Experimental and Numerical Analysis of the Polyurethane Foam Effects on Geotechnical Seismic Isolation

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1 Experimental and Numerical Analysis of the Polyurethane Foam 2 Effects on Geotechnical Seismic Isolation

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12 ABSTRACT

13
14 The paper focuses on the detailed analysis of the dynamic characterisation of polyurethane to
15 evaluate the effects of polyurethane injections into the soil with the aim of geotechnical
16 seismic isolation (GSI). To determine the dynamic properties, resonant column (RC) tests
17 were performed at the University Kore of Enna (Italy) on specimens of pure polyurethane
18 (PUR) with different values of density and subjected to different mean confining pressures.
19 The results obtained by means of RC tests, in terms of shear modulus G and the damping ratio
20 D as a function of shear strain γ_c , allowed to develop an analytical formulation for G - γ_c and
21 D - γ_c curves, taking into account the linear relationship with density of both the maximum
22 value of shear modulus G_{max} and the minimum value of damping ratio D_{min} . The analytical
23 formulation derived from the experimental results is applied for ground response seismic
24 analyses of cohesive soils injected with polyurethane, using a finite element code. The
25 numerical results show that the polyurethane injections reduce the value of maximum
26 acceleration at ground surface and the reduction ranges with the thickness of the soil involved
27 by polyurethane injection.

28 *Keywords: polyurethane injection; geotechnical seismic isolation; numerical analyses;*
29 *resonant column.*

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34 specimens

1 Introduction

The seismic risk reduction is a topic of great interest in earthquake engineering, due to the need to protect civil works from earthquakes, unpredictable phenomena that frequently cause damage to people and property. The most widespread interventions for seismic protection are carried out directly on structures (Aşıkoğlu et al. 2019; Zizi et al. 2021) or on foundations (giving rise to base isolation, Tsiavos et al. 2017; Natale et al. 2021) and are aimed at decreasing the energy transmitted by the earthquake. Among the isolation techniques based on the use of devices placed underneath the foundation, it is innovative the use of polymeric bearings (Falborski and Jankowski, 2016) and scrap tire rubber pad (Mishra et al. 2013; Shirai and Park, 2020).

Even more recent is the direct intervention in the soil, defined by Tsang (2008) as geotechnical seismic isolation (GSI), which is receiving growing interest. These techniques can be used to reduce earthquake-induced loads acting on superstructures, allowing to protect them from the potential effects of earthquakes. The soil, indeed, is responsible to transmit the seismic energy to the superstructures (Castelli et al. 2017; 2021; Ciancimino et al. 2020). GSI allows a reduction of the seismic risk by including into the soil the geomaterial layers with better dynamic properties (Banović et al. 2018) or other materials able to reduce accelerations at ground surface. Among the latter, rubber is receiving great attention because of its dissipative properties, low costs and the environmental sustainability of the interventions based on the use of recycled materials (Argyroudis et al. 2016; Brunet et al. 2016; Chew and Leong, 2019; Tsang and Pitilakis, 2019; Ecemis et al. 2021; Tsang et al. 2021; Rios et al. 2021; Pitilakis et al. 2021).

Other less studied but no less efficient materials in GSI are polymeric materials (Yegian and Kadakal, 2004; Tsiavos et al. 2020). The first uses of the soil - polymer combination date back to the 1970s, as evidenced by Horvath (1992) who used for the first time the term “geofoam” to indicate the cellular materials produced by an expansion process and used in the soil. Geofoams are rigid foams, obtained as a result of chemical reactions, with good mechanical characteristics and low density. Among these, expanded polystyrene (EPS) has been extensively studied for various applications (Ramli Sulong et al. 2019), all of which involving its use in the form of slabs: in slope stabilisation (Jutkofsky et al. 2000; Akai, 2016), in the embankments (Avesani Neto and Rodrigues, 2021), in the earth retaining structures (Horvath, 1997; AbdelSalam and Azzam, 2016; Wang and Huang, 2021), and for the reduction of earth pressure in seismic conditions (Zarnani and Bathurst, 2007; Alzawi and El Naggar, 2011; Gao et al. 2017) or as vibration dampers (Baziar et al. 2019a; Jayawardana et al. 2019) in the dynamic field. Baziar et al. (2019b) show a recent application of EPS for the protection of shallow foundations from fault ruptures.

