EFFETTI DELLE SCHIUME POLIURETANICHE SULLA PROPAGAZIONE DELLE ONDE

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Sommario

La storia del nostro Paese è stata da sempre funestata da molteplici eventi sismici di forte intensità, dalle conseguenze disastrose su edifici e popolazione. Le principali tecniche esistenti per la riduzione del rischio sismico riguardano interventi sulle sovrastrutture; nella presente nota vengono proposte soluzioni innovative basate su interventi diretti sul terreno, che rappresenta il primo mezzo attraverso cui le onde meccaniche, generate a chilometri di profondità, si propagano. Vengono presi in esame i materiali poliuretanici, materiali di bassa densità e elevate capacità dissipative, ampiamente diffusi in vari settori e largamente caratterizzati da prove di laboratorio di natura geotecnica. Gli effetti legati al loro inserimento sotto forma di lastre o mediante iniezioni nel terreno nei confronti della propagazione delle onde verranno analizzati estendendo a campioni misti sabbia-poliuretano un sistema sperimentale-numerico già calibrato su campioni di pura sabbia, che prevede l'adattamento a scopi geotecnici di prove modali sperimentali eseguite con martelli strumentati.

Keywords: Wave Propagation; Numerical Model; Impact hammer test

1. INTRODUCTION

The great damages caused by recent seismic events on existing structures have determined an increasing interest on the study of solutions finalised to the seismic risk mitigation. Common solutions are mainly structural interventions, generally invasive. However, improving the soil condition of sites in order to mitigate earthquake damages can be one of the methods of enhancing site condition and its effects on seismic site response. Considering that earthquakes generate from soil, interfering wave propagation in such a way could be a clever solution.
Trenches and barriers represent the most common isolation systems employed to obstacle vibrations of different nature (Beskos 1986; Woods and Richart 1967). It deals with discontinuities placed between the vibration source and the system to be protected. According to their stiffness, barriers can be hard or soft. An ever-increasing interest on synthetic materials application on wide fields is spreading and first attempts of application in soil are in literature (Faryar et al. 2015, Tsirinaris et al. 2017)
Wave propagation mechanics well explains how a vibration isolation system works at the interface soil – screen. When an incident wave field encounters a discontinuity surface, a partition of the transported energy takes place, which mainly depends on the geometric characteristics of the barrier, as well as its physical properties.
A large experimental campaign finalised to the realisation of solid barriers by means of synthetic materials injected in the soil has been already started in University of Parma. Thanks to the collaboration with B.A.S.F. Italia, it has been possible to introduce the polyurethane study for seismic mitigation risk purposes. Polyurethane specimens realised from industrially-produced sheets or ad-hoc in laboratory prepared mixing isocyanate and polyol have been preliminary subjected to geotechnical common laboratory tests (Montrasio and Gatto 2016, Montrasio and Gatto 2017), in order to see how this material behaves in geotechnical conditions.
The effect of the synthetic materials on the wave propagation wants to be studied by means of a little scale experimental system which is now introduced. It consists of a small Plexiglas box filled with sandy soil and subjected to impact hammer tests, which allow the introduction of controlled waves inside the system. Every unknowns related to the soil have been minimized by choosing granular geomaterials in dry conditions (avoiding any kind of coupled mechanical – hydraulic behaviour) and by defining any characteristic by a wide laboratory tests campaign on the sand, in order to identify uniquely the soil properties on the experimental system.
It is important to underline that the present paper does not show any results related to the effects of the polyurethane

on the wave propagation, but the process of realisation of the experimental system, numerically validated by finite element model, defining in the end a well consolidated experimental – numerical system. Next phase will regard the application of the system to put in evidence how the polyurethane foams, in different types and configurations, obstacle and modify the expected seismic motion generated by a controlled source.

