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Use of rubberised backfills for improving the seismic response of Integral Abutment Bridges

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Abstract:	<p>Reuse of the 1.5 billion waste tyres that are produced annually is a one of the major worldwide challenges, as waste tyres are toxic and cause pollution to the environment. In recognition of this problem, this paper introduces the reuse of tyres, in the form of derived aggregates in mixtures with granulated soil materials, as previous studies indicated the potential benefits of these materials in the seismic performance of structures. The objective of the present research study is to investigate whether use of rubberised backfills benefits the seismic response of Integral Abutment Bridges (IABs) by enhancing soil-structure interaction (SSI) effects. Numerical models including typical integral abutments on surface foundation with nonlinear conventional backfill material and its alternative form as soil-rubber mixtures are analysed and their response parameters are compared. The research is conducted on the basis of parametric analysis, which aims to evaluate the influence of different rubber-soil mixtures on the dynamic response of the abutment-backfill system under various seismic excitations, accounting for dynamic soil-abutment interaction. The results provide evidence that the use of rubberised backfill leads to reductions in the backfill settlements, the horizontal displacements of the bridge deck, the residual horizontal displacements of the top of the abutment and the pressures acting on the abutment, up to 55%, 18%, 43% and 47% respectively, with respect to a conventional backfill comprising of clean sand. Considerable amount of decrease in bending moments and shear forces on the abutment wall is also observed. Therefore, rubberised backfills offer promising solution to mitigate the earthquake risk, towards economic design with minimal damage objectives for the resilience of transportation networks.</p>
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1 Use of rubberised backfills for improving the seismic response of Integral 2 Abutment Bridges

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29 structure interaction

30 1. Introduction

31 More than 3 million tons of waste tyres are produced annually in Europe only, whilst billions of tyres are
32 produced annually worldwide. End-of-life tyres are usually disposed in landfills, stockpiles and abandoned in
33 the nature, imposing major threats to societies and environment. It is only very recently that waste tyres are

used in engineering applications, towards sustainable structures, reducing at the same time the stockpile quantities of the toxic tyres. Among sustainable solutions in construction industry, tyre shreds have been previously used as separate layers or mixtures with granulated soil materials such as sand or gravel. The use of rubber-soil mixtures was found to be a beneficial solution for foundations, embankments, backfilling in retaining walls and other geotechnical works as per Hall (1991), Edeskar (2006), Karmokar (2007), Ravichandran and Huggins (2014). In particular, tyre derived aggregates have been found to have high shear resistance, low shear modulus (Humphrey and Manion, 1992; Youwai and Bergado, 2003), controllable stress-strain behaviour and increased damping. These unique properties are ideal in geotechnical design, foundations of structures and infrastructures subjected to dynamic loads because: (1) both the mass of the soil and hence the inertial loads are reduced due to lightweight material and (2) the tyre derived aggregates have smaller permanent deformations compared to earth materials under dynamic loading, resulting to lower residual displacements. Thus, rubber-soil mixtures for foundations are expected to offer ground motion attenuation, to promote a new dynamic isolation scheme for structures and consequently, to mitigate efficiently the earthquake risk (Tsang et al. 2012; Pitilakis et al. 2015). The dynamic properties and strength characteristics of rubber-soil mixtures can be adjusted through the percentage of rubber content for different design applications (Senetakis et al. 2012a, b; Anastasiadis et al. 2012; Pistolas 2015).

A potential application of rubber-soil mixtures is for backfilling material in the approach embankments of IABs, which suffer from interaction effects due to both thermal and seismic loads (England et al. 1995; Shamsabadi et al. 2007; Bloodworth et al. 2012; Mitoulis et al. 2015; 2016). In particular, the response of IABs is affected by the interaction between the abutment, foundation and backfill, which involves relative displacement and soil stress-strain behaviour due to the lateral earth pressures. This interaction causes settlements or heaving of the backfill and ratcheting of the soil resulting in overstressing of the abutment (Figure 1). Additionally, a common result is the bump-at-the-end of the bridge, leading to discomfort and potentially unsafe driving conditions (Briaud et al. 1997). The effect of the abutment-backfill interaction in the dynamic response of bridges has been addressed in several studies (Shamsabadi et al. 2007, 2013; Kotsoglou and Pantazopoulou 2007, 2009; Aviram et al. 2008; Mitoulis 2012; Erhan and Dicleli 2015, among others). To mitigate the aforementioned interaction effect different seismic performance improvement methods have been proposed such as mechanical stabilisation of backfills (Horvath 2010), the use of expanded polystyrene behind the abutment (Hoppe 2005; Pötl and Naumann, 2005), and more recently, the use of compressible inclusions that contain reused tyre-derived aggregates (Mitoulis et al. 2016). However, the aforementioned papers provide compressible inclusions as a means to isolate the abutment from the backfill soil in combination with a mechanically stabilised soil. Yet, the backfill material remains conventional, as opposed to the rubberised soil that is proposed in this paper, which offers benefits such as smaller residual deformations and smaller self-weight.