69 The advantage of the GSI techniques, based on geomaterials, rubber and EPS, is not to be
70 invasive of the structure aesthetics, contrary to classic strengthening interventions. However, they are
71 applicable only to new construction works. This limit is overcome by a particular GSI technique,
72 based on the use of polyurethane that is an organic polymer injectable into the soil, which allows the
73 preservation of the aesthetic appearance even of existing structures. This makes the technique
74 particularly useful in the seismic isolation of buildings belonging to the artistic and cultural heritage.
75 Polyurethane, discovered by Otto Bayer in 1937, is obtained from an expanding chemical reaction
76 between the polyol and the isocyanate, related to the production of CO₂ trapped in the inner spaces
77 of the polymer. The resulting material has a cellular structure (open-cell or closed-cell), low density
78 but excellent mechanical properties, comparable to those of EPS. In the geotechnical field,
79 polyurethane is used in the reduction of swelling of expansive soil (Al-Atroush and Sebaey, 2021)
80 and in the ground improvement (Buzzi et al. 2010), as well as in wave barrier applications (Huang et
81 al. 2021).

82 Since 2015, polyurethane has attracted interest from the geotechnical researchers of the
83 University of Parma which studies it as a GSI technique. The research aim is to verify the material
84 ability in reducing the seismic energy and, consequently, the suitability of the injection technique in
85 the protection of existing structures even from a seismic point of view. The first activities were
86 carried out at a volume element scale and were finalised to the geotechnical characterisation of the
87 material, field in which it had never received interest, contrary to EPS which was largely
88 characterised by both mechanic rather than dynamic point of view (Athanasopoulos et al. 1999;
89 Trandafir et al. 2010, Chen et al. 2015). In particular, triaxial and oedometric tests were performed
90 (Montrasio and Gatto, 2016, 2017). Furthermore, dynamic impact tests were carried out to assess the
91 material's ability to reduce ground surface accelerations (Gatto et al. 2020, 2021a). To reach the final
92 goal, namely the use of polyurethane injections in large-scale interventions in real soils, further
93 investigations are necessary.

94 To reach the aim of large-scale applications, it is essential to understand the role of the soil-
95 polyurethane interaction, depending on the physical, mechanical and hydraulic characteristics of the
96 soil. Sabri and Shashkin (2018) show, for example, how the polyurethane expansion in cohesive soils
97 occurs with poor mixing with the soil, giving rise to areas of pure polyurethane surrounded by soil.
98 In cohesionless soils it is expected that a soil - polyurethane mixture is created.

99 In order to deepen the dynamic characterisation of polyurethane for its use in large-scale
100 applications, the article presents the results of resonant column tests performed on pure polyurethane
101 samples, realised varying densities and subjected to different mean confining stress. Based on the
102 experimental results, an analytical relationship is provided for the evaluation of the dynamic

properties of the material at any density and confining pressure. The experimental results and the analytical modelling of the polyurethane dynamic behaviour are finally used to numerically simulate the seismic response of soil, modified with pure polyurethane inclusions.

2 Dynamic characterisation of pure polyurethane

To determine the dynamic properties of pure polyurethane, several RC tests were performed at the Soil Dynamics and Geotechnical Engineering Laboratory of the University Kore of Enna (Italy) on samples with different values of density and subjected to different mean confining pressures. The results are obtained in terms of G - γ_c and D - γ_c curves.

2.1 Sample preparation

The polyurethane used in the experimental investigation, namely MasterRoc MP 355, is a highly reactive two-component (polyol and isocyanate) polyurethane foam, used in ground improvement. The polyol (density 1.00 kg/l) and the isocyanate (1.25 kg/l), liquid at room temperature, are mixed with a 1:1 volume ratio using a drill equipped with a propeller (mixing duration 15 seconds). The polyol-isocyanate reaction must take place in the presence of water in order to obtain a rigid closed-cell foam. Therefore, a water volume equal to 2% of the polyol volume is added to the polyol before mixing, as indicated in the technical data sheet.

The density ρ_{PUR} of the hardened polyurethane depends on the ratio between the mass m_{PUR} and the final volume V_{fin} . To realise polyurethane samples with different values of ρ_{PUR} , the mass m_{PUR} was varied while V_{fin} was kept constant, pouring the liquid mixture into plastic tubes closed at the ends (Figure 1a). The tubes have a length of 500 mm, $V_{fin} = 980$ ml and an internal diameter of 50 mm, equal to the required diameter for specimens to be placed in the resonant column equipment. Three tubes were filled with liquid mixtures having initial volumes V_{in} 200 ml, 140 ml and 110 ml and the same length. After waiting for 24 hours for the foam to harden (Figure 1b), from each tube three samples were obtained on which resonant column tests were performed. In particular, cylindrical samples 100 mm high are cut from the central part of each tube. A sample is shown in Figure 1c, as an example.

Fig. 1 Sample preparation: a) Plastic tube closed at the ends for the volume control; b) tube section after polyurethane hardening; c) final sample to use in the resonant column test

The specimens are classified as: 1A, 1B, 1C (derived by tube 1); 2A, 2B, 2C (derived by tube 2); 3A, 3B, 3C (derived by tube 3). Table 1 reports the main characteristics of samples in terms of mass m_{PUR} , density ρ_{PUR} and expansion coefficient CE . CE quantifies the foam expansion and it is defined by the ratio V_{fin}/V_{in} where V_{in} is evaluated from m_{PUR} . The data confirm the difficulty to realize pure polyurethane samples identical to each other, as already observed by previous studies (Golpazir et al. 2016). The explanation could be related to the influence of the closing force applied to control the volume of the samples: for large V_{in} , the expansion pressure of the polyurethane is high (Dei Svaldi et al. 2005) and the closing force is fundamental in supporting the caps placed at the tube ends.