2. GEOTECHNICAL LAB CHARACTERISATION OF POLIURETHANE FOAM

For seismic risk reduction purposes, solutions finalized to the creation of discontinuities in the soil have been thought. Due to their wide application in many fields, studies aimed at the polyurethane foams insertion in soil has been started in University of Parma. Generally, polyurethane foams are obtained from the synthesis of two basic components, polyol (A-component) and isocyanate (B-component), realizing therefore a bi-component material (Figure 1)

Figure 1. Polyurethane foam realisation

As a starting point, the first type of material considered is a rigid polyurethane foam (ELASTOPOR), even because of its possible future application by injection in the soil. Its properties have been compared with the ones of an extruded polystyrene foam (STYRODUR), since the latter has been already applicated for vibration attenuation purposes but it is however incompatible with the injection technologies and can be employed only in sheet form. For both materials, two densities have been taken into account, because a linear dependence between void percentage and seismic risk reduction power has been intuitively thought.
In order to analyse the static behavior of these materials in geotechnical conditions, oedometric and compression triaxial tests have been performed on specimens obtained from sheets industrially produced and specimens laboratory-produced, directly from the mixture ready to be injected in the soil. Figure 2 shows the oedometric tests results. Although none of the specimens had been subjected to a previous stress history, all the results show an "apparent pressure of pre-consolidation" that increases with the material density; this pressure is approximately 60 kPa for lower density materials, i.e. XPS B and PUR 35 and about 100 kPa for XPS A and PUR 40.

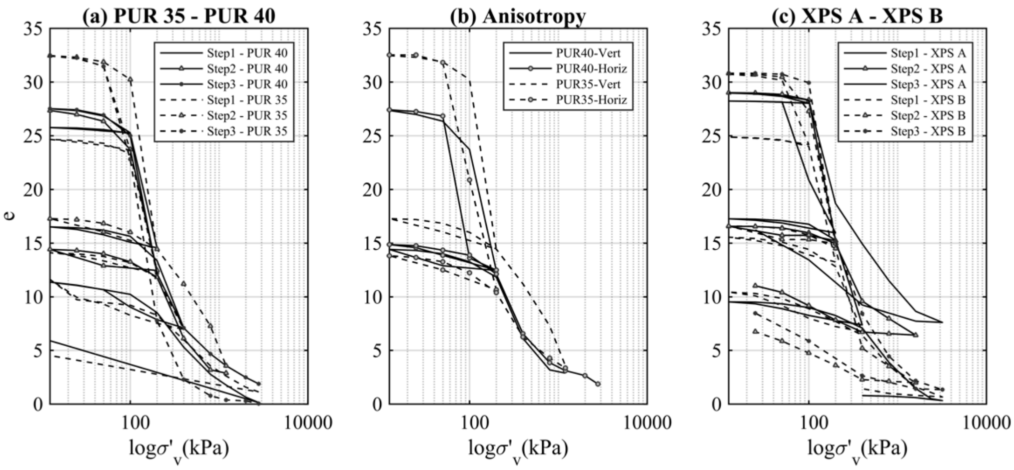

Figure 2. Oedometric test results on specimens obtained from sheets of PUR and XPS.

The main evidence from triaxial tests results (Figure 3) is that in collapse condition the polyurethane material shows a rigid behaviour with the confining pressure till the yielding confining stress, which depends on the density, as shown from oedometric tests results, after which it collapses.

