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The dynamic behaviour of polyurethane foams in geotechnical conditions

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ABSTRACT: During the last decades, the scientific attention to the seismic risk reduction has been increasing. Principal solutions are still generally based on interventions on structures. However, geotechnical researchers have recently started experimental campaigns regarding the study of possible applications of synthetic materials directly to the soil, as the latter is the first medium through which seismic waves propagate.

Polyurethane (PU) foams already have a wide application range in many sectors; in civil engineering their use is mostly related to thermic insulation purposes. For transient phenomena, these synthetic materials have already been employed for the mitigation of traffic-induced vibrations, while poor attention has been paid to the study of their effect with respect to seismic wave propagation.

University of Parma has already investigated the mechanical behavior of PU foams in specimens obtained from panels or by mixing the two main components (Polyol and Isocyanate) in liquid form directly in laboratory realizing ad-hoc specimens; both oedometric and failure conditions have been studied.

The dynamic properties of PU foams have been analyzed by performing Resonant Column Tests in the Laboratory of Soil Mechanics, Foundations and Geotechnical Earthquake Engineering of Aristotle University of Thessaloniki, on specimens of pure synthetic materials realised in the laboratory. The aim of the paper is to present and discuss the experimental results obtained and to focus on the future research development, starting from the present results

1 INTRODUCTION

In the international seismic history, many catastrophic events, often responsible for large damage on structures and consequently, on people, have occurred. In the last century, an increasing attention of scientists to the study of the seismic risk has lead to the important conclusion that in some cases site effects and amplification due to soft soil layers occur, causing different effects in site very close to each other (Romo and Seed, 1986; Capotorti et al., 1997). Soil is indeed the first medium through which seismic waves generated after an earthquake rupture propagate. Several examples from literature show attempts of vibration reduction based on intervention on soil, by means of materials characterized by low impedance (Woods and Richart, 1967; Dolling, 1970; Sridharan et al., 1981; Massarsch, 1986; Beskos et al., 1986; Chouw and Schmid, 1992; Tsang et al., 2007; Kirtas et al., 2009; Kellezi, 2011; Goktepe et al., 2014). Impedance is defined as:

$$I = \rho \cdot \upsilon^2 \tag{1}$$

being ρ the material density and υ the wave velocity.

On the basis of this concept, the Geotechnical Laboratory of University of Parma has started an experimental campaign finalized to the study of the effect of synthetic material inclusions in sandy soils by means of an experimental system aiming at the analysis of the propagation of body waves (Gatto and Montrasio 2018). The starting point materials are by **polyurethanes**.

The term polyurethane is used to define plastics (*polymers*) produced by a polyaddition reaction of polyfunctional isocyanates (providing $N{=}C{=}O$ group) with compounds containing at least two hydroxyl groups (OH), i.e. polyols, giving gives rise to *urethane groups* (NHCOO). For the production of a polyurethane foam, **blowing agents** are required; they are responsible for the cellular structure of the resulting product with gas included in the foam composition. Due to the presence of more or fewer gas bubbles in the structure, polyurethane may have different density values, ranging from 30 to more than $200 kg/m^3$; compared with the typical value of soil density, they are low density materials. Nevertheless, they show rigid behavior in failure conditions and values of stiffness comparable to the ones of the soil; in this sense, isocyanates play a fundamental role, affecting the elastic properties of the foam (Montrasio and Gatto, 2016; Montrasio et al., 2017). Polyurethanes are commonly employed in many field applications; in civil engineering, they already find application in the reduction of vibration induced by high-speed trains (in slab form) or for settlement reduction (by injection in soil).

The paper focuses on the definition of the dynamic properties of pure polyurethane specimens, ad-hoc realized, as well as the study of the influence of polyurethane inclusions, in slice form, on the dynamic response of sandy specimens. The study has been conducted at the Soil Dynamics and Geotechnical Earthquake Engineering Laboratory of Aristotle University of Thessaloniki by performing Resonant Column (RC) tests with the use of a Drnevich‘s type apparatus in fixed - free end conditions.