Table 1 Main characteristics of the samples obtained from each of the three tubes poured with different initial polyurethane volume V_{in} : mass (m_{PUR}), density (ρ_{PUR}) and expansion coefficient (CE)

<i>Specimens</i>										
		A			B			C		
Tube	V_{in} (ml)	m_{PUR} (g)	ρ_{PUR} (kg/m ³)	CE (-)	m_{PUR} (g)	ρ_{PUR} (kg/m ³)	CE (-)	m_{PUR} (g)	ρ_{PUR} (kg/m ³)	CE (-)
1	110	17.79	90.8	13.2	17.62	89.9	13.3	17.35	88.5	13.6
2	140	22.73	116.0	10.3	21.46	109.5	11.0	21.77	111.1	10.8
3	200	21.41	109.2	11.0	23.06	117.7	10.2	22.80	116.3	10.3

2.2 Resonant Column test device

The dynamic properties of pure polyurethane samples, as G - γ_c and D - γ_c curves, are obtained by means of a detailed test program performed with the device available at the Soil Dynamics and Geotechnical Engineering Laboratory of the University Kore of Enna (Italy). The combined Resonant Column/Torsional Shear device (Figure 2) is of the type fixed-free so that a cylindrical sample 50 mm in diameter and 100 mm in height is fixed at the base and free to rotate on the head. A torsional load is applied to the specimen free-end by means of an electromagnetic motor, consisting of 4 magnets and 8 coils. Amplitude and frequency-controlled torsional inputs are applied to each sample. For each amplitude, the excitation frequency is changed to search the sample resonant frequency f_n , to which G and D are related. Specifically, G is obtained by the specimen density ρ through the relation $G = \rho V_s^2$, where V_s is the shear wave velocity, related to f_n ; D is determined using the half-power bandwidth method applied to the frequency-response curve, identifying the two frequencies f_1 and f_2 where the response is $\sqrt{2}$ smaller than the maximum one occurring at f_n .

The tests were performed by changing the input amplitude, to investigate the behaviour of the soils for shear strains ranging between 0.0001 and 1%. As usual, the tests were interpreted in terms of G - γ_c and D - γ_c curves.

Fig. 2 Fixed-free resonant column apparatus available at University Kore of Enna (Italy)

2.3 Test results

The RC tests were carried out on several pure polyurethane samples, having density ranging between 88.5 and 117.7 kg/m³. Three values of confining pressure p'_c equal to 100, 200 and 300 kPa respectively were applied on each sample. Figures 3-5 show the $G - \gamma_c$ and $D - \gamma_c$ curves. for the samples tested.

For all samples, the maximum value of the shear modulus G_{max} increases with p'_c , with a smaller increment going from 200 a 300 kPa. In particular, the ratios $G_{max} (p'_c=200 \text{ kPa}) / G_{max} (p'_c=100 \text{ kPa})$ and $G_{max} (p'_c=300 \text{ kPa}) / G_{max} (p'_c=200 \text{ kPa})$ are respectively equal to 1.2 and 1.03 for specimen 1B, 1.12 and 1.01 for the 2A, 1.8 and 1.09 for the 3A. This could be due to the cellular structure of the samples which changes up to a certain value of p'_c , first stiffening the sample and then tending towards a more stable specimen structure no longer affected by the cell pressure. At the same value of p'_c , G_{max} is overall directly proportional to the specimen density (for example, at $p'_c=100 \text{ kPa}$ G_{max} is equal to 8.29, 11.66 and 11.75 MPa for specimens 1C,1B and 1A, characterized by increasing density, as reported in Table 1).

The trend of the minimum damping ratio D_{min} is not standard with cell pressure; almost all the samples show a maximum D_{min} at $p'_c=100 \text{ kPa}$ while it becomes quite constant going from 200 to 300 kPa. A not well-defined trend is also observed in the variation of D_{min} with the cell pressure. Cell pressure and specimen density affect the entire trend of the curves and, specifically, it is observed an influence on the variation of the shear strain corresponding to a fifty-percent reduction of the shear modulus with respect to its initial value.

The results obtained are compared with those derived by Golpazir et al. (2016) and Koyama et al. (2021), which represent the only existing dynamic characterisation studies on polyurethane by means of cyclic triaxial tests. However, the samples tested by Golpazir et al. (2016) and Koyama et al. (2021) are less dense than those of this study and are subjected to lower cell pressure. In particular, the values of density and confining pressure are 31.3 kg/m³ and 25 kPa for Golpazir et al. 2016, 36.0 kg/m³ and 20 kPa or 40 kPa for Koyama et al. 2021, respectively.

