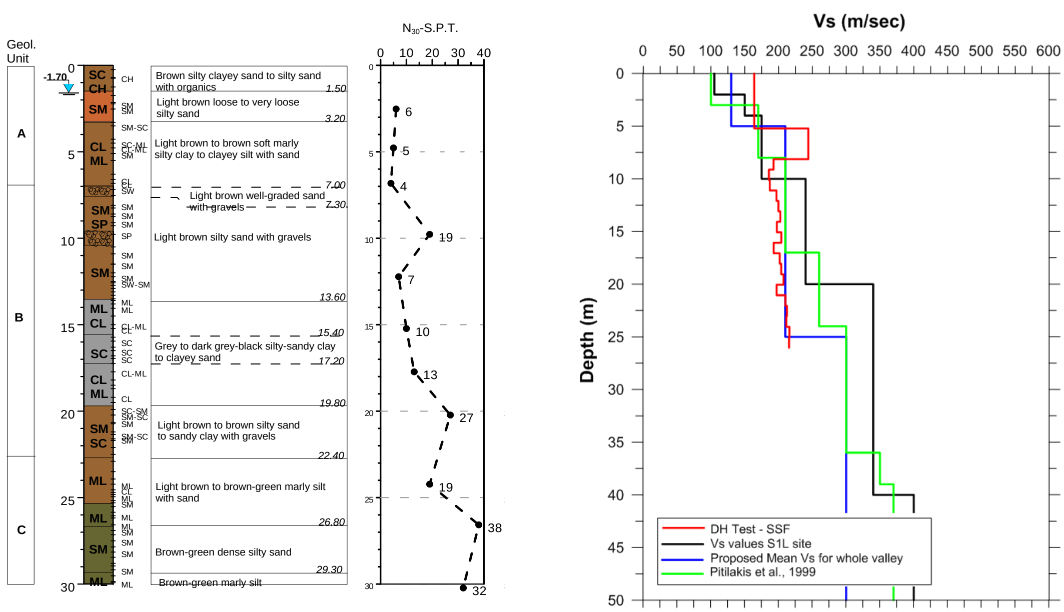
Description of the EuroProteas Experimental Facility

Soil Description

Soil stratigraphy and dynamic properties in Euroseistest site are already well-documented from extensive geotechnical and geophysical surveys (Raptakis et al., 2000). However, in order to define the detailed soil stratigraphy immediately below EuroProteas, a 30m borehole was drilled in the geometric center of the foundation slab, and a 12m borehole was drilled at 0.5m from the east edge of the model. Standard penetration tests were conducted in the 30m deep hole and undistributed soil samples were retrieved for laboratory testing, to establish soil properties. In addition, resonant column tests were performed at representative soil specimens. The boreholes were then cased to perform down-hole tests and install a down-hole accelerometer in the geometrical center of EuroProteas' foundation and shape-acceleration-arrays (SAAR, Measurand, Inc.) sensors at the edge of the model. Figure 1 shows the soil stratigraphy and different shear wave velocity (*Vs*) profiles below the foundation slab of the structure. The *Vs* profile computed from the down-hole array is compared with results related to another similar site - S1L site and with Pitilakis et al. (1999). In the uppermost 7m of the soil profile discrepancies exist between the updated down-hole results and the proposed mean *Vs* from former experiments. The latter are considered to be more accurate, and therefore the proposed mean *Vs* profile presented in Figure 1 was used.