Tests consist of two main phases: consolidation and resonance phase. After the first phase, **consolidation time** needs to be taken into account, depending on the material type, the stiffness of the specimen (density and fine percentage) and the amplitude of the consolidation stress itself. Being the first time that RC tests are performed on polyurethane specimens, the consolidation time influence on the resulting properties is also shown.

The paper is organized as follows:

- **Pure polyurethane material investigation**,
  - Study of the effects of consolidation time on low-strain properties;
  - Definition of the $G — \gamma$ and $D — \gamma$ curves for different confining pressures.
- **Sand - polyurethane composite specimens**: study of the influence of different percentages of polyurethane inclusions in sandy specimens.

2 RESONANT COLUMN TESTS ON PURE POLYURETHANE SPECIMENS

2.1 *Specimen preparation*

In this section the results of RC tests performed in polyurethane (*PUR*) specimens are shown. Specimens have been ad-hoc realized by mixing the two raw components, i.e. polyol and isocyanate. After mixing, the foam is poured inside a specific mould, so that the realized specimens have dimensions suitable for the Resonant Column test (in this work, 70x140 mm^2 specimens have been realized). All the operations of specimen realization are shown in Figure 1. In order to study the influence of the material density on the dynamic properties of the foam, two types of polyurethane specimens *PUR 1* and *PUR 2* are considered. The polyol quantity is kept constant, while the isocyanate mass is varied; this is due to the fact that isocyanate is considered to be the main factor responsible for the mechanical properties of the foam, and its influence on the dynamic properties needs to be studied. Quantities, component ratio and density of the specimens of pure polyurethane specimens are reported in Table 1.

2.2 *Effect of consolidation time on the results*

After being realized, specimens have been installed in Drnevich‘s apparatus and tests have been performed. Five confining pressures have been investigated: 10, 50,100, 200 and 300 kPa. The consolidation time is fundamental before performing the second phase of the test; it depends on

Table 1. Mixing quantities

	PUR1	PUR 2
Polyol (g)	45	45
Isocyanate (g)	80	100
Mixing ratio	1:1.78	1:2.22
Density (kg/m^3)	90	120

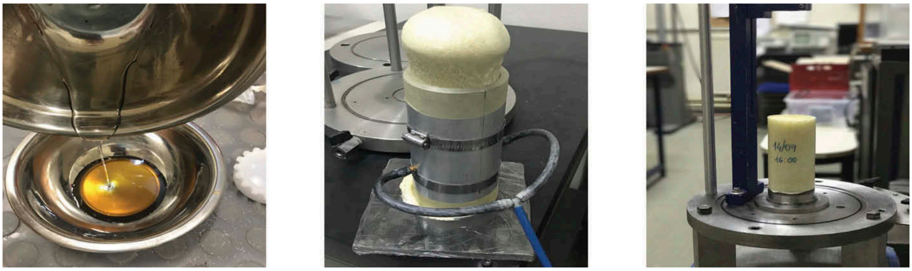

Figure 1. PUR specimen realization

the material type, as well as the consolidation pressure value itself. However, since no indication is present in the scientific literature regarding the consolidation time required for RC test performance on polyurethane specimens, as a first step, a study of the influence of the consolidation time on the dynamic properties is shown. Times from 30 to about 4000 minutes are considered.

Figure 2 shows how the low-strain shear modulus G_0 and damping ratio D_0 vary with time. *PUR 1* specimen shows a quite standard behavior for confining pressures from 100 to 300 kPa; the shear modulus G_0 increases slightly with time, while the damping ratio is almost constant. The dependence of the consolidation time on confining pressure is confirmed by the behavior at *10 kPa*; this value being very low, in order be stable, specimens require longer times. For high confining pressures of 200 kPa and 300 kPa, *PUR 2* specimens need a longer consolidation time before one can assess the final elastic properties; the low-strain shear modulus G_0, in fact, seems to decrease by increasing the confining pressure from 10 to 200 kPa, in the time interval from 30 to 90 minutes. For a long consolidation time (almost 4320 minutes), it is shown that the behavior for a confining pressure of 300 kPa returns to be standard. Since the final values of G_0 and D_0 at cell pressure of 200 kPa have not been recorded for consolidation time longer than 90 minutes (i.e. when the behavior is supposed to be stable) the relative $G — \gamma$ and $D — \gamma$ curves are not shown in what follows.