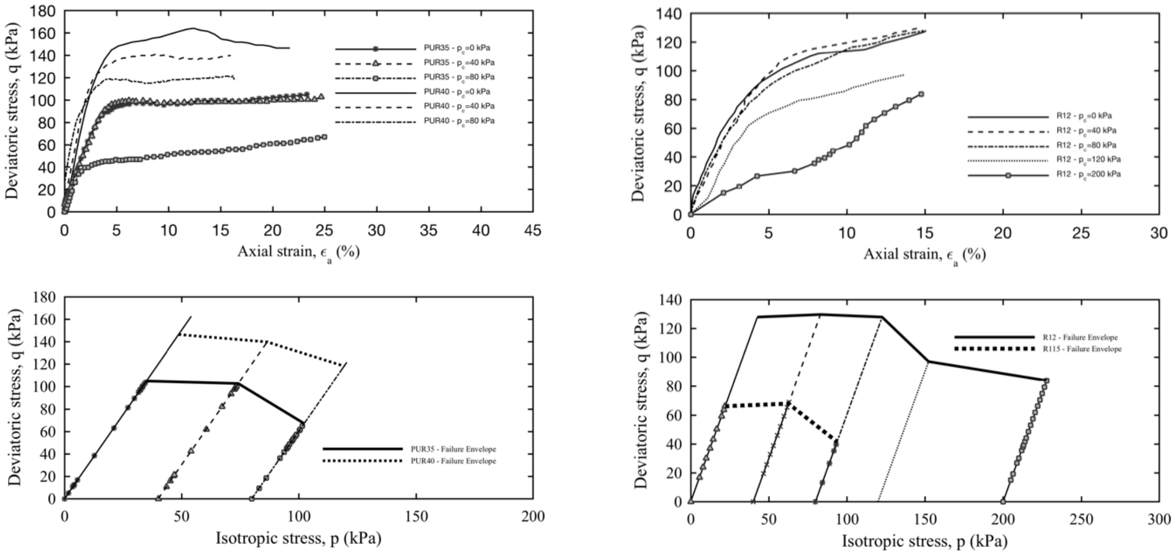

Figure 3. Triaxial tests results on polyurethane foams

In Figure 3 it is also shown a good comparison between TX tests on PUR specimens obtained from industrially produced sheets (PUR35-40) and specimens laboratory-produced. In fact, even if the laboratory produced foam is aimed to be injected, a preliminary study of its properties in free expansion condition have been therefore conducted in order to support the capability of the realisation.

3. EXPERIMENTAL IMPACT HAMMER TESTS

The aim of this section is to show the process of realisation of a small experimental apparatus, capable of catching the wave propagation phenomenon through a system of only soil first and soil and synthetic material then.
A system dynamic response is commonly evaluated by applying a well-known measured force and recording the response in some points by means of accelerometers, suitably chosen. In most cases, the force is applied by an impulse hammer or a shaker (Ramsey 1975). Hammer impacts produce a broad-banded excitation signal ideal for modal testing with a minimal amount of equipment and set-up. This is the reason why this kind of forcing source has been selected.
As a starting point, unidirectional vertical wave propagation phenomenon wanted to be studied. For this purpose, a single input – single output (SISO) system has been thought to be sufficient.
Dry granular geomaterials have been employed in order to minimize the unknowns of the problem, related to the coupled mechanical and hydraulic behaviour of the soil.
Impact hammer tests have been performed on a experimental system consisting of a Plexiglas box of cm 30x30x40 (Figure 7) realised by assembling 0.8 cm thick plates. The box has been filled with Po sand.

3.1 Geotechnical characterization of Po Sand

The geotechnical characteristics of the Po Sand have been determined in collaboration with the Soil Dynamics Laboratory of Aristotle University of Thessaloniki . In particular, ASTM D4253 and ASTM D4254 procedures have been followed in order to evaluate respectively the e_{max}=0.777 and e_{min}=0.465 values, necessary to a proper evaluation the sand relative density in the box.

Figure 4. Geotechnical characterization of Po Sand

Resonant column tests in the modified Drnevich apparatus (Drnevich, 1967) have then been performed on sand specimens of dimensions 70x140 mm (Figure 5), in two relative density configuration (D_R=55 % and D_R=75%). The RC measurements have been useful in order to evaluate the G_0 and D_0 values inside the box for the numerical interpretation of the experimental results. Due to its small dimensions, the confining pressure inside the box is very low; the small strain properties of the sand have been therefore evaluated from (1) (Hardin and Black 1968)

$$G_0 = A \cdot F(e) \cdot \sqrt{\sigma_0'} \quad (1)$$

where

e is the void ratio, strictly related to D_R through e_{max} and e_{min} values

$$F(e) = \frac{(2.97-e)^2}{1+e} \quad (2)$$

σ_0' is the confining pressure, related to the vertical depth

A value obtained from a comparison with the experimental RC results (The mean and final value which allow a correct interpretation of the experimental results is 3028).