The results of this study are in good agreement with those proposed by Koyama et al. (2021), both in terms of G and D . D increases with γ_c (as in Koyama et al. 2021) and this is opposite to what observed by Golpazir et al. (2016), who showed a damping decreasing as the shear strain increases.

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Fig. 3 Results of RC tests performed on specimens 1A (a), 1B (b), 1C (c) obtained from Tube 1 subjected to cell pressures $p'_c=100$ kPa (triangles), 200 kPa (circles) and 300 kPa (squares) in terms of $G - \gamma_c$ (empty white markers) and $D - \gamma_c$ (blue filled markers) curves

Fig. 4 Results of RC tests performed on specimens 2A (a), 2B (b), 2C (c) obtained from Tube 2 subjected to cell pressures $p'_c=100$ kPa (triangles), 200 kPa (circles) and 300 kPa (squares) in terms of $G - \gamma_c$ (empty white markers) and $D - \gamma_c$ (blue filled markers) curves

Fig. 5 Results of RC tests performed on specimens 3A (a), 3B (b), 3C (c) obtained from Tube 3 subjected to cell pressures $p'_c = 100$ kPa (triangles), 200 kPa (circles) and 300 kPa (squares) in terms of $G - \gamma_c$ (empty white markers) and $D - \gamma_c$ (blue filled markers) curves

2.4 Prediction of the G/G_{max} - γ_c and D - γ_c curves for pure polyurethane by means of analytical formulation

The results of the RC tests are used to derive a relationship with the aim to highlight the dependence of the dynamic behaviour of pure polyurethane on its density and confining pressure. The relationship allows to estimate the shear deformability and damping parameters for generic conditions that may occur in a possible application of polyurethane injections.

The values of G_{max} and D_{min} obtained by RC tests are plotted versus ρ_{PUR} for cell pressures equal to 100 (Figure 6a), 200 (Figure 6b) and 300 kPa (Figure 6c): it is observed that the points can be interpolated by straight lines passing through the origin.

Fig. 6 Small-strain dynamic properties G_{max} and D_{min} vs polyurethane specimen density ρ_{PUR} at different values of confining pressure $p'_c = 100$ kPa (a), 200 kPa (b) and 300 kPa (c)

In particular, for G_{max} , the coefficient of determination R^2 is high (greater than 0.96) and the linear trend is in good agreement with previous literature results (Gatto et al. 2021b); for D_{min} , the R^2 value is lower but the linear approximation is accepted because describing the dissipative behaviour is complicated even in the most well-known materials. According to experimental results, the dependence of G_{max} and D_{min} on ρ_{PUR} and p'_c can be expressed by means of two following relations:

$$G_{max}(p'_c, \rho) = g_I(p'_c) \rho_{PUR} \quad (1a)$$

$$D_{min}(p'_c, \rho) = d_I(p'_c) \rho_{PUR} \quad (1b)$$

where g_I and d_I are the slopes of the two straight lines, depending on the cell pressure. Specifically, Fig. 6 highlights that the slope of the G_{max} - ρ_{PUR} interpolating lines increases as the cell pressure increases. This means that ρ_{PUR} has a greater influence on the G_{max} value when the cell pressure is higher. Furthermore, the influence of p'_c on the D_{min} - ρ_{PUR} trend is opposite.

The slope values g_I and d_I are plotted versus p'_c in Figure 7, together with those obtained by Koyama et al. (2021) by means of the cyclic triaxial tests performed on polyurethane samples with $\rho_{PUR} = 36 \text{ kg/m}^3$ at the lower values of cell pressures of 20 and 40 kPa respectively.

Using Eq. (1a) for the values of $G_{max} = 3 \text{ MPa}$ and $G_{max} = 3.25 \text{ MPa}$ deduced by the experimentation of Koyama et al. (2021), it is possible to obtain $g_I(p'_c=20\text{kPa})=0.0833$ and $g_I(p'_c=40\text{kPa})=0.0903$. The values of g_I thus derived are represented in Figure 7.a as blue circle markers together with those obtained by the Authors as pink triangle markers, corresponding to $p'_c = 100, 200$ and 300 kPa . At the same way, using the Eq. (1b) for $D_{min} = 1.18\%$ and $D_{min} = 0.53\%$ reported by Koyama et al. (2021), the corresponding values of d_I are evaluated for p'_c equal to 20 and 40 kPa (Figure 7.b).