Figure 1. (a) Initiatory abutment position, (b) Expansion of the bridge and heaving of the backfill, (c) Contraction of the bridge and settlements, (d) Final position of the abutment.

In this paper, a feasibility assessment is conducted, to demonstrate the advantages of backfills comprising of optimised sand and granulated rubber mixtures. To this end, a two dimensional (2D) numerical model including a typical integral abutment on surface foundation with the backfill and foundation soil is introduced. A parametric analysis is performed to evaluate the influence of different rubber-soil mixtures in the dynamic response of the abutment-backfill system under various earthquake excitations. Nonlinear time-history analyses are carried out for comparison of analysis results of different rubber-soil mixtures with their conventional counterpart under the selected suite of ground motion records. Residual displacements of the backfill materials, displacement at the top of the abutment, variation of earth pressure and internal forces are critical for the performance assessment of IABs, which primarily affect the design perspective and prospected maintenance cost of the IABs during the service life. In this context, the application of rubberised backfills addresses two challenges, i.e. the reuse of tyres towards environmental protection and the mitigation of seismic interaction effects on IABs, towards economic design and minimal damage.

2. Numerical modelling

2.1 Integral abutment-backfill model

A typical integral abutment of a height of 8.5 m on surface foundation is considered, as shown in Figure 3a. The transverse dimension of the abutment is 13.0 m. All the analyses considered a unit transverse dimension of 1.0 m (unit width), thus all properties and results are given per metre. The abutment is made of reinforced concrete of strength class C30/37 (EN 1992-1-1, 2004), with unit weight of 25.0 kN/m³, modulus of elasticity 30.0 GPa and Poisson ratio 0.30. The abutment is presumed to respond in the elastic range where the

nonlinear response of the wall is beyond the scope of this research study. The deck is considered prestressed and thus uncracked, having stiffness substantially greater than the one of the abutment wall. Hence, it is assumed that the deck restrains the rotation of the abutment top, whilst it is also considered that the stiff wing walls are not connected monolithically to the abutment. The aforementioned fixity is modelled through a vertical beam element with fixed ends, embedded at the top of the abutment as shown in Figure 3b. A linear elastic fixed-end anchor (equivalent to a linear spring element) is applied on the abutment stem to model the contribution of the bridge deck stiffness under longitudinal translational movements. The elastic axial stiffness of the anchor EA , is set equal to $2.6E+07$ kN per unit width of the abutment. Given the substantial number of the time history analyses that were conducted for this study, it was considered that the representation of the bridge stiffness by a linear spring element is adequate, as the computation cost to analyse the entire bridge system, i.e. both abutments and backfill, would be significantly higher. The 2D finite element code PLAXIS ver.8.2 (2008) is used in order to build the abutment-backfill numerical model. The entire bridge system was also analysed to validate the abutment-backfill system model. In particular, the validation of the 2D abutment-backfill model was based on its comparison with the entire bridge model on the basis of (i) displacements of abutment top at the maximum seismic displacement and (ii) the soil pressure distributions along the height of the abutment. The results showed that the simplified abutment-backfill model reproduced accurately the response of the entire bridge model. Results are not presented herein due to length limitations.

The abutment is founded at a depth of 3.5 m from the ground surface on a 6.0 m long spread footing. Stability checks were performed and the abutment was found to fulfil the requirements of Eurocode 7 (EN 1997-1, 2004) and Eurocode 8-5 (EN 1998-5, 2004). The 30.0 m deep foundation soil deposit beneath the footing of the abutment consisted of medium stiffness clay. It is classified as ground type C according to Eurocode 8-1 (EN 1998-1, 2004) with unsaturated weight per unit volume 19.0 kN/m^3 , Poisson ratio 0.35 and undrained shear strength c as given in Table 1. The variation of undrained shear strength and shear wave velocity with depth is give in Figure 2.