Structure Description

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 Figure 2, it consists of a simple steel frame with removable X-bracings founded on a reinforced concrete slab of 3x3x0.40m.



a) b)

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

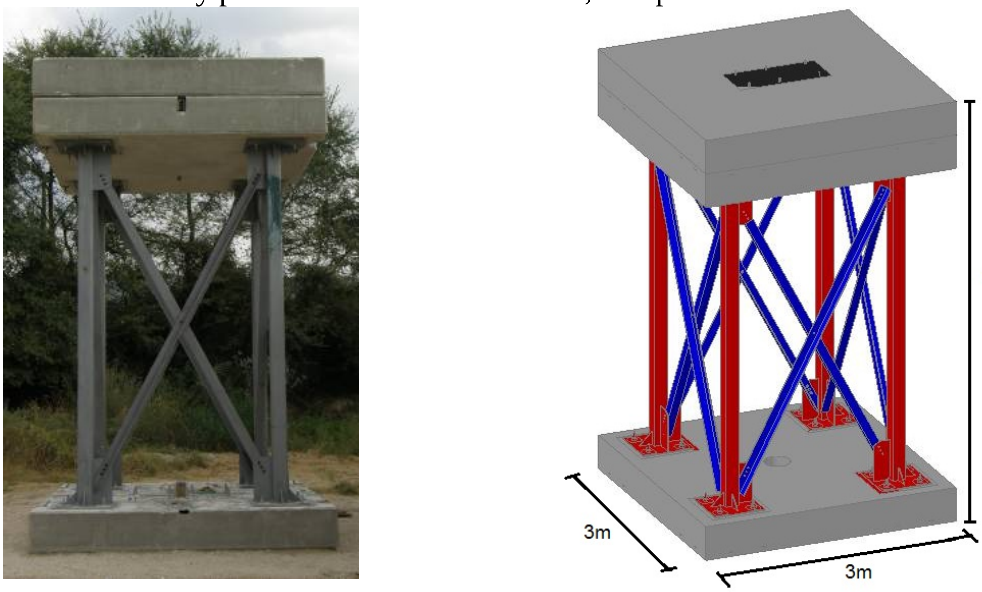


Figure 2: (a) *EuroProteas* structure constructed at *EuroSeistest* site (b) FE model

Two similar RC slabs of 9Mg mass each represent the superstructure mass at a free height equal to 3.8m, while the upper slab is also removable. The structure's outer dimensions are 3x3x5m. With reference to the stiffness configuration, EuroProteas is totally symmetric, ensuring equal bending stiffness in both plane directions. The removable parts of EuroProteas mentioned above (X-bracings, upper RC slab) allow four different configurations of mass and stiffness, covering a wide range of natural fixed-base frequencies, between 3Hz and 11Hz, as determined from analytical and numerical calculation.

Instrumentation

EuroProteas was instrumented by a large number of instruments (more than 80) of various types, placed both on the structure and in the soil. The aim was to obtain a well-instrumented 3D set of recordings to investigate wave propagation and SFSI due to the vibration of the structure. The instrumentation included digital broadband seismometers (GuralpCMG-6TD and CMG-40T), triaxial accelerometers (GuralpCMG-5TD), borehole accelerometers (GuralpCMG-5TB) and shape-accelerations-arrays (SAAR, Measurand Inc). All the sensors were connected with external GPS receivers and configured at a sampling rate of 200Hz.

As seen in Figure 3, seismometers were placed on the soil surface at every 1.5m, up to a distance of 9m from the foundation, in two directions (parallel and perpendicular to the loading direction). The distance of 1.5m between the sensors was specifically chosen to match half of the foundation width, while the distance of the 9m was chosen equal to three times the foundation width, after which structural vibration effects on soil response are negligible according to Gazetas (1983). A down-hole unit was installed in the borehole located in the center of the foundation, with the lower sensor at 3m below ground surface (equal to the foundation width) and the upper sensor coinciding with the top of the foundation slab. In addition, a 12m-long shape-acceleration-array instrument was placed in the 12m borehole next to the surface footing of the structure. In this manner, soil instrumentation monitors a volume of 21m x 21m x 12m (due to symmetry) in the NS, EW and vertical directions respectively, around EuroProteas.