3.2 Experimental system

In the purpose to analyse a vertical wave propagation inside the box of only sand, single Input – single output (SISO) tests have been performed. Figure 7 shows the elements of the instrumental system.

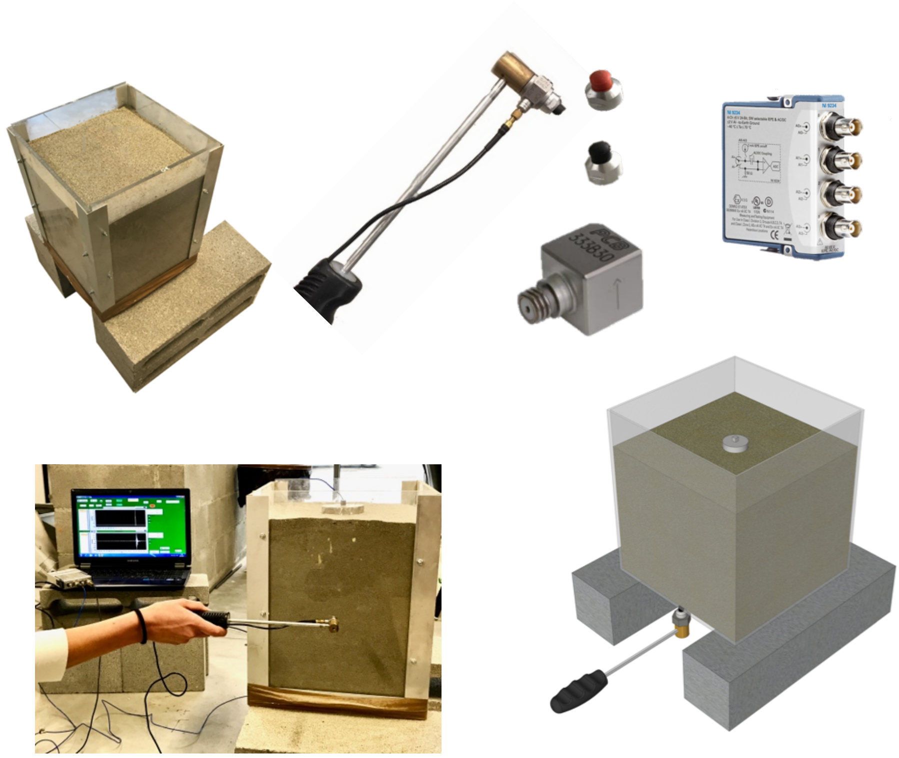

Figure 7. Experimental system; Hammer PCB 086C01, Accelerometer PCB 333B30, Acquisition module NI923

Controlled input have been generated by means of a PCB 086C01 impact hammer, whose tip is constituted of a quartz sensor that converts the applied impulse into an electrical signal, recorded by an acquisition module. In order to excite different frequencies, three tips can be mounted on the hammer. The output response have been recorded by PCB 333B30 uniaxial accelerometer, with sampling frequency in the measure range 0.5-3000 Hz. For the experimental tests, the sampling frequency has been set to 2048, assuming it compatible with the frequency range to be investigated. Both the impact hammer and the accelerometer have been connected to the NI9234

acquisition module which allows a simultaneous recording of the force input and the acceleration output. LabView software has been used to visualise live results and save them.
Finally, a Matlab file has been written to process and analyse such recorded data.
Impact hammer test output is represented by a collection of accelerations and forces in the time domain. As a first step, the entire recording has been divided into single hits – free vibration acceleration response, rejecting ,first, double hits which commonly alter the system response; then, a trigger interval has been selected, going 0.10 and 0.35 seconds, respectively backward and forward the considered peak. This interval has been assumed congruently to catch the whole free vibration response of the damped system. Such a nonlinear system response could be hard affected by the input magnitude. Although it hasn't been possible to obtain a reproducible input, its amplitude is well-known thanks to the hammer force cell. In such a way, the experimental data have been collected in groups, whose force peak has a certain tolerance from an established peak value.

