Dynamic properties of polyurethane from resonant column tests for numerical GSI study

Michele Placido Antonio Gatto1 · Valentina Lentini2 · Lorella Montrasio1

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

Keywords Polyurethane injection · Geotechnical seismic isolation · Numerical analyses · Resonant column

Lorella Montrasio
lorella.montrasio@unipr.it
Michele Placido Antonio Gatto
micheleplacidoantonio.gatto@unipr.it
Valentina Lentini
valentina.lentini@unikore.it

1 Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze 181/A, 43100 Parma, Italy
2 Faculty of Engineering and Architecture, University Kore of Enna, Via delle Olimpiadi, 94100 Enna, Italy
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 (i.e. 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, the use of polymeric bearings (Falborski and Jankowski 2016) and scrap tire rubber pads (Mishra et al. 2013; Shirai and Park 2020) is innovative.

Even more recent is the direct intervention in the soil, defined by Tsang (2008) and Tsang et al. (2012) 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 is responsible for transmitting the seismic energy to the superstructures (Castelli et al. 2017; 2018; 2021; Ciancimino et al. 2020). GSI allows a reduction of the seismic risk by modifying the soil with geomaterial layers of 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 cost 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 for GSI are polymeric materials (Yegian and Kadakal 2004; Tsiavos et al. 2020, 2021). 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. Geofoam is rigid foam, 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 embankments (Avesani Neto and Rodrigues, 2021), in earth retaining structures (Horvath 1997; AbdelSalam and Azzam 2016; Wang and Huang 2021), and in the dynamic field 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). Baziar et al. (2019b) show a recent application of EPS for the protection of shallow foundations from fault ruptures.

The advantage of the GSI techniques, based on geomaterials, rubber and EPS, is not to be invasive of the structure aesthetics, contrary to classic strengthening interventions. However, they are applicable only to new construction works. This limit is overcome by a particular GSI technique, based on the use of polyurethane that is an organic polymer injectable into the soil, which allows the preservation of the aesthetic appearance even of existing structures. This makes the technique particularly useful in the seismic isolation of buildings belonging to the artistic and cultural heritage. Polyurethane, discovered by Otto Bayer in 1937, is obtained from an expanding chemical reaction between the polyol and the isocyanate, related to the production of CO$_2$ trapped in the inner spaces of the polymer. The resulting material has a cellular structure (open-cell or closed-cell), low density but excellent mechanical properties, comparable to those of EPS. In the geotechnical field,
Polyurethane is used in the reduction of swelling of expansive soil (Al-Atroush and Sebaey 2021) and in ground improvement (Buzzi et al. 2010), as well as in wave barrier applications (Huang et al. 2021).

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

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

In order to deepen the dynamic characterisation of polyurethane for its use in large-scale applications, this article presents the results of resonant column tests performed on pure polyurethane samples of varying densities, subjected to different mean confining stress. Based on the experimental results, an analytical formulation 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 $G-\gamma_c$ and $D-\gamma_c$ 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), which are liquid at room temperature, are mixed with a 1:1 volume ratio using a drill equipped with a propeller (mixing duration 15 s). In order to obtain rigid closed-cell foam, water must be added to the polyol before mixing it with isocyanate (water volume 2% of the polyol’s volume, as indicated in the technical datasheet).
The density $\rho_{\text{PUR}}$ of the hardened polyurethane depends on the ratio between the mass $m_{\text{PUR}}$ and the final volume $V_{\text{fin}}$. To realise polyurethane samples with different values of $\rho_{\text{PUR}}$, the mass $m_{\text{PUR}}$ was varied while $V_{\text{fin}}$ was kept constant, pouring the liquid mixture into plastic tubes closed at both ends (Fig. 1a). The tubes have a length of 500 mm, $V_{\text{fin}} = 980$ ml and an internal diameter of 50 mm, equal to the required diameter for specimens to be placed in the resonant column equipment. Three same-length tubes were filled with the liquid mixtures having initial volumes $V_{\text{in}}$ of 200 ml, 140 ml and 110 ml. After 24 h for the foam to harden (Fig. 1b), from each tube three samples were obtained on which resonant column tests were performed. In particular, cylindrical samples 100 mm thick are cut from the central part of each tube. A sample is shown in Fig. 1c, as an example.