The conventional backfill behind the abutment is a compacted sand with weight per unit volume 18.5 kN/m^3 , angle of friction 42° , dilatancy angle 10.9° and Poisson ratio 0.43. The selection of the parameters is based on experimental testing and the literature (Pistolas 2015). In order to account for the soil nonlinear behaviour for the low to medium strain range, the parameters of the shear modulus and damping were estimated from one dimensional equivalent linear analyses (Argyroudis et al. 2013a; Pitilakis et al. 2013). For higher strain levels the effect of nonlinearity is accounted for through the Mohr-Coulomb yield criterion, which is adopted in the 2D numerical model for both the foundation and backfill soil. The specific model is commonly used by researchers (e.g. Evangelista et al., 2010; Callisto et al., 2010; Argyroudis et al., 2013a) and practitioners due to its easy calibration and control. The soil material damping is introduced in the form of Rayleigh damping coefficients, which were estimated for the frequency interval that includes the fundamental frequency of the soil-backfill. The effect of pore water pressures in the foundation and the backfill soil is not taken into account. The soil properties are summarised in Table 1.

126 **Table 1.** Properties of the foundation soil and conventional backfill materials.

		weight		undrained		
		per unit	Poisson	shear	shear wave	maximum
	depth	volume	ratio	strengthc	velocity	shear modulus
	z (m)	γ (kN/m ³)	v	(kN/m ²)	V _s (m/s)	G _{max} (kN/m ²)
conventional						
backfill soil	8.5	18.5	0.43	0.01	269.0	136219.0
(17 layers)						
foundation soil (10 layers)	3.0	19.0	0.35	50.0	180.0	62752.0
	6.0	19.0	0.35	78.5	210.0	85413.0
	9.0	19.0	0.35	92.8	225.0	98050.0
	12.0	19.0	0.35	107.0	240.0	111560.0
	15.0	19.0	0.35	121.3	255.0	125940.0
	18.0	19.0	0.35	135.5	265.0	136012.0
	21.0	19.0	0.35	149.8	280.0	151845.0
	24.0	19.0	0.35	164.0	290.0	162885.0
	27.0	19.0	0.35	178.3	300.0	174312.0
	30.0	19.0	0.35	192.5	310.0	186126.0

129 **Figure 2.** Variation of the undrained shear strength (a) and shear wave velocity (b) of the foundation subsoil with depth.

130 The numerical model built in PLAXIS is discretised in a total number of 2682 15-node triangular elements, as
131 shown in Figure 4. In the vicinity of the abutment, the mesh is refined and satisfies the condition for the
132 maximum element size (Kuhlemeyer and Lysmer, 1973). In particular, the average element dimensions are
133 4.5 m by 3.0 m in the foundation soil and 1.5 m by 0.5 m in the vicinity of the abutment. The longitudinal
134 dimension of the entire model is equal to 250.0 m, and was properly selected in order to minimise the
135 boundary effects (Visone et al. 2008). The foundation soil is discretised into 10 layers of 3.0 m thickness,

while the backfill soil is discretised into 17 layers of a thickness 0.5 m each. The base of the model is assumed to be rigid and the lateral sides are characterised by absorbent boundaries. Interface elements are introduced to model the friction and detachment between the backfill and the abutment, as well as the sliding and detachment between the abutment footing and foundation soil. In particular, the interface is characterised by a friction coefficient ($R_{inter}=0.70$) allowing relative movement between the soil and the structure.

Figure 3. (a) Geometry of the analysed integral abutment and (b) the numerical model in the vicinity of the abutment.

Figure 4. The 2D numerical model of the integral abutment with the backfill soil.

2.2 Dynamic loading

The model is subjected to earthquake ground motions. The seismic excitation is applied uniformly at the base of the numerical model, which corresponds to outcropping bedrock, in the form of prescribed displacements, and it corresponds to vertically propagating shear waves. At the same time the dynamic motion that excites horizontally the integral abutment is applied on the abutment top. This dynamic motion simulates the longitudinal response of the entire bridge due to the earthquake excitation. This longitudinal response of the bridge system was defined by the response of an equivalent single degree of freedom (SDOF) model, including the abutment-backfill stiffness and damping (radiation and hysteretic material) based on the research of Mylonakis et al. (2006). This model takes into account the kinematic and inertial interaction of the abutment-foundation-backfill system. The response of the bridge system is imposed as a force time history acting horizontally and in plane, on the top of the abutment. For all the analyses, the initial geostatic stresses

and the construction stages of the abutment and the backfill were modelled as per Argyroudis et al. (2013b) and Mitoulis et al. (2016).