2.2 *Effect of the confining pressure on the shear modulus and the damping ratio at low-strain level*

In order to study the dynamic behavior with the confining pressure, test results with longer consolidation time, shown in the previous section, have been selected and the general results plotted in terms of $G — \gamma$ and $D — \gamma$ (Figure 3),as well as in terms of $G_0 — p_c$ and $D_0 — p_c$ curves (Figure 4) From Figure 4 it can be observed that for both PUR 1 and PUR 2 specimens, G_0 and D_0 are quite independent from the confining pressures *pc*; this is more evident in the confining pressure ranging from 50 to 300 kPa. A confining pressure of 10 kPa results, in fact, in being too low to guarantee the stability of specimens investigated.

Figure 4 also shows a big anomaly: although PUR2 is denser and it should present a stiffer behavior in comparison with PUR1, this is not shown experimentally. The reasons of this strange behavior can be due to a not successful mixing of raw materials, which should give rise to homogeneous color in the resulting foam (brown parts were evident in the section area of PUR2 specimen). A bad mixture of isocyanate and polyol is responsible for a lack of complete realization of the polyurethane structure, without which a complete definition of the mechanical properties of the resulting foam cannot be achieved.

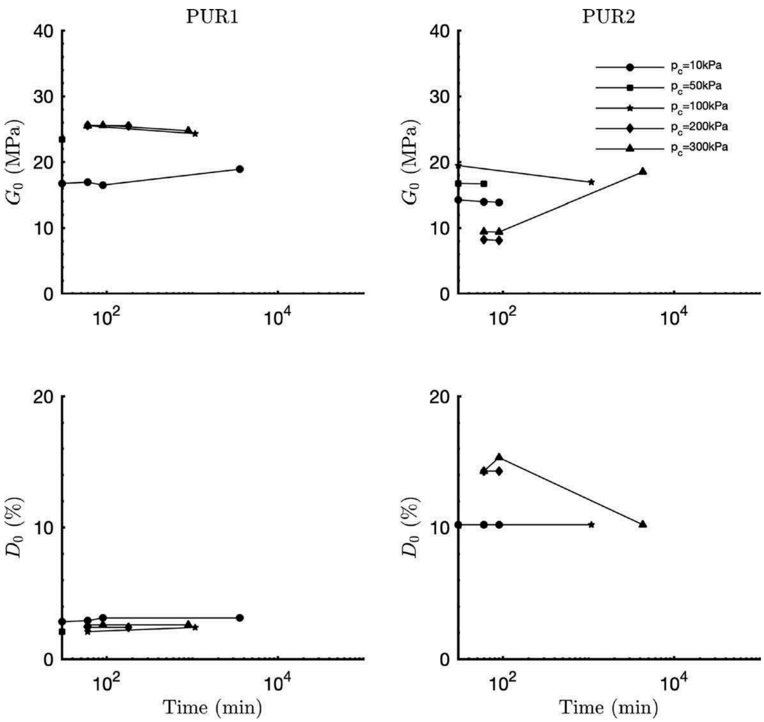

Figure 2. Effect of consolidation time on G_0 and D_0 for PUR specimens

3 RESONANT COLUMN TESTS ON COMPOSITE SAND - POLYURETHANE SPECIMENS

Resonant column tests have been therefore extended to the study of the behavior of composite specimens, consisting in two sandy layers interspersed with one of polyurethane, placed at half height (Figure 5). PUR1 and PUR2 specimens, analyzed in the previous section, are cut in slices of thickness 15,25 and 45 mm (representing respectively 10, 20 and 30 % of the total specimen volume).

Sandy layers have been realized with a relative density of 69%; for sake of simplicity, in the plots a label of just "S", followed by "PUR" and its thickness. In a preliminary phase of the experimental campaign, pure sand specimens at 69-per-cent relative density have been tested in RC tests; results are shown in the final plot, in order to understand the modifications provided by the polyurethane slices. It is important to notice that the elaboration of raw results from the RC test has been conducted considering an average value of the material density, weighted on the height of each layer.