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 $m_{\text{PUR}}$, density $\rho_{\text{PUR}}$ and expansion coefficient $CE$. $CE$ quantifies the foam expansion and it is defined by the ratio $V_{\text{fin}}/V_{\text{in}}$ where $V_{\text{in}}$ is evaluated from $m_{\text{PUR}}$. The data confirms the difficulty to realise pure polyurethane samples identical to each other, as already observed in 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 ends of the tubes.

2.2 Resonant column test device

The dynamic properties of pure polyurethane samples, as $G- \gamma_c$ and $D- \gamma_c$ 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 (Fig. 2) is a fixed-free type so that a cylindrical sample 50 mm in diameter and 100 mm in thickness is fixed at the base and free to rotate on the head. A torsional load is applied to the free end of the specimen 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 $\rho$ 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 occurring at $f_n$.

The tests were performed by changing the input amplitude, to investigate the behaviour of the soil for shear strains ranging between 0.0001 and 1%. As usual, the tests were interpreted in terms of $G- \gamma_c$ and $D- \gamma_c$ 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 densities ranging between 88.5 and 117.7 kg/m$^3$. Three values of confining pressure $p'_c$ equal to 100, 200 and 300 kPa respectively were applied to each sample. Figures 3, 4 and 5 show the $G$-$\gamma_c$ and $D$-$\gamma_c$ curves for the samples tested.

**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)
Overall, the maximum value of the shear modulus $G_{\text{max}}$ increases with $p'_c$, with a smaller increment going from 200 to 300 kPa. In particular, the ratios $G_{\text{max}}(p'_c = 200 \text{ kPa})/G_{\text{max}}(p'_c = 100 \text{ kPa})$ and $G_{\text{max}}(p'_c = 300 \text{ kPa})/G_{\text{max}}(p'_c = 200 \text{ kPa})$ 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.

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)
no longer affected by the cell pressure. At the same value of $p'_c$, $G_{\text{max}}$ is overall directly proportional to the specimen density (for example, at $p'_c = 100 \text{ kPa}$ $G_{\text{max}}$ is equal to 8.29, 11.66 and 11.75 MPa for specimens 1C, 1B and 1A, characterised by increasing density, as reported in Table 1).

The trend of the minimum damping ratio $D_{\text{min}}$ is not standard with cell pressure; almost all the samples show a maximum $D_{\text{min}}$ 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 $D_{\text{min}}$ with the cell pressure; this is considered acceptable because the definition of a regular damping variation is difficult even for the soil. Cell pressure and specimen density affect the entire trend of the curves and, specifically, 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 is observed.

Previous studies showed that the chemical structure of the reacted foam strongly affects the mechanical behaviour of polyurethane (Zimmer et al. 2018; Gatto et al. 2019). This can explain several remarkable differences between the experimental measurements related to specimens of similar densities.

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/m$^3$ and 25 kPa for Golpazir et al. (2016), 36.0 kg/m$^3$ 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 $D$. The observed increase in $D$ is opposite to what Golpazir et al. (2016) obtained, showing a damping decrease as the shear strain increases.

2.4 Prediction of the $G/G_{\text{max}} - \gamma_c$ and $D - \gamma_c$ 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 modulus and damping ratio curves for different values of density and confining pressure that may occur in the applications with polyurethane injections.

The values of $G_{\text{max}}$ and $D_{\text{min}}$ obtained by RC tests are plotted versus $\rho_{\text{PUR}}$ for cell pressures equal to 100 (Fig. 6a), 200 (Fig. 6b) and 300 kPa (Fig. 6c): the points can be interpolated by straight lines passing through the origin of the reference system, as highlighted by the equations reported in the Figures. Both the regression line and the coefficient of determination have been derived through the related built-in Excel function. Null values of $G_{\text{max}}$ and $D_{\text{min}}$ at zero densities interpret the physical reality: stiffness and damping of a zero-density polyurethane are expected to be zero.