Thus, coupling the experimental results obtained by the Authors by means of RC tests with those derived by Koyama et al. (2021) from CTX test, the following best fit trend lines between the g_I , d_I , and the confining pressure p'_c were derived (Figure 7):

$$g_I(p'_c) = -10^{-6} \cdot p'^2_c + 0.0006 \cdot p'_c + 0.0682 \quad (2a)$$

$$d_I(p'_c) = 0.0865 \cdot p'^{-0.331}_c \quad (2b)$$

Fig. 7 g_I (a) and d_I (b) dependency by confining pressure p'_c

As known, the polyurethane density and the confining pressure affect the G - γ_c and D - γ_c curves. To better understanding of the dynamic behaviour of polyurethane within the shear strain range investigated by RC tests, the experimental data are fitted using the following relationships proposed by Romo (1995) and used successively by Ossa and Romo, 2011 for the expanded polystyrene EPS:

$$G(\gamma_c) = G_{max} - (G_{max} - G_{min}) \cdot H(\gamma_c) \quad (3a)$$

$$D(\gamma_c) = D_{min} + (D_{max} - D_{min}) \cdot H(\gamma_c) \quad (3b)$$

where G_{max} e D_{min} have the well-known significance; G_{min} and D_{max} are the minimum value of shear modulus and the maximum value of damping ratio with reference to the high shear strain. Since high strain are out of range of RC test, the Authors assumed $G_{min}=1$ MPa and $D_{max}=18\%$, which provide a good match with the experimental results. Finally, the function $H(\gamma_c)$ is given by:

$$H(\gamma_c) = \left[\frac{\left(\frac{\gamma_c}{\gamma_R}\right)^{2B}}{1 + \left(\frac{\gamma_c}{\gamma_R}\right)^{2B}} \right]^A \quad (4)$$

with γ_R the shear strain for which the shear modulus is reduced by 50% with respect to the initial value, while A and B are coefficients.

Ossa and Romo (2011) evaluated the values of γ_R , A and B for EPS samples with density ranging between 24 and 32 kg/m³ and confining stress ranging between 0 and 60 kPa. Therefore,

279 taking into account the different values of ρ_{PUR} and confining stress of the RC tests, the Authors have
 280 obtained the values of A , B and γ_R , reported in Table 2 for this laboratory experimentation, according
 281 to a good fit with the experimental data. As an example, the Figure 8 shows the analytical-
 282 experimental comparison for samples 1A, 1B and 1C.

283

284 **Table 2** Values of A , B and γ_R to fit experimental results in terms of G - γ_c and D - γ_c curves according to the relations
 285 proposed by Romo, 1995 for samples with density ρ_{PUR} subjected to the confining stress p'_c

Specimen	ρ_{PUR} (kg/m ³)	$p'_c = 100$ kPa			$p'_c = 200$ kPa			$p'_c = 300$ kPa		
		A	B	γ_R	A	B	γ_R	A	B	γ_R
1C	88.5	1	0.50	0.38	1	0.60	0.90	1	0.65	1.30
1B	89.9	1	0.60	0.40	1	0.65	1.00	1	0.67	1.20
1A	90.8	1	0.60	0.40	1	0.60	1.00	1	0.68	1.10
3A	109.2	1	0.60	0.32	1	0.62	0.60	1	0.70	0.90
2B	109.5	1	0.60	0.35	1	0.65	0.65	1	0.70	0.90
2C	111.1	1	0.67	0.33	1	0.71	0.63	1	0.80	0.86
2A	116.0	1	0.73	0.33	1	0.80	0.60	1	0.90	0.75
3C	116.3	1	0.75	0.32	1	0.75	0.50	1	0.80	0.70
3B	117.7	1	0.65	0.30	1	0.70	0.60	1	0.90	0.85

Fig. 8 Fitting of the RC test results on specimen 1A (a), 1B (b) and 1C (c) using the relationships proposed by Osso e Romo (2011)

The analysis of the data reported in Table 2 highlights that A is 1 for all cases while B and γ_R vary both with specimen density and the confining stress. The functions $B(\rho_{PUR}, p'_c)$ and $\gamma_R(\rho_{PUR}, p'_c)$ are represented in Figure 9, together with the pairs $B - \rho_{PUR}$ and $\gamma_R - \rho_{PUR}$ for values of p'_c equal to 100 (a), 200 (b) and 300 (c) kPa.

Fig. 9 B and γ_R vs polyurethane specimen density ρ_{PUR} at different values of confining pressure $p'_c = 100$ kPa (a), 200 kPa (b) and 300 kPa (c)

As depicted in the plots, the values of B and γ_R are affected by density and the data can be interpolated by following equations.

$$B(p'_c, \rho) = b_1(p'_c) \rho_{PUR} \quad (5a)$$

$$\gamma_R(p'_c, \rho) = c_1(p'_c) \rho_{PUR} + c_2(p'_c) \quad (5b)$$

where b_1 , c_1 and c_2 depend on the confining stress with the following expressions:

$$b_1(p'_c) = 6 \cdot 10^{-6} p'_c + 0.0053 \quad (6a)$$

$$c_1(p'_c) = 8 \cdot 10^{-7} p'^2_c - 4 \cdot 10^{-4} \cdot p'_c + 0.0286 \quad (6b)$$

$$c_2(p'_c) = -3 \cdot 10^{-5} p'^2_c + 1.78 \cdot 10^{-2} \cdot p'_c - 0.3311 \quad (6c)$$