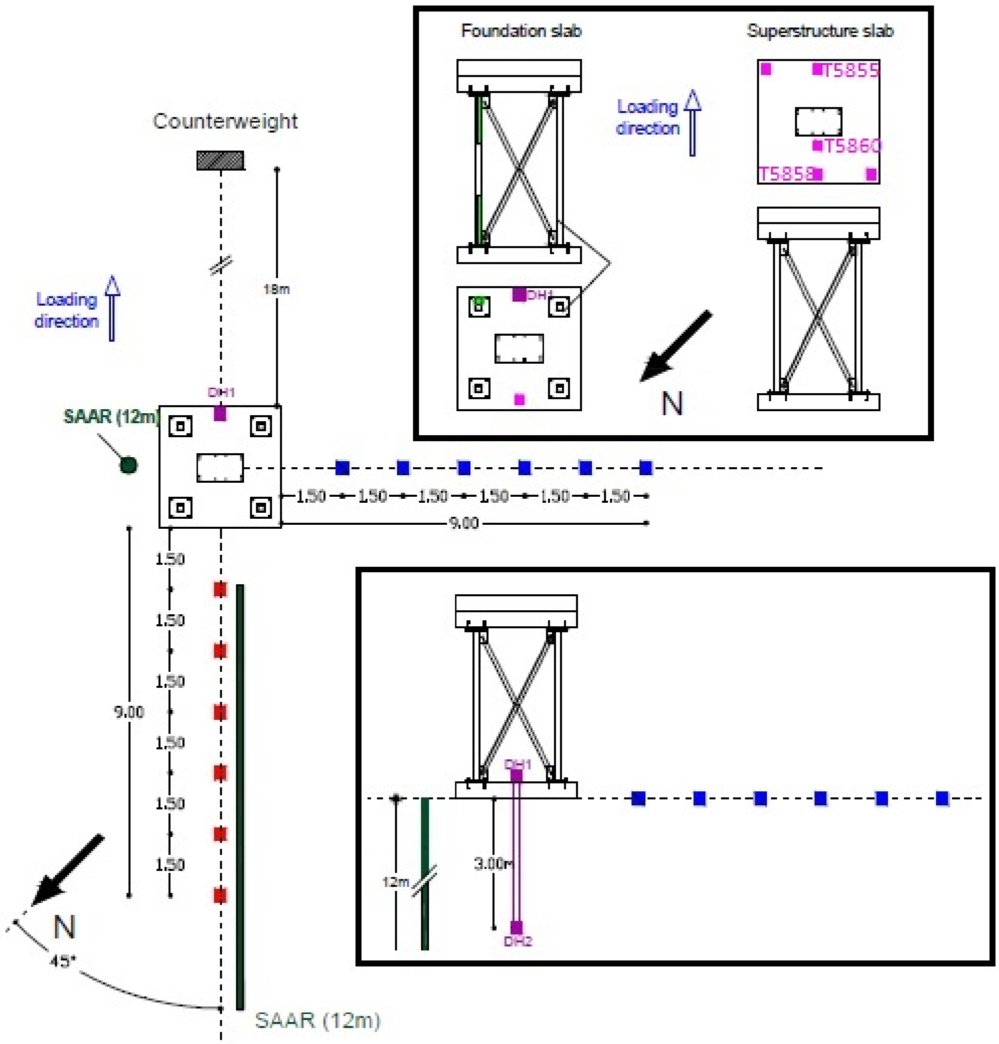


Figure 3: Instrumentation layout of the experimental campaign at *EuroProteas*

The structure was instrumented with 8 accelerometers covering all directions, in both foundation and roof slabs. Five accelerometers were placed on the top of the roof slab; three of them were installed along the axis of the slab parallel to the direction of shaking (in-plane) and other two at opposite corners of the roof slab (Figure 3), in order to capture possible out-of-plane vibration due to mobilization of torsional response modes.