In particular, for $G_{\text{max}}$, 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 $D_{\text{min}}$, 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 $G_{\text{max}}$ and $D_{\text{min}}$ on $\rho_{\text{PUR}}$ and $p'_{c}$ can be expressed by means of two following relations:

\begin{align}
G_{\text{max}}(p'_{c}, \rho) &= g_{1}(p'_{c}) \rho_{\text{PUR}} \\
D_{\text{min}}(p'_{c}, \rho) &= d_{1}(p'_{c}) \rho_{\text{PUR}}
\end{align}

(1a)

(1b)
where $g_1$ and $d_1$ are the slopes of the two straight lines, depending on the cell pressure. Specifically, Fig. 6 highlights that the slope of the $G_{\text{max}} - \rho_{\text{PUR}}$ interpolating lines increases as the cell pressure increases. This means that $\rho_{\text{PUR}}$ has a greater influence on the $G_{\text{max}}$ value when the cell pressure is higher. Furthermore, the influence of $p'_c$ on the $D_{\text{min}} - \rho_{\text{PUR}}$ trend is opposite.

The values of our slopes $g_1$ and $d_1$ are plotted versus $p'_c$ in Fig. 7; to extend the formulation to other confining pressures, the small-strain results of Koyama et al. (2021), performed on polyurethane samples with $\rho_{\text{PUR}} = 36$ kg/m$^3$ subjected to cell pressures of 20 and 40 kPa, are used. This choice is considered lawful since both studies investigate closed-cell polyurethanes. Moreover, the small-strain dynamic properties derived from

![Fig. 6 Small-strain dynamic properties $G_{\text{max}}$ and $D_{\text{min}}$ versus polyurethane specimen density $\rho_{\text{PUR}}$ at different values of confining pressure $p'_c = 100$ kPa (a), 200 kPa (b) and 300 kPa (c)]
cyclic triaxial tests performed by Koyama et al. (2021) are related to a strain level of 0.007% and are therefore comparable with the ones of this study.

Using Eq. (1a) for the values of $G_{\text{max}} = 3$ MPa and $G_{\text{max}} = 3.25$ MPa deduced by the experimentation of Koyama et al. (2021), it is possible to obtain $g_1(p'_c = 20\text{kPa}) = 0.0833$ and $g_1(p'_c = 40\text{kPa}) = 0.0903$. The values of $g_1$ thus derived are represented in Fig. 7a as blue circle markers together with those obtained by the Authors as pink triangle markers, corresponding to $p'_c = 100$, 200 and 300 kPa. In the same way, using the Eq. (1b) for $D_{\text{min}} = 1.18\%$ and $D_{\text{min}} = 0.53\%$ reported by Koyama et al. (2021), the corresponding values of $d_1$ are evaluated for $p'_c$ equal to 20 and 40 kPa (Fig. 7b).

Thus, coupling the experimental results obtained by the Authors by means of RC tests with those derived by Koyama et al. (2021) from CTX tests, the following best-fit trend lines between the $g_1$, $d_1$, and the confining pressure $p'_c$ were derived (Fig. 7):

$$g_1(p'_c) = -10^{-6} \cdot p'_c^2 + 0.0006 \cdot p'_c + 0.0682$$ (2a)

$$d_1(p'_c) = 0.0865 \cdot p'_c^{-0.331}$$ (2b)

As known, the polyurethane density and the confining pressure affect the $G$-$\gamma_c$ and $D$-$\gamma_c$ curves. To better understand 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:

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

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

where $G_{\text{max}}$ and $D_{\text{min}}$ have the well-known significance; $G_{\text{min}}$ and $D_{\text{max}}$ are the minimum values of shear modulus and the maximum values of damping ratio with reference to the high shear strain. Since high strain is out of range of the RC test, the Authors assumed $G_{\text{min}} = 1$ MPa and $D_{\text{max}} = 18\%$, which provide a good match with the experimental results. Finally, the function $H(\gamma_c)$ is given by:
With $\gamma_R$ 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 $\gamma_R$, $A$, and $B$ for EPS samples with density ranging between 24 and 32 kg/m$^3$ and confining stress ranging between 0 and 60 kPa. Therefore, taking into account the different values of $\rho_{PUR}$ and confining stress of the RC tests, the Authors have obtained $A$, $B$, and $\gamma_R$, suitable for this laboratory experimentation, selected according to the good comparison with the experimental data. For $\gamma_R$ the back-analysis is considered more appropriate than the application of its definition (i.e. the strain where $G_{\text{max}}$ is halved), because half of $G_{\text{max}}$ has not been measured from all the tests. Values of $A$, $B$, and $\gamma_R$ are reported in Table 2. Based on these values, the correlation between the experimental and theoretical data (evaluated through MATLAB corr function) determines $R^2$ that is overall greater than 0.9. As an example, Fig. 8 shows the analytical-experimental comparison for samples 1A, 1B and 1C.