Equations are applied to fit both the experimental results reported by Koyama et al. (2021) and Golpazir et al. (2016), although it has already been pointed out that the tests results performed by the Authors are more consistent with those reported in Koyama et al. (2021). The comparison between analytical and literature experimental results is shown in Figure 10. A good agreement can be observed between analytical and experimental results by Koyama et al. (2021) in terms of G and D . Instead, the experimental results reported by Golpazir et al. (2016) are well fitted by analytical curve only as regards G in the shear strain range $\gamma_c > 10^{-1} \%$. The experimental value of G_{max} is underestimated by analytical formulation. Finally, the experimental values of D are not in good agreement with those obtained from analytical formulation.

Fig. 10 Prediction of literature results through the analytical formulation

3 Finite element analysis of seismic response of soil injected with polyurethane

To evaluate the effect of the polyurethane injections into the soil for GSI, finite element analysis of seismic response has been performed for the well-investigated site of Augusta, in the south-east cost of Sicily (Italy). The Augusta area, characterized by a high seismic risk, has been studied in the recent past by several researchers (Cavallaro et al. 2018, Lentini et al. 2019). For this reason several data deriving from a detailed in situ and laboratory tests are available.

Coupling previous experimental data with those deduced by means RC tests performed on PUR samples, a realistic numerical model has been done with the aim to compare the results of seismic analysis of the Augusta soils with and without polyurethane injections. Thus, it is possible to estimate the reduction of surface acceleration due to polyurethane injections into the soil.

3.1 Soil properties of the test site

A detailed static and dynamic characterization (Lo Presti et al. 1999a; Cavallaro et al. 1999; Lo Presti et al. 1999b; Cavallaro et al. 2018) is available for the Augusta area. In particular, in situ (boreholes, standard penetration tests, Field Vane Tests, Ménard Pressumeter Tests, Down-Hole Tests) and laboratory (Oedometer Tests, Direct Shear Tests, Consolidated Drained Triaxial Tests, Undrained Triaxial Tests, Cyclic Loading Torsional Shear Tests, Resonant Column Tests) tests have been carried out also for the seismic improvement of the Augusta Hangar, a cultural heritage monument.

The stratigraphic profile, deduced by the available boreholes, shows four main geotechnical units which, from the surface to the depth, are: sandy silt (Layer 1), clayey silt (Layer 2), silty clay (Layer 3) and grey clay (Layer 4). The soil profile for the numerical analysis is shown in Fig. 11a, together with the shear wave velocity profile, obtained by the Down-Hole tests. The RC tests (Cavallaro et al. 1999; Lo Presti et al. 1999b) performed on samples retrieved correspond to four geotechnical units allowed to obtain the $G/G_{max}-\gamma_c$ and $D-\gamma_c$ curves, shown in Figure 11b.

Cavallaro et al. (2018) also report that the soil strength parameters (c' effective cohesion, φ' friction angle) vary in the ranges $c'=15-28$ kPa e $\varphi'=17-23^\circ$. Furthermore, the low permeability of the soil allows to assume that the injected polyurethane does not mix with it, giving rise to areas of pure polyurethane as evidenced by Sabri and Shashkin (2018). Precisely for this reason, the numerical analyses will refer to the presence of polyurethane into the soil as columnar inclusions of different heights.

Fig. 11 Soil dynamic properties of Augusta area (Italy): a) Shear wave velocity profile; b) normalized shear modulus and damping ratio curves.

3.2 Modelling of the polyurethane inclusions

The polyurethane inclusions are modelled in the numerical analysis as columns of diameter d_{PUR} and height h_{PUR} . Both the geometric characteristics d_{PUR} and h_{PUR} as well as the density of the columns have been chosen according to the configurations usually adopted for the ground improvement.

The MasterRoc 355 polyurethane is injected into the soil, where can expand 5 to 10 times ($CE=5-10$). Previous results (Gatto et al. 2021b) have shown that the surface accelerations are reduced more when the polyurethane expands more. For this reason the value of expansion coefficient CE equal to 10 has been considered for the numerical analysis. In this way, when 10 kg of injected polyurethane expand radially 10 times, the diameter d_{PUR} is equal to 0.33 metres and the density of the hardened polyurethane is $\rho_{PUR} = 120 \text{ kg/m}^3$. As regards the polyurethane columns' heights, three cases are considered: h_{PUR} equal to 2, 3 and 4 metres according to the typical values of the ground improvement interventions performed by Master Builder Solutions. For each of the three cases, the columnar inclusion is subjected to the different soil pressure. Evaluating the confining pressure p_0 as

384 $(1+2k_0)/3 \cdot \gamma' \cdot h_{PUR}/2$, with k_0 the coefficient of earth pressure at rest and γ' the unit weight of the
 385 submerged soil, in the Augusta soil we obtain $p_0 = 10.3$ kPa, 15.5 kPa and 20.6 kPa, respectively for
 386 $h_{PUR} = 2$ m, 3 m and 4 m. The Figure 12 shows the $G/G_{max}-\gamma_c$ and $D-\gamma_c$ curves of the polyurethane
 387 deduced by applying the analytical formulation proposed by the Authors for the abovementioned
 388 values of ρ_{PUR} and p_0 .