Experimental Campaign

In total, more than 50 intensity levels (and the corresponding frequencies) were exerted in the forced-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. For the forced-vibration tests, the MK-500U eccentric mass vibrator system owned by the Earthquake Planning and Protection Organization EPPO-ITSAK was used as a source of harmonic excitation imposed on the model structure (Salonikios et al. 2005).The presented forced-vibration tests were performed with eccentricity 6.93kg-m at frequency range 1-10 Hz.

Numerical Modelling of the Forced Vibration Tests in EuroProteas

In order to simulate the forced vibration tests in EuroProteas, a 3D finite element model of the soil-foundation-superstructure system has been created using OpenSees (PEER, 2008). The soil, the foundation and the roof RC slabs were modelled using Standard Brick Elements, i.e. 8-node brick elements, which use a trilinear isoparametric formulation. The steel columns and the X-braces were modelled using Elastic Beam Column Elements, i.e. 2-node Hermitian beam elements.
Results from 2D FE analyses showed that significant soil amplification occurs in the upper 30m of the Euroseistest soil profile, which were consequently modelled numerically. In the horizontal dimension of the 3D FE model along the loading direction, mesh length of four times the depth was considered, to minimize boundary effects related to wave scattering. Regarding the out-of-plane dimension of the soil model (orthogonal to the excitation direction), three times the out-of-plane dimension of the foundation slab was considered. Both the structure and the soil were modelled using linear elastic model.

Fixed boundary constraints were imposed at the base nodes and equal DOFs were imposed at the nodes at the vertical boundaries. In this manner, equal displacement patterns were defined for the lateral nodes. For sake of simplicity, between the nodes of the two slabs on the top of the structure, between the foundation and the soil, and between the slabs and the steel columns and X-braces, equal DOFs were used, too. Although, interface characteristics are crucial for the dynamic response of soil and/or structures, this assumption is quite common in engineering practice and can be assumed in some cases, as the investigated ones (Massimino and Maugeri, 2013, Abate et al., 2010, 2014).

Two load conditions were applied: i) gravity load was applied to the whole system, in order to take into account the unit weight of the soil, the concrete and the steel members; ii) a sinusoidal input motion in the “loading direction was applied at the center of the roof to simulate the excitation.

Furthermore, to account for the soil damping in the dynamic analysis, Rayleigh damping factors α and β were calculated with corner frequencies that include the resonant frequency of the flexible soil-foundation-structure system, determined at 4.11Hz by system identification analysis (Pitilakis et al, 2014).

Numerical versus experimental results

Two different cases of vibration forcing frequency are chosen and presented herein, notably f_{input} = 3Hz and f_{input} = 5Hz, considering the five different monitoring points in the soil surface, situated every 1.5m from the structure (Figure 3). The recorded and the numerical response was filtered using a bandpass Butterworth filter with corner frequencies at 0.1Hz and 9Hz. Waves propagating in the soil are not expected to carry significant energy above frequency 9Hz, and can be safely filtered out.

Time and frequency domain response for the forcing frequency f_{input} = 3Hz

Figure 4 shows a time window of the numerical and experimental acceleration time histories and the Fourier spectra for forcing frequency equal to 3Hz (force amplitude = 2.46kN) at the five soil surface points monitored by seismometers, placed on every 1.5m, up to a distance of 9m from the foundation along the loading direction (Figure 3). The numerical results are in a very good agreement with the experimental recordings for this forcing frequency case at low frequency. The soil damping ratio is 3%, adjusted for low strain levels. Parasitic resonant frequencies exist in both numerical and experimental response, probably due to the sinusoidal excitation. For low excitation amplitude, linear elastic behavior of the soil describes the response near, and further away from the structure. Small discrepancy in the amplitude is noted at distance one time the foundation width.