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

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

$$B(p'_{c}, \rho) = b_1(p'_{c})\rho_{\text{PUR}}$$

$$\gamma_R(p'_{c}, \rho) = c_1(p'_{c})\rho_{\text{PUR}} + c_2(p'_{c})$$

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

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

Table 2: Values of $A$, $B$ and $\gamma_R$ necessary to interpret the experimental results in terms of $G(\gamma_c)$ and $D(\gamma_c)$ curves according to the relations proposed by Romo 1995 for samples with density $\rho_{\text{PUR}}$ subjected to the confining stress $p'_{c}$

| Specimen | $\rho_{\text{PUR}}$ (kg/m$^3$) | $p'_{c} = 100$ kPa | $p'_{c} = 200$ kPa | $p'_{c} = 300$ kPa |
|----------|-------------------------------|-------------------|-------------------|-------------------|
| 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       |
\[ b_1(p'_c) = 6 \cdot 10^{-6}p'_c + 0.0053 \]  
\[ c_1(p'_c) = 8 \cdot 10^{-7}p'_c^2 - 4 \cdot 10^{-4} \cdot p'_c + 0.0286 \]  
\[ c_2(p'_c) = -3 \cdot 10^{-5}p'_c^2 + 1.78 \cdot 10^{-2} \cdot p'_c - 0.3311 \]  

Fig. 8  Fitting of the RC test results on specimen 1A (a), 1B (b) and 1C (c) using the relationships proposed by Osso and Romo (2011)
The derived analytical formulation is now applied to interpret the results of Koyama et al. (2021) and Golpazir et al. (2016). Figure 10 shows the comparison of the analytical curves, evaluated with the confining pressures and densities reported in the mentioned studies, and the related experimental results.

A good agreement can be observed between analytical and experimental results by Koyama et al. (2021) in terms of $G$ and $D$. However, the experimental results reported by Golpazir et al. (2016) are well fitted by the analytical curve only as in regard to $G$ in the shear strain range $\gamma_c > 10^{-1}\%$. The experimental value of $G_{\text{max}}$ is underestimated by analytical formulation. Finally, the experimental values of $D$ are not in good agreement with those obtained from the analytical formulation; note that the experimental points are not reported because damping derived by Golpazir et al. (2016) ranges from 11.5 to 38%.

Fig. 9 $B$ and $\gamma_R$ versus polyurethane specimen density $\rho_{\text{PUR}}$ at different values of confining pressure $p'_c = 100$ kPa (a), 200 kPa (b) and 300 kPa (c)
3 Finite element analysis of seismic response of soil injected with polyurethane

The effects of polyurethane injections on GSI are here investigated through finite element analyses performed on the site of Augusta (south–east coast of Sicily, Italy), where we find an extraordinary building of historical heritage: the Augusta Hangar. The structure was affected by damage attributable to earthquakes, which often occur in this area; it is considered as a target building for polyurethane-based GSI because an intervention into the soil for seismic protection would preserve its original aesthetics.

Dealing with a rigid structure, it is possible to decouple the soil-structure interaction problem and investigate the effects of the proposed GSI technique only through ground response analysis, as the surficial ground acceleration directly affects the inertial forces acting on the structure.

In the last few years, the area has been studied by several researchers because of its high seismic risk; specifically, geotechnical data deriving from detailed in situ and laboratory tests are available (Cavallaro et al. 2018; Lentini et al. 2019). After a summary of the previous soil characterisation and the general description of the adopted numerical model, we discuss how to simulate the effects of polyurethane injections and introduce the properties of pure polyurethane derived from the previous section.

3.1 Soil properties of the test site

A detailed static and dynamic characterisation (Lo Presti et al. 1999a, b; Cavallaro et al. 1999, 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 tests (Oedometer Tests, Direct Shear Tests, Consolidated Drained Triaxial Tests, Undrained Triaxial Tests, Cyclic Loading Torsional Shear Tests, Resonant Column Tests) have been carried out.