Even in this case, the consolidation time effects on G_0 and D_0 trend have been studied; as in the previous section, the results of tests performed with longer consolidation time have been considered. The confining pressures considered are the same as in the previous cases; however, a confining pressure of 10 kPa continues to be too low and not enough to give stability to the system.

All the results are shown in terms of $G_0 — p_c$ and $D_0 — p_c$ trend in Figure 6. In each case, how the percentage of polyurethane affects the behavior of the composite specimens is studied, compared to the results obtained for the specimens of pure polyurethane and sand, separately investigated.

In terms of shear modulus, the *PUR1-15mm* specimen shows values and a trend with the confining pressures similar to the pure sand case, since in this case the polyurethane percentage is really low (10% in volume). When the percentage increases, from 20 to 30 % with respect to the specimen volume, the behavior seems to be closer to the one of the pure polyurethane.

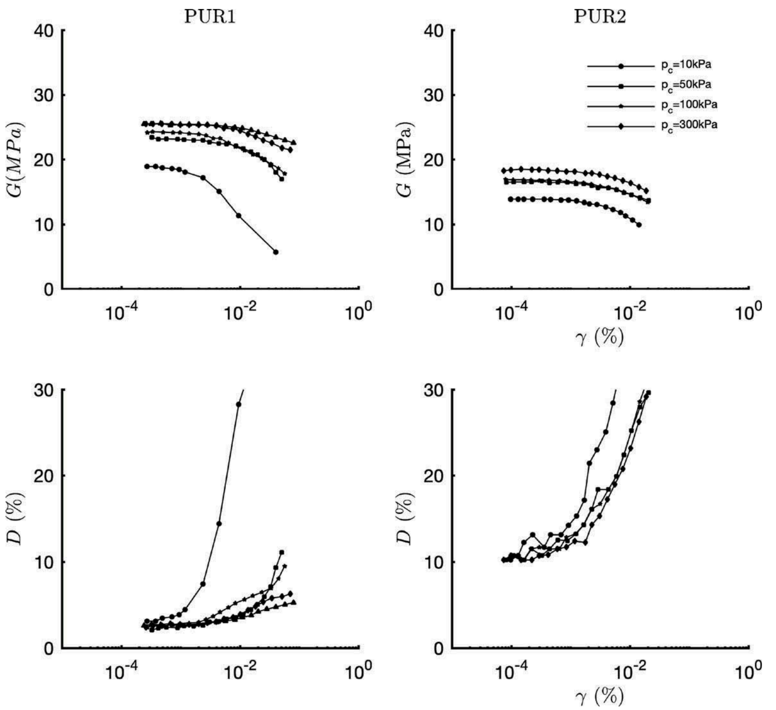

Figure 3. G — γ and D — γ curves for PUR specimens

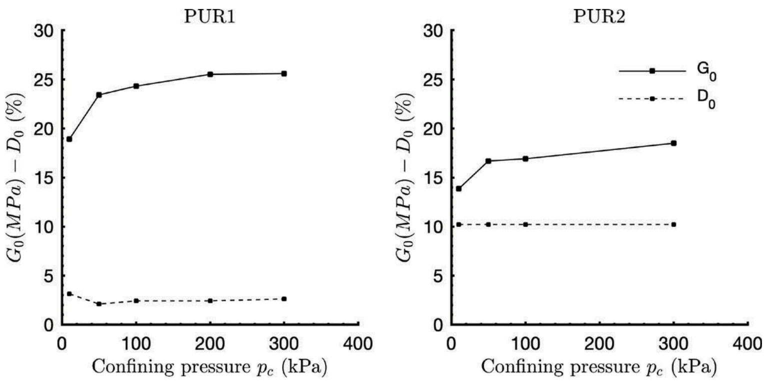

Figure 4. Effect of confining pressure on low-strain shear modulus Go and damping ratio D_0 for PUR specimens

As regards the damping ratio, values are generally independent of the confining pressure; in particular, in both *PUR1-15mm* and *PUR1-25mm* specimens, damping seems to be greater than the pure sand but no difference of all is present among them. Damping ratio changes very much when the percentage of polyurethane in volume is higher (around 30 %), assuming values of around 10 percent. Practically, an increase of 10% (from *PUR1-25mm* to *PUR1-45mm* specimen), gives rise to a double value of damping ratio.