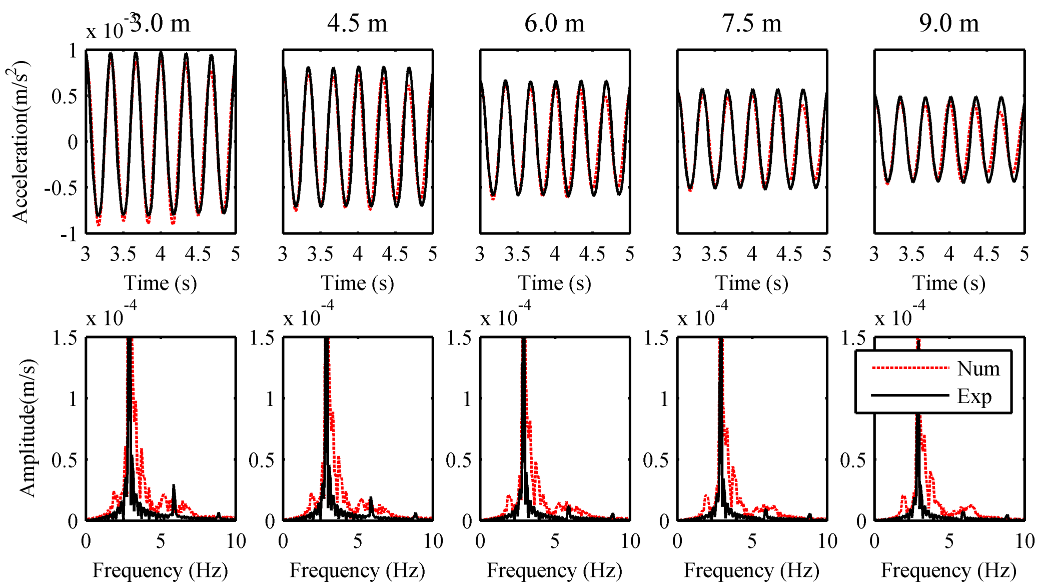


Figure 4. Acceleration time-histories and Fourier spectra for excitation frequency at 3Hz: comparison between numerical and experimental results at the five points on soil surface

Time and frequency domain response for the forcing frequency f_{input} = 5Hz

Figure 5 shows the numerical and experimental acceleration time histories and the Fourier spectra for forcing frequency equal to 5Hz (force amplitude = 6.84kN) at the five monitoring points. In this case, due to the larger excitation force, the soil damping is assumed equal to 8%. We observe that the linear elastic model for the soil is able to reproduce the recorded acceleration time histories, even though larger discrepancies exist than for the case of forcing frequency 3Hz. The decreasing amplitude with increasing distance from the foundation is reproduced satisfactorily by the numerical model, with minor discrepancies at distance 9m.