The stratigraphic profile, deduced by the available boreholes, shows four main geotechnical units which are, from the surface to the depth: sandy silt (Layer 1), clayey silt (Layer 2), silty clay (Layer 3) and grey clay (Layer 4). The soil profile considered 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 from each geotechnical unit allowed to obtain the $G/G_{\text{max}} - \gamma_c$ and $D - \gamma_c$ curves, shown in Fig. 11b. Cavallaro et al. (2018) also report that the soil strength parameters ($c’$, effective cohesion, $\phi’$, friction angle) vary in the ranges $c’ = 15–28$ kPa and $\phi’ = 17–23^\circ$.

3.2 Numerical model

Finite elements analyses of ground response are performed through OpenSees software (Mazzoni et al. 2006), together with GID for graphic interface (Papanikolaou et al. 2017; Coll et al. 2018). Figure 12a shows the soil model, which consists of a regular hexahedron with length 1 m, width 1 m and height 70 m, according to the position of the bedrock reported by Cavallaro et al. (2018); moreover, it is horizontally divided into four zones, based on the soil’s stratigraphy described in Sect. 3.1. The domain is discretised into 3D StandardBrick 8-node elements, each node having three degrees of freedom (DOF).

Analyses are conducted in two phases: first a static phase, during which the self-weight is applied; then a dynamic phase, when the response of the soil to a base input is studied. Specifically, we study the response to the 1990 Santa Lucia earthquake, recorded at Sortino (25 km from Augusta), suitably scaled to give a peak ground acceleration coherent with a high-risk area.

The base nodes of the model are fixed in the vertical direction; this boundary condition, together with a point dashpot applied to a corner base node allows us to model a viscous-elastic bedrock. The input is applied as a point viscous force, following the methodology suggested by Joyner and Chen (1975); a uniform base shaking is then simulated through a planar
master–slave condition among the base nodes. These features are illustrated in Fig. 12b. For a pure shear analysis, the nodes in the domain’s vertical faces are also tied together through a master–slave condition involving all the DOFs.

Since the soil is mainly cohesive, its mechanical behaviour is modelled through the “Pressure Independent Multi Yield” (PIMY), proposed by Parra (1996), Yang et al. (2003) and Elgamal et al. (2003); the frequency-dependent Rayleigh approach is then adopted to account for the soil’s damping (Chopra 2011). The PIMY model has three main characteristics: (i) the material non-linearity, through a specific law relating the generic octahedral stress $\tau$ and strain $\gamma_c$; (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 $\tau_f$ with $p’$. All of this can be expressed by the following equations:

$$\tau = \frac{G \cdot \gamma_c}{1 + \frac{\gamma_c}{\gamma_{ref}} \left( \frac{p’_{ref}}{p’} \right)^d} \quad (7a)$$

$$G = G_{ref} \left( \frac{p’}{p’_{ref}} \right)^d \quad (7b)$$

$$\tau_f = \frac{2\sqrt{2} \sin \varphi’}{3 - \sin \varphi’} p’ + \frac{2\sqrt{2}}{3} c’ \quad (7a)$$

where $G_{ref}$ and $\gamma_{ref}$ are respectively the shear modulus and the octahedral strain referred to the reference pressure $p’_{ref}$. The parameters of Eqs. (7) are derived from the comparison

---

**Fig. 12** Overview of the FE numerical modelling. **a** 3D Mesh; **b** Details on the modelling of the viscous—elastic bedrock and the seismic input.
with the available experimental data, i.e. the shear modulus decay curves and the shear wave velocity profile shown in Fig. 11. Values are reported in Table 3.

Figures 13a and b show the goodness of the parameters used for numerical modelling. According to the soil’s properties, the maximum height of the adopted 3D finite element is 1 m, adherent to the relation reported in Lysmer and Kuhlmeyer (1969); the analyses are finally performed with a time step of 0.005 s, which satisfies the Courant-Friedrich-Lewy relation (Courant et al. 1967) discussed by LeVeque (2007), which ensures numerical stability, based on the mesh discretisation and the shear wave velocity.