3.4 Experimental tests

The system response has been investigated in different directions by realising an experimental campaign consisting of two main test classes:

- P waves generated in vertical direction;
- P waves generated in horizontal direction.

In the first case, input is applied at the base of the experimental box, trying to keep a vertical input direction; in the second case, hits at half box height have been generated. In both cases, the uniaxial accelerometer has been placed on a rigid support at the sandy stratum top, since it is difficult to maintain the verticality simply placing it on the sand. In the following, material accelerometer support on the experimental response has been focused, in order to analyse its influence on the results.

3.4.1 Vertical P-waves

Figure 8 shows the experimental results, already selected for double hits absence (see force time domain response). As obvious, the force time duration is the same independently on its magnitude, since it exclusively depends on the hammer – system materials on contact (Black tip and Plexiglas, in the present case). The input frequency content is determinable from the input duration by (3)

$$f_{input} = \frac{1}{2\Delta t} \tag{3}$$

As regards the acceleration response, its shape is a typical free vibration decay of a damped SDOF system. The damping ratio is inferable from the exponential decay and it is about 3 per-cent, a typical literature value for small strain dynamic behavior of sandy soils (Seed et al. 1969).
Fast Fourier Transforms on top acceleration response show a completely independence of the frequency response on the input magnitude, since the system vibrational frequencies are quite similar in all cases. In particular, the fundamental frequency of the system in vertical direction is equal to 112 Hz. This is important to calibrate the numerical model in the following.