3. Parametric study

3.1 Backfill properties

Three different backfill materials are examined; the conventional, as per the representative backfilling material, which is common in European bridges, and two rubber-soil mixtures with varying percentage of rubber content. The conventional backfill is non-cohesive soil comprising of dry river sand. The rubberised soil comprised of sand and recycled rubber in varying proportions per weight. The rubber content is in the form of granulated rubber produced by mechanically shredded waste tyres. Mixtures of composition 90% sand and 10% rubber (referred here as 90-10) or 70% sand and 30% rubber (referred here as 70-30) by weight are considered in this study. Their mechanical and dynamic properties were obtained by a series of laboratory tests, including torsional resonant column and cyclic triaxial tests in wide range of shear strain amplitudes. The tests have been conducted in the Laboratory of Soil Mechanics, Foundation and Geotechnical Earthquake Engineering at Aristotle University of Thessaloniki (Senetakis et al. 2012a, b; Anastasiadis et al. 2012; Pistolas 2015). The rubber particles in the mixtures that were tested in the laboratory, and to which the present study refers, was a granular material with diameter ranging from 0.43 to 2.00 mm, diameter ratio $D_{50}=1.55$, mass density equal to 6.0 kN/m^3 and Poisson ratio equal to 0.5 (Pistolas 2015). The properties of the three backfill soil materials are summarised in Table 2.

Two zones of improved rubberised backfill soil are examined to identify their influence on the dynamic response of the IAB. These analyses reveal to what extent the improvement influences the seismic actions on the abutment, i.e. pressures and internal forces on the structural components of the abutment and the deformations of the backfilling material. First a large improvement zone having length equal to half of the dimension of the numerical model (i.e. 125.0 m) is analysed. Then, a second model with smaller improvement zone of length equal to twice the height of the abutment, i.e. 17.0 m, is investigated. General recommendations for the use and placement of tyres in civil engineering applications are given in the literature (e.g. Eldin and Senouci 1992; Humphrey 2011). Based on the preparation procedure in the laboratory testing it is recommended to install the material in layers of relatively small thickness (e.g. 300-500mm) and compact them thoroughly by a road roller with gradually increased passes from the bottom to top layers, to ensure a uniform compaction of all layers.

3.2 Seismic input motion

Five actual acceleration recordings from different earthquakes, scaled to peak ground acceleration of 0.3 g, are used for the dynamic analyses as input motion (Table 3). All of them were recorded to soil conditions similar to ground type A (rock) or B (stiff soil) according to Eurocode 8-1 (EN 1998-1, 2004), varying in amplitude, frequency content and significant duration of the seismic excitation. The ground motions were selected so as

190 their mean spectrum to match the EC8-1 spectrum for ground type A in the range 0.15-0.40 s as shown in
 191 Figure 5. The fundamental period of the abutment-backfill systems (i.e. 0.15-0.30 s) falls within this region.

192 **Table 2.** Material properties of the conventional and rubberised backfills.

	weight per unit volume γ (kN/m ³)	undrained shear strength c (kN/m ²)	friction angle ϕ (°)	dilatancy angle ψ (°)	Poisson ratio ν	shear wave velocity V_s (m/s)	normalised shear modulus $G/G_{\max}$	damping ratio D (%)
Conventional backfill	18.5	0.01	42.0	10.9	0.43	269.0	0.75	12.0
backfill 90-10	17.5	30.0	34.0	4.3	0.36	218.0	0.70	5.0
backfill 70-30	15.5	37.0	25.6	2.8	0.39	155.0	0.65	7.0

193

194 **Table 3.** Selected earthquake ground motions.

earthquake	station	magnitude M_w	PGA (g)	fundamental period T_0 (sec)
Parnitha, Greece, 09/07/1999	Athens 4 (Kipseli) ¹	6.0	0.12	0.43
Kozani, Greece, 05/13/1995	ST1320, Prefecture building ²	6.5	0.14	0.35
Aigio, Greece, 06/15/1995	Telecommunication building ²	6.5	0.54	0.48
Friuli, Italy, 05/06/1976	ST20, Tolmezzo-Diga Ambiesta ¹	6.4	0.32	0.27
Montenegro, former Yugoslavia, 04/15/1979	ST64 ²	6.9	0.18	0.55

195 ¹: SHARE database (Giardini, 2013), ²: European Strong Motion Database (ESD)

Figure 5. Elastic response spectra of the selected records and their mean spectrum in correlation to the Eurocode 8 elastic response spectrum for ground type A, all scaled to $PGA=0.3g$.