### 3.3 Simulation of the intervention in post-expansion configuration

Polyurethane injections are realised underneath the foundations of existing buildings in perforations of diameter $d_0$, involving several metres in depth; here, the injected isocyanate-polyol mixture (liquid) expands with the pressure $p_{\text{exp}}$. For our analyses, the target soil has mainly a low permeability and the polyurethane can be therefore assumed to expand by poorly permeating the soil (Sabri and Shashkin 2018). When the expansion pressure $p_{\text{exp}}$ is greater than the soil’s confinement $p_0$, radial displacements are observed in the confining soil, by obtaining pure polyurethane cylinders of diameter $d_{\text{PUR}}$ in the post-expansion configuration. The closed-form solutions for cavities expanding in an elastic–plastic medium,
formulated by Carter et al. (1986) and Yu and Houlsby (1991), are here applied to estimate the polyurethane cylinders’ diameter \(d_{\text{PUR}}\), \(f\)-times larger than \(d_0\), being \(f\) a factor depending on the involved pressures \(p_{\text{exp}}\) and \(p_0\), the soil’s strength parameters (friction angle \(\varphi'\), effective cohesion \(c'\) and dilatancy angle \(\psi\)) and deformability parameters (Young modulus \(E\), shear modulus \(G\) and Poisson ratio \(\nu\)), as well as the cavity shape (shape factor \(m\)):

\[
d_{\text{PUR}} = d_0 \cdot f(p_{\text{exp}}, p_0, c', \varphi', \psi, E, G, \nu, m)
\]

Table 4 Results of polyurethane density, expansion pressure and diameter evaluated according to Yu and Houlsby (1991) and Dei Svaldi et al. (2005)

| \(h_{\text{PUR}}\) (m) | \(m_{\text{PUR}}\) (kg) | \(m_{\text{PUR}}\) (kg) | \(p_{\text{exp}}\) (kPa) | \(p_{\text{exp}}\) (kPa) | \(d_{\text{PUR}}\) (m) | \(d_{\text{PUR}}\) (m) |
|---|---|---|---|---|---|---|
| 3 | 10 | 15 | 313.45 | 324.71 | 0.20 | 0.24 |
| 4 | 10 | 15 | 336.22 | 348.47 | 0.19 | 0.23 |
| 5 | 10 | 15 | 356.63 | 369.81 | 0.19 | 0.23 |

For sake of simplicity, the explicit formulation for \(f\) is here omitted, but can be found in Yu and Houlsby (1991), Dei Svaldi et al. (2005) and Nowamooz (2016). From \(d_{\text{PUR}}\), the cylinders’ volume and accordingly the density \(\rho_{\text{PUR}}\) is evaluated, the latter depending on the injected mass \(m_{\text{PUR}}\). However, the polyurethane density \(\rho_{\text{PUR}}\) is not only the output of the abovementioned formulation, but also the input for the evaluation of the expansion pressure \(p_{\text{exp}}\) through the experimentally derived relationship proposed by Dei Svaldi et al. (2005):

\[
p_{\text{exp}} = 240 \cdot e^{3.63 \cdot 10^{-2} \rho_{\text{PUR}}}
\]

\(p_{\text{exp}}\) is in kPa and \(\rho_{\text{PUR}}\) in kg/m³. Since \(p_{\text{exp}}\) allows us to compute \(f\), a trial value of \(\rho_{\text{PUR}}\) is first assumed to start a convergence procedure which ends when a small difference (~0.1 kg/m³) is observed between the trial and the output density. With the final \(\rho_{\text{PUR}}\) the dynamic properties of the pure polyurethane are evaluated, also depending on the soil confinement \(p_0\).

Six analysis cases are here analysed, assuming three thicknesses for the injected soil layer, \(h_{\text{PUR}}\) = 3, 4 and 5 m, and two hypothetic polyurethane masses for each metre of injection thickness, i.e. \(m_{\text{PUR}}\) = 10 kg and 15 kg; in both cases, the values are selected from the application ranges suggested by Master Builders Solutions, one of the companies realising the polyurethane injections. The confining pressure \(p_0\) changes according to the injected thickness \(h_{\text{PUR}}\), while the masses \(m_{\text{PUR}}\) govern the density. Table 4 summarises the values of \(\rho_{\text{PUR}}, p_{\text{exp}}, \text{and } d_{\text{PUR}}\) obtained at the end of the convergency procedure.