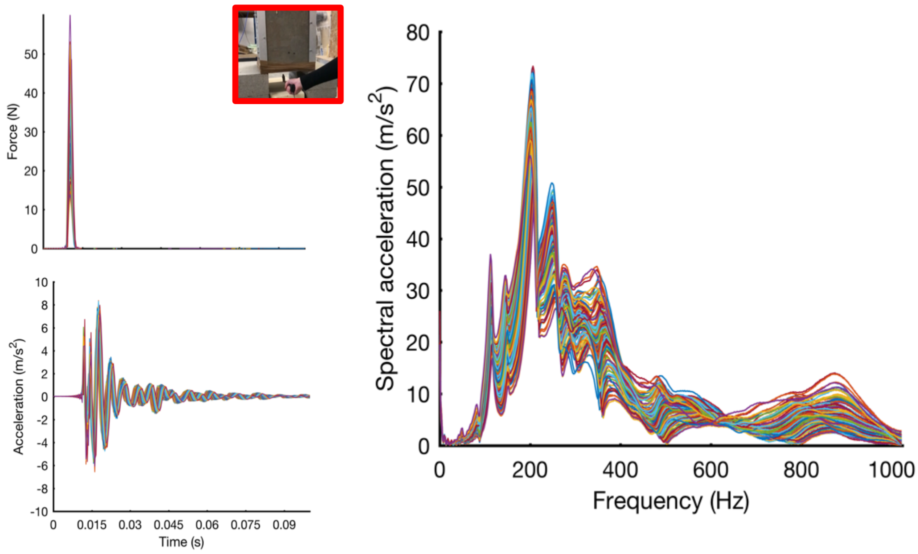

Figure 8. Vertical P-wave experimental propagation tests

3.4.2 Horizontal P-waves

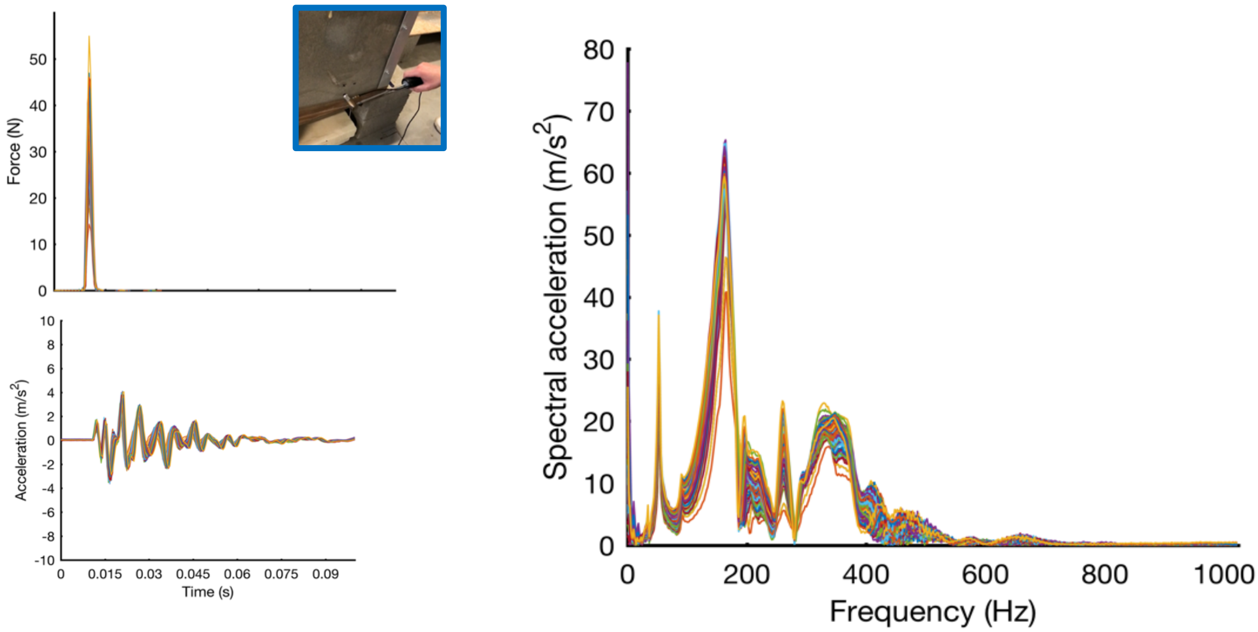

Figure 9. Horizontal P-wave experimental propagation tests

Figure 9 shows a general smaller system response in horizontal direction, due to a different stiffness of the mass involved in horizontal direction. The fundamental frequency in this direction is equal to 50 Hz; it will be compared to the first numerical frequency which excites most of the mass in this direction.

4. FINITE ELEMENT NUMERICAL MODELING

Impact hammer tests have been numerically modeled by means of a FE software (K.J. Bathe 1996). A 3D numerical model ,consisting of 27-nodes 3D solid elements for soil modelling and 3-nodes Plate elements for Plexiglas plate modelling, has been built (Figure 10).

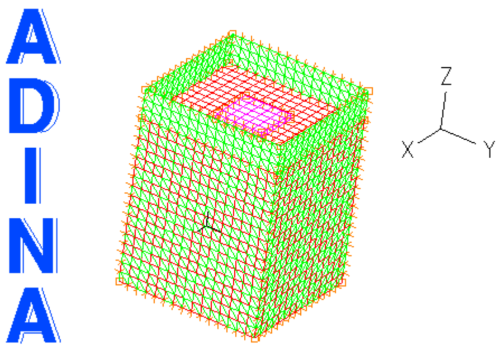

Figure 10. Numerical model

Since small strains have been assumed to be reasonably involved in the impact hammer process, linear visco-elastic constitutive model has been employed for the whole system.
Preliminary experimental tests (Montrasio and Gatto 2017) have already shown that the lateral response of such a system has the same top response magnitude order. That's why nodal coincidence between soil and plate nodes has been taken into account. Both vertical and horizontal impact hammer tests have been numerically simulated. Each analysis consists of two phases: first, the system self-weight, not negligible for the sand, has been considered in static analyses. Implicit dynamic analyses have been then performed by applying the experimental force recording to the numerical system.