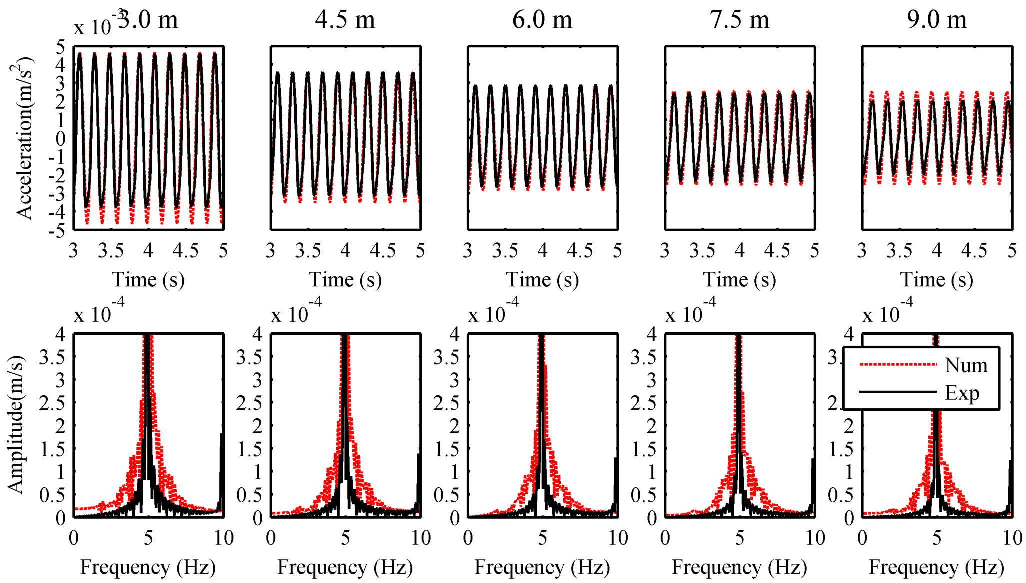


Figure 5.Acceleration time-histories and Fourier spectra for excitation frequency at 5Hz: comparison between numerical and experimental results at the five points on soil surface

General view of the response for all the forcing frequencies cases

Figure 6 shows the peak acceleration amplitude decay with distance from the foundation for excitation frequencies at 3Hz and 5Hz. It is seen that the numerical model reproduces adequately the emanating wave field away from the oscillating structure almost up to 9m. A minor deviation is observed at the distance of 9m when the operating frequency of the vibrator is configured at 5Hz. In this case, the recorded acceleration amplitude is lower, indicating stronger attenuation due to higher soil damping.

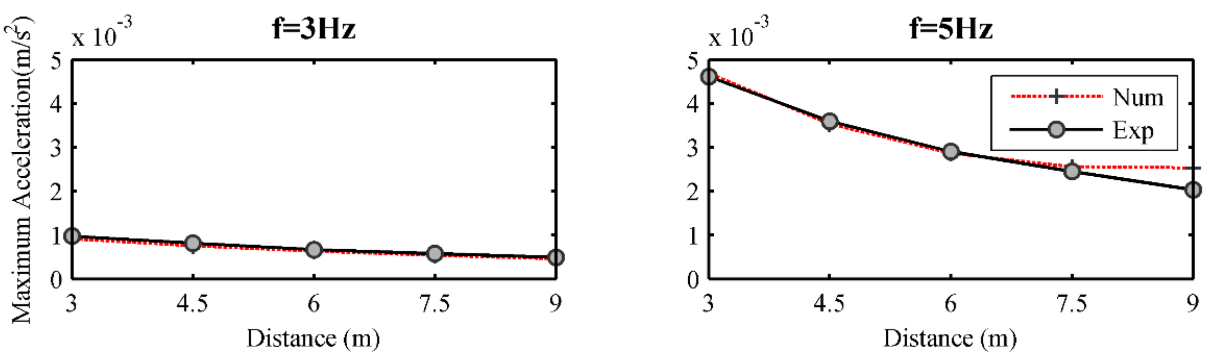


Figure 6. Profiles of maximum accelerations against excitation frequency for two monitoring points at 3m and 9m far from the foundation

Conclusions

We simulated the experimental response of the prototype structure of EuroProteas under forced-vibration by means of 3D finite element modeling. The comparison between the experimental and numerical responses is adequate for forcing frequencies up to 5Hz and excitation forces up to 6.8kN. For larger excitation force, the soil appear to behave in a nonlinear way. In addition, we found that the 2D FE model was not efficient for capturing this complex 3D phenomenon.

EuroProteas is ideal for studying SFSI and wave propagation phenomena due to structural oscillation, in the soil and in the structure. It is a simple and reconfigurable system, suitable for forced- and free-vibration experiments, as well as for ambient noise measurements. The Research Unit of Soil Dynamics and Geotechnical Earthquake Engineering of AUTH has the necessary qualification and know-how to perform state-of-the-art full-scale SFSI experiments. EuroProteas can be integrated into international experimental facility networks, given its simple setup, ease of instrumentation and monitoring capability, whereas its soil-structure configuration is effortlessly reproduced in small-scale laboratory facilities.

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