The analytical formulation derived in Sect. 2.4 is applied with the reported \(p_0\) and \(\rho_{\text{PUR}}\) to deduce the \(G-\gamma\) and \(D-\gamma\) curves illustrated in Fig. 14 to be assigned to the cylinders of pure polyurethane; it can be seen that the dynamic behaviour is linear up to 2%.

An important aspect to take into account is the increase in the effective pressure of the soil surrounding the polyurethane cylinders, because of the expansion pressure \(p_{\text{exp}}\). This can be considered by updating the small-strain shear modulus of the soil through the simple Hardin and Black (1969) formulation, adding \(p_{\text{exp}}\) to \(p_0\) with the
soil’s type-dependent parameters derived from \( G_0 \) coming from the \( V_s \) profile. The updated soil’s small-strain shear modulus is referred to as \( G_{0,\text{soil}} \) in the following.

In the final post-expansion configuration, the injected layer is made up of soil and pure polyurethane; for the dynamic behaviour of the composite, we refer to the RC results obtained from layered polyurethane-soil specimens by Gatto et al. (2019), which highlighted that the polyurethane mainly affects the small-strain properties of the composite, according to its properties and volumetric percentage, while the non-linear behaviour of the composite is mostly governed by the soil. The latter consideration appears consistent with the results of Fig. 14. Based on these results, Gatto et al. (2021b) derived a formulation to compute homogenised small-strain properties for the soil-polyurethane composite, depending on the small-strain soil properties (\( G_{0,\text{soil}} \) and \( D_{0,\text{soil}} \)) and polyurethane properties (\( G_{0,\text{PUR}} \) and \( D_{0,\text{PUR}} \)), as well as the polyurethane volumetric percentage \( Q_{\text{PUR}} \). The injected layer made up of soil and polyurethane cylinders can be therefore replaced by soil of modified small-strain properties (\( G_{0,\text{homo}} \) and \( D_{0,\text{homo}} \)), according to the abovementioned relations:

\[
G_{0,\text{homo}} = G_{0,\text{soil}} \cdot e^{-\ln(G_{0,\text{soil}} / G_{0,\text{PUR}})Q_{\text{PUR}}}
\]  

\[
D_{0,\text{homo}} = D_{0,\text{soil}} + Q_{\text{PUR}} \cdot (D_{0,\text{PUR}} - D_{0,\text{soil}})
\]

In our analyses, four polyurethane cylinders are present in the soil domain by assuming centre distances of injection 0.5–0.75 m. In such a way, \( Q_{\text{PUR}} \) is equal to \( \pi d_{\text{PUR}}^2 \). For the unit weight, a linear homogenisation of the properties is assumed. Table 5 summarises the parameters evaluated according to what has been described. Note that the first layer of our stratigraphy is three metres thick and the assumptions of \( h_{\text{PUR}} = 4 \) and 5 m also involves the modification of the second layer; \( G_{0,\text{soil}} \) and \( G_{0,\text{homo}} \) present two values, one referred to the first layer and the other to the second layer rate.
3.4 Numerical analyses results and discussion

The results obtained from the numerical analyses are shown in terms of time histories of the horizontal surficial acceleration evaluated in the central node (Fig. 15), maxima of horizontal accelerations varying with depth in the central nodes (Fig. 16) and the amplification functions, computed by dividing the Fourier spectra of the top and base time histories of horizontal accelerations (Fig. 17).

Figure 15 shows that the maximum of surficial acceleration is reduced when the modified soil is modelled, meaning that the soil improvement here considered, resulting in a soil stiffening, is beneficial for the ground response. For the original soil, the maximum acceleration is 2.61 m/s²; reductions therefore range from 17.6 to 20.7%. The best seismic improvement is achieved when a minor polyurethane mass is injected, as a result of the lower density for the hardened polyurethane. Moreover, a better performance of the polyurethane-based GSI is found when a whole layer is modified with the effect of polyurethane injection and expansion.

From Fig. 16, a reduction of the maximum acceleration is seen up to 25 m. Finally, in the frequency domain a general reduction of the amplification is observed for the first natural frequencies (Fig. 17).