Numerical time step has been chosen equal to the experimental one (0.005 s), since it is suitable to the system natural frequencies to be caught.
System viscosity has been introduced through Rayleigh's damping formulation, i.e. the damping matrix is given by a linear combination of the mass and the stiffness matrix by means of α and β coefficients evaluated as:

$$\alpha = 2 \cdot \frac{D}{\omega_1+\omega_2} \cdot \omega_1 \omega_2 \quad (4)$$

$$\beta = 2 \cdot \frac{D}{\omega_1+\omega_2} \quad (5)$$

being
D damping ratio evaluated from the theoretical interpretation of the experimental results
ω_1 and ω_2 determined from numerical modal analyses, shown in the following.

4.1 Numerical model validation

The numerical model has been preliminary validated by performing numerical modal analyses and ensuring a good match between the numerical and the experimental natural frequencies. Figure 11 shows the system modal shapes; in Table 2 corresponding values of natural frequencies are reported. Generally, the numerical model should provide a good interpretation of the experimental tests in the frequency domain.

Table 2 Natural frequencies of the numerical system

Mode	f (Hz)	Direction
1	86.15	Trans. y
2	86.17	Trans. x
3	135.4	Trans.z
4	159.6	Tors. xy

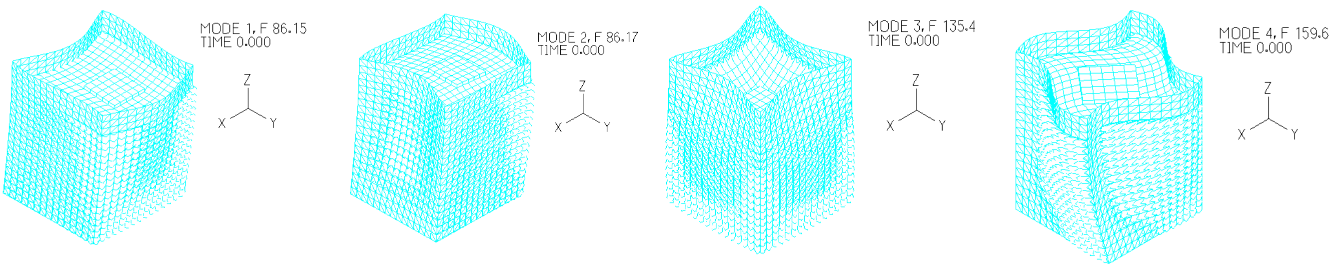

Figure 11. Numerical system modal shapes

Table 3 resumes the final properties employed in the model. α and β are therefore computed considering the first two natural frequencies which excite the system in x and z direction.

Table 3. Numerical model properties

Mat.	E (MPa)	γ (kN/m^3)	D	α	β
Plex.	3200	11.7	3	31.62	2.7 e-4
Sand	23	17	3	31.62	2.7 e-4
Steel	210000	72.6	2	31.62	2.7 e-4

4.2 *Numerical vs Experimental top results*

After introducing the system self-weight by performing a static analysis, implicit dynamic analyses have been performed, applying in both base and lateral specified nodes the time history of the recorded force. Figure 12 and Figure 13 show the final experimental – numerical comparison of one vertical and one horizontal wave propagation test. A great agreement is finally reached in vertical direction, for both time and frequency domain, while a bit worse comparison is shown in horizontal direction, generally good results.