389
 390 **Fig. 12** Predicted $G/G_{max}-\gamma_c$ and $D-\gamma_c$ curves for $\rho_{PUR}=120$ kg/m³ and p_0 equal to 10.3 kPa, 15.5 kPa and 20.6 kPa
 391

392 3.3 Numerical model

393

394 Finite elements analyses are performed by means of code OpenSees (Mazzoni et al. 2006) and
 395 GID (Coll et al. 2018) for graphic interface. The soil is modelled as square-shaped element with size
 396 1 meter x 1 meter in plan and 0.7 m height according to the position of the bedrock reported by
 397 Cavallaro et al. 2018.

398 The mesh, divided into four zones (Figure 13a) according to the soil stratigraphy, is
 399 representative of the soil underneath the foundation, where ground improvement is assumed to be
 400 realised. The numerical analyses are carried out tacking into account the soil without polyurethane
 401 injections and subsequently with polyurethane inclusions modelled as elements having $d_{PUR} = 0.33$ m
 402 in diameter and h_{PUR} equal to 2, 3 and 4 metres in length.

403 The pure polyurethane inclusions have a centre distance equal to 0.75 m. In the numerical
 404 modelling the geometry of the polyurethane inclusions has been simplified as parallelepipeds with
 405 square plan with size equal to d_{PUR} (Figure 13b).

406

Fig. 13 Overview of the FE numerical modelling. a) 3D Mesh; b) Mesh detail in x-y plane

The constitutive model used for the soil as well as for polyurethane is the “Pressure Independent Multi Yield”, proposed by Parra (1996), Yang et al. (2003) and Elgamal et al. (2003), suitable for cohesive soils. The abovementioned constitutive model has three main characteristics: i) the material is assumed to be non-linear behaviour (a specific law is considered to relate the generic octahedral stress τ and strain γ_c) relating to decay law of shear modulus; ii) the exponential dependence (with exponent d) of the shear modulus on the isotropic pressure p' ; iii) the variation of the octahedral stress at failure τ_f with p' . All of this can be expressed by the following equations:

$$\tau = \frac{G \gamma_c}{1 + \frac{\gamma_c}{\gamma_{ref}} \left(\frac{p'_{ref}}{p'} \right)^d} \quad (13a)$$

$$G = G_{ref} \left(\frac{p'}{p'_{ref}} \right)^d \quad (13b)$$

$$\tau_f = \frac{2\sqrt{2} \sin \phi'}{3 - \sin \phi'} p' + \frac{2\sqrt{2}}{3} c' \quad (13c)$$

where G_{ref} and γ_{ref} are respectively the shear modulus and the octahedral strain referred to the reference pressure p'_{ref} . The parameters of Eqs. (13a) and (13b) have been calibrated on the available data. Experimental shear modulus decay curves and the shear wave velocity profile were used for the soil, while the predicted curves shown in Fig. 12 were used for the polyurethane. The values of G_{ref} , p'_{ref} , d , c' and ϕ' chosen for the best experimental - numerical comparison are reported in Table 3.

428 **Table 3** Main parameters required for the Pressure Independent Multi Yield constitutive model.

Layer	G_{ref} (kPa)	p'_{ref} (kPa)	d (-)	c' (kPa)	ϕ' (°)
1	150000	200	0.2	10	25
2	50000	100	0.5	20	20
3	40000	80	4	20	20
4	95000	200	0.4	20	20
PUR	27800	10	1.2	1000	0

429

430

431 Figures 14a and 14b show the comparison between the experimental and numerical curves for the
432 soil, highlighting the goodness of the parameters used for numerical modelling. The soil damping is
433 introduced with the Rayleigh frequency-dependent method (Chopra, 2011), through two coefficients
434 dependent on the material damping ratio. This approach is also used for polyurethane, although there
435 are no further examples of numerical modelling to the authors' knowledge and this aspect would
436 require an experimental study at large scale for its validation.

437

438 **Fig. 14** a) Numerical (dashed line) and experimental (markers x) shear modulus decay; b) Comparison between
439 experimental (continuous line) and numerical (dashed line) V_s profile

440

441 The numerical analysis have been performed under dynamic condition, in which the seismic
442 input is applied to the bedrock as a viscous nodal force (Joyner and Chen, 1975, widely described in
443 Gatto et al. 2021b). In particular, the seismic input is the recording at Sortino of the 1990 Santa Lucia
444 earthquake, suitably scaled.