The interpretation of composite specimens realized with PUR2 slices has to take into account the bad realization of the specimen. The behavior is standard when the percentage of polyurethane is low and results are governed by the sand behavior. The cases of 25 and 45 millimeter are not so standard; a strange trend is mainly present in the damping behavior. It

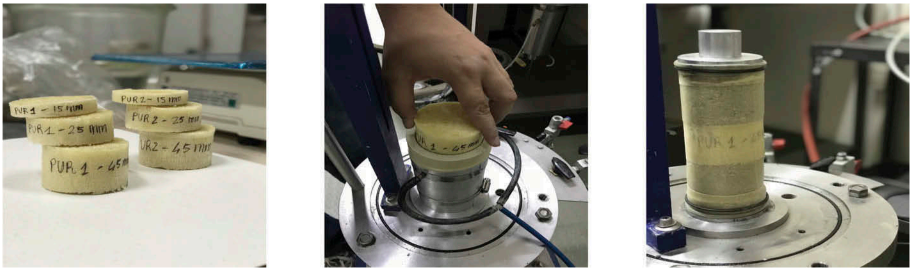

Figure 5. Composite specimens

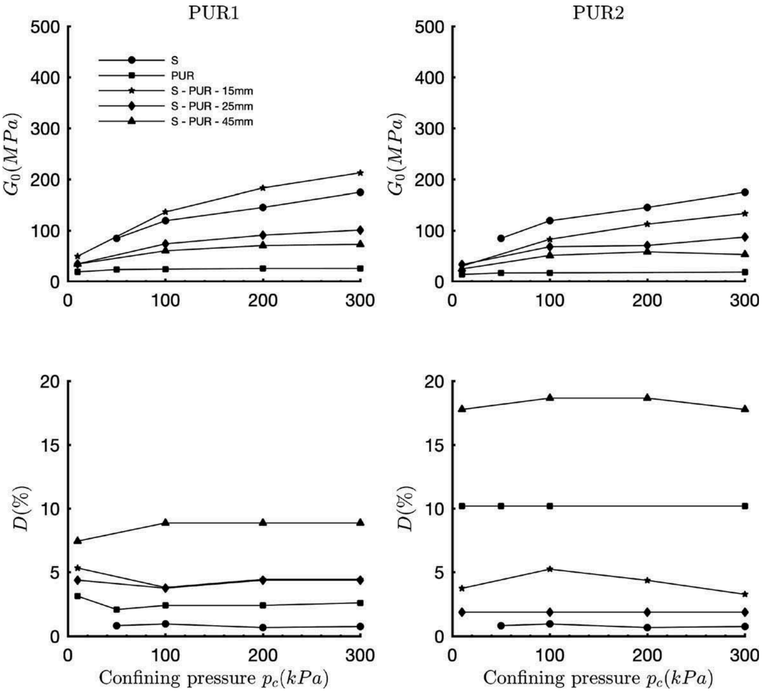

Figure 6. Effect of polyurethane - G_0 and D_0 trend with confining pressure

seems in fact that the bad realization of the specimen has affected only the damping behavior of the composite specimens.

Figures 7 and point out the influence of the polyurethane percentage on the dynamic properties of the resulting pure/composite specimens, by fixing the confining pressure at values of 100, 200 and 300 kPa. In each case, Go generally decreases by increasing the percentage of polyurethane, while the damping ratio increases in the composite specimens, assuming the maximum values for higher polyurethane percentage.