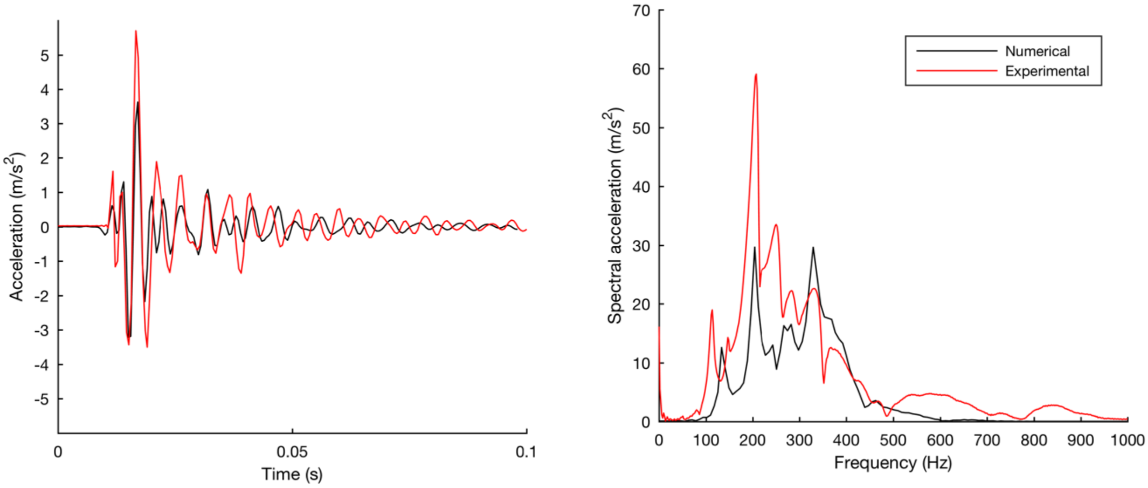

Figure 12. Experimental vs Numerical results of vertical wave propagation tests

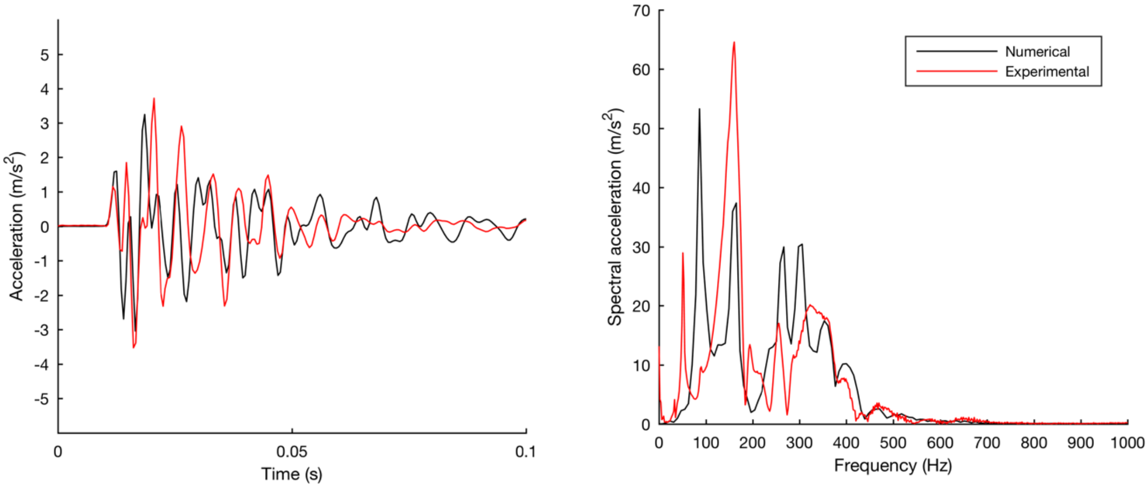

Figure 13. Experimental vs Numerical results of horizontal wave propagation tests

5. CONCLUSIONS

Impact hammer tests represent a fast and cheap instrument of a system frequency response and free vibration investigation.

A large experimental campaign of impact hammer tests have been conducted on an experimental system in University of Parma. The scope is to evaluate how much the introduction of synthetic materials in different forms changes the soil response both in the frequency and in the time domain. Vertical and horizontal wave propagation directions have been investigated. In order to validate the experimental results, a numerical model for their interpretation was required to be realised.

A 3D FE model has been created; both vertical and horizontal direction experimental results have been numerically modeled.

The numerical model has given good interpretation of the experimental results, both in the frequency and in the time domain, suggesting that the system is numerically well-calibrated and can be extended to other experimental cases.

Further studies will regard the experimental investigation and related numerical interpretation on the presented experimental system, modified by introducing innovative materials in the soil and evaluating seismic amelioration and risk reduction at eventual structure.

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