Table 5 Summary of the material properties used for the numerical analysis accounting for the polyurethane injection

|            | \(h_{\text{PUR}}=3 \text{ m} \) (\(p_0=32.04 \text{ kPa}\)) | \(h_{\text{PUR}}=4 \text{ m} \) (\(p_0=42.72 \text{ kPa}\)) | \(h_{\text{PUR}}=5 \text{ m} \) (\(p_0=53.40 \text{ kPa}\)) |
|------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|
|            | \(m_{\text{PUR}}=10 \text{ kg}\) | \(m_{\text{PUR}}=15 \text{ kg}\) | \(m_{\text{PUR}}=10 \text{ kg}\) | \(m_{\text{PUR}}=15 \text{ kg}\) | \(m_{\text{PUR}}=10 \text{ kg}\) | \(m_{\text{PUR}}=15 \text{ kg}\) |
| \(G_{0,\text{PUR}}\) (MPa) | 27.08 | 28.05 | 30.94 | 32.06 | 34.73 | 36.02 |
| \(D_{0,\text{PUR}}\) (%) | 8.61 | 8.91 | 8.39 | 8.70 | 8.27 | 8.57 |
| \(Q_{\text{PUR}}\) (-) | 0.13 | 0.19 | 0.12 | 0.17 | 0.11 | 0.16 |
| \(G_{0,\text{soil}}\) (MPa) | 401.34 | 409.29 | 417.59 | 426.63 | 432.76 | 442.88 |
| \(G_{0,\text{homo}}\) (MPa) | 282.68 | 245.95 | 305.58 | 274.76 | 327.90 | 296.43 |
| \(D_{0,\text{homo}}\) (%) | 3.88 | 4.27 | 3.80 | 4.12 | 3.73 | 4.04 |
| \(\rho_{\text{homo}}\) (kg/m³) | 1750 | 1653 | 1769 | 1690 | 1788 | 1709 |

The results are prominent and remark that the soil improvement technique based on polyurethane injections also allows to improve the seismic performance in the ground response. The beneficial effects can be transferred directly into buildings by neglecting the soil-structure interaction for rigid structures. The latter are the most common types among the monuments of historical heritage, to which our proposed GSI technique is finalised for the prevention of aesthetic damage during seismic retrofit. The most studied GSI techniques based on different material (e.g. rubber-soil mixture, PVC, pebbles) are thought to be placed under new buildings and have shown their effects mainly on flexible structures, since the mechanism is sliding and rocking. Further analyses will be done to investigate if/when polyurethane injections can be effective even for the improvement of the seismic performance of flexible structures, through analyses involving the soil-structure interaction.
Fig. 15  Comparison of the surface accelerations among ‘no injections’ and with polyurethane inclusions of heights $h_{PUR} = 2$, 3 and 4 m, resulting after the injection of masses $m_{PUR} = 10$ and 15 kg for injection level. The peak ground acceleration evaluated in the original soil is $2.61 \text{ m/s}^2$.

Fig. 16  Profile of maximum horizontal accelerations evaluated in nodes of the central vertical for the six analysed cases.
4 Conclusions

This article shows a detailed study on GSI based on polyurethane injections, referring to interventions realised in low permeability soils, where the injected polyurethane does not permeate, and its 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 pressures, 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 summarised as follows.

- The trend of $G$ and $D$ with $\gamma_c$ is similar the one of the soil: $G$ decreases while $D$ increases, as the shear strain level increases.
- The maximum value of the shear modulus $G_{\text{max}}$ is influenced by both the polyurethane density and the confining pressure. With reference to $\rho_{\text{PUR}}$, the results confirm the linear dependence shown in literature. An increase in confining pressure results in an increase in stiffness, with a less noticeable improvement towards high cell pressure.

Fig. 17 Amplification functions evaluated from the Fourier spectra of the time histories recorded in the top and base central nodes

![Graphs showing amplification functions for different $h_{\text{PUR}}$ values](image)
• Even the minimum value $D_{\text{min}}$ of the damping ratio is influenced by density and confining pressure; in particular, $D_{\text{min}}$ increases with the density, while it decreases with the cell pressure.

The efficiency of the GSI based on polyurethane injections was then evaluated at a large scale, with 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 depending on the volume of the soil modified with the inclusions and the injected mass. 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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**Declarations**

**Conflict of interest** The authors have not disclosed any competing interests.

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