4 CONCLUSIONS

In the research field of seismic risk reduction, University of Parma has recently started an experimental campaign resulting in the study of the effect related to polyurethane foam inclusions with regard to wave propagation phenomenon. Resonant Column tests have been so

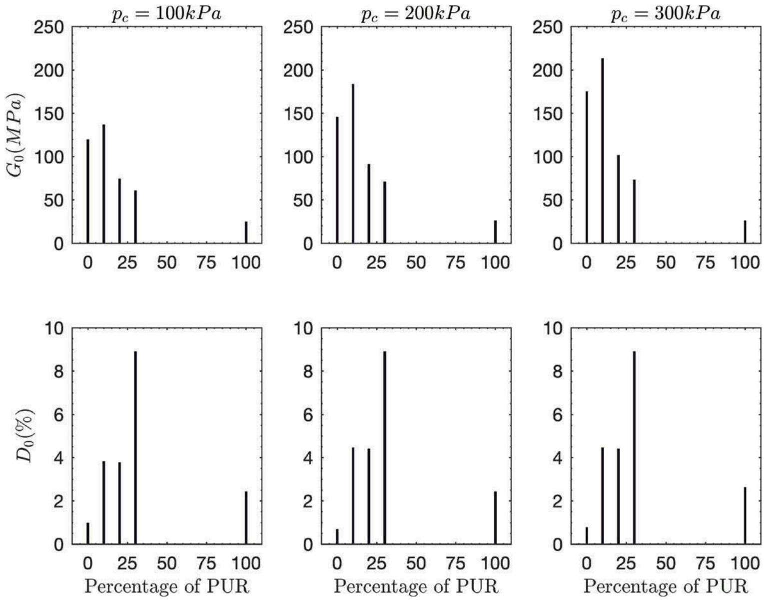

Figure 7. PUR 1 percentage (by volume) influence on G_0 and D_0 for each confining pressure

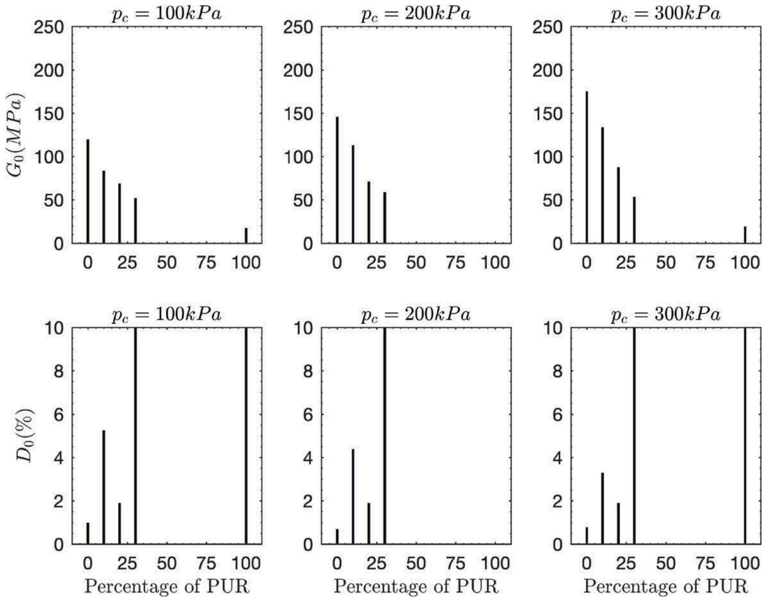

Figure 8. PUR 2 percentage (by volume) influence on G_0 and D_0 for each confining pressure

performed at the Soil Dynamics and Geotechnical Earthquake Engineering Laboratory of Aristotle University of Thessaloniki on specimens of pure polyurethane, realized at two different densities, as well as on composite specimens realized including polyurethane slices of different thickness at half height of sandy specimens.

Results can be summarized as follows:

- Consolidation time generally does not affect the dynamic properties of the pure polyurethane specimens properly realized;
- Low-strain shear modulus G_0 and damping ratio D_0 behavior with the confining pressure is quite constant for pure polyurethane specimens;
- Polyol - isocyanate mixture quality is of fundamental importance in the realization of a polyurethane foam with its proper mechanical characteristics. Even if a specimen is denser, due to a bigger quantity of the densest raw material in the mixture, if the polyurethane reaction is not completed, the properties of the foam will be poor, despite bigger density.
- Composite specimens show a little decrease of the shear modulus, compared with the pure sand specimen value, while damping experiences a meaningful increase, according to the inclusion percentage.

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