The column's walls are tied to simulate a pure shear deformation; moreover, the bedrock is assumed to be visco-elastic, by means of a point damper modelled with a zero length element of viscous material. The domain is discretised with standard brick 3D eight-node elements (as provided by Open Sees), each of maximum height 1 meter which adheres to the relation reported in Lysmer and Kuhlmeyer (1969). The time step of the dynamic analysis is 0.005 s to satisfy the Courant - Friedrich-Lewy (Courant et al. 1967) relation discussed by LeVeque (2007), which ensures the stability of the numerical analysis, based on the mesh discretisation and the shear wave velocity.

3.4 Numerical Analyses Results and discussion

Figure 15 shows the comparison among time histories of the surface acceleration obtained by the numerical analyses in the case in which no polyurethane injections there are into the soil with the cases in which polyurethane columns of heights $h_{PUR}=2, 3$ and 4 m are realized. Generally, the results confirm that accelerations are reduced by polyurethane inclusions. Moreover, a greater reduction (up to 5%) is observed when a larger soil volume is modified with polyurethane. In terms of the amplification function, polyurethane columns do not affect the fundamental frequency of the model: this means that the reduction in the surface accelerations is mainly due to material damping. The results are consistent with previous experimental studies (Brunet et al. 2016; Tsang and Pitilakis, 2019; Gatto et al. 2021a).

Fig. 15 Comparison of the surface accelerations among ‘no injections’ and with polyurethane inclusions of heights h_{PUR} = 2, 3 and 4 m

The numerical results can be useful to deduce very important suggestions about the diameter of the perforation to realise, where polyurethane subjected to the p_0 confining pressure by soil, can expand up to CE = 10 and a final diameter $d_{PUR} = 0.33$ m. This can be done by using the theoretical solutions of cylindrical cavities expansion issue in elastic - plastic material (Carter, 1986; Yu and, Houlsby 1991), already extended to the theoretical interpretation of the expansion of polyurethane injected into the soil (Dei Svaldi et al. 2005; Nowamooz 2016; Gatto and Montrasio 2021). Specifically, a perforation diameter of 0.2 m is derived when $h_{PUR} = 4$ m and $p_0 = 20.6$ kPa, while it is 0.18 m when $h_{PUR} = 3$ m and $p_0 = 15.5$ kPa. Note that solutions are derived for an expansion pressure $p_{exp} = 371$ kPa, evaluated as a function of the hardened foam unit weight (Dei Svaldi et al. 2005). However, further investigations are needed to understand if this pressure is also influenced by the high pressure of the injection.

4 Conclusions

The seismic risk reduction of existing buildings is generally carried out by direct interventions on the structural elements aimed at reducing the seismic vulnerability, with invasive techniques which might not guarantee the conservation of the aesthetic aspect. GSI, considering the soil as the intervention place for seismic protection, is an alternative to structural techniques: However, the most studied materials in use would allow to intervene into the soil mainly on new constructions.

The paper shows a detailed study on GSI by means of polyurethane injections, one of the few techniques that can be used for the seismic protection of existing buildings. The technique, already widespread for ground improvement, is analysed to extend its applicability to the site effect reduction in seismic conditions. In particular, the suggestions provided by the Authors refer to interventions realised in low permeability soils, where the injected polyurethane does not mix with the soil and the inclusions are similar to cylinders made up of pure polyurethane. Several RC tests carried on polyurethane specimens having different densities and subjected to different confining pressure, allowed to study the dynamic properties of the foam and to define an analytical formulation for estimating the parameters at any confining pressure and density. The main considerations deduced by the results of this study can be summarized as following.

- The trend of the G and the D with γ_c is similar to the soil's one: G decreases while D increases, as the shear strain level increases.
- The maximum value of the shear modulus G_{max} is influenced by both the polyurethane density and the confining pressure. With reference to ρ_{PUR} , the results confirm the linear dependence shown by the literature. An increase in confining pressure results in an increase in stiffness, with a less noticeable improvement towards high cell pressures.
- Even the minimum value D_{min} of the damping ratio is influenced by density and confining pressure; in particular, D_{min} increases with the density, while it decreases with the cell pressure. This latter result means that the polyurethane should not be injected at shallow depths, where it is subjected to a low confining pressure.

The efficiency of the GSI based on polyurethane injections was then evaluated at large scale, with a finite element numerical simulation on a true-scale model with characteristics as closely as possible to the experimental reality. The numerical results show that the polyurethane application reduces the surface accelerations proportionally to the volume of the soil modified with the inclusions. The results are encouraging to continue towards a real experimentation, expensive but certainly

essential to confirm the numerical results and validate some of the assumptions made.

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