4. Results and discussion

The potential benefits of the rubberised backfills is primarily indicated by the response of the backfill in terms of vertical residual displacements (settlements) at the approach area to the bridge, as well as by the response of the abutment in terms of residual displacements and rotations. The pressures and the forces on the abutment wall are also evaluated as they influence the design of the abutment and the foundation.

4.1 Displacements of the backfill

Residual displacement of the backfill is related to ratcheting effect, thus is considered to be an important parameter that affects the long-term sustainability of the abutment. It is correlated to the long-term in-service conditions of the bridge, as well as to the immediate access for emergency vehicles following a strong earthquake. Therefore, residual displacement is required to be minimised in order to achieve a near-zero-downtime for maintenance or repair of the abutment-backfill system. The displacements presented herein are obtained for a distance up to 10.0 m from the abutment.

Figure 6 and Figure 7 illustrate the residual vertical displacements in the conventional (black line) and the two rubberised backfills (green line for backfill 90-10 and red line for backfill 70-30) for the Parnitha (Greece) earthquake motion. In the conventional backfill, settlements are developed up to a distance of approximately 2.0 m from the abutment, while swelling develops at larger distances. The maximum observed settlement is 29.0 mm behind the abutment. On the contrary, the rubberised backfills prevented the soil settlements and exhibited swelling at a distance up to 5.0 m from the abutment with maximum values ranging from 10.0 mm and 5.0 mm, respectively. The backfill remains undisturbed at larger distances.

218 It is noteworthy that the residual vertical displacements are practically insensitive to the length of
 219 improvement, as shown in Figure 6. In particular, the maximum swelling in the backfill 90-10 is 9.0 mm and
 220 10.0 mm for improvement lengths of 125.0 m and 17.0 m respectively (dashed vs. continuous green line). In
 221 the backfill 70-30 the maximum swelling is 3.0 mm and 5.0 mm for improvement lengths of 125.0 m and 17.0
 222 m respectively (dashed vs. continuous red line). Similar results are obtained for all the earthquake records.
 223 Therefore it is concluded that soil improvement in a distance equal to twice the height of the abutment, i.e.
 224 17.0 m, is effective and sufficient to mitigate the disturbance of the backfill under seismic loading. Thus, the
 225 results presented hereafter are referred to this length.

226 Figure 8 shows the mean plus and minus one standard deviation of the residual vertical displacements at the
 227 backfill surface for the five earthquake records analysed. The backfill behind the conventional abutment
 228 exhibits settlements in the range of 24.0 to 62.0 mm, while at larger distances the soil exhibits either
 229 settlements or swelling, with the latter being maximised at a distance equal to 4.0 m. On average, the residual
 230 deflection of the conventional backfill is found to be either a swelling of 40.0 mm or a settlement of 12.0 mm.
 231 On the contrary, the rubberised backfills exhibit slight swelling and negligible settlements (green and red
 232 lines).

233 **Figure 6.** Residual vertical displacements of the backfill surface after the Parnitha (Greece) seismic motion.

Figure 7. Residual vertical displacements in the vicinity of the abutment after the Parnitha (Greece) seismic motion, in the (a) conventional backfill, (b) backfill 90-10, (c) backfill 70-30.

Figure 8. Mean plus and minus one standard deviation of residual vertical displacements of the backfill surface for the five earthquake records.

4.2 Displacements of the abutment

The displacement of the abutment induces stresses and strains to the bridge during an earthquake, which might affect the performance (i.e. loading and stresses) of the prestressed deck. This is depicted in Figure 9 that shows the horizontal displacements of the abutment top for an indicative seismic motion. The area of positive displacements denotes movements of the abutment towards the backfill. It was found that the abutment exhibits slightly larger displacements towards the rubberised backfills (8.0 mm and 7.0 mm for the backfills 90-10 and 70-30, respectively) than towards the conventional one (6.0 mm). This is attributed to the lower shear resistance provided by the flexible rubberised mixtures in comparison to the conventional sandy backfill (Senetakis et al. 2012a, b), minimising SSI effects. This remark is also validated by the larger pressures that are developed at the top of the abutment in the rubberised backfills, in comparison with the conventional one (Figure 11). On the other hand, rubberised backfills have a positive impact on the reduction of the maximum displacements introduced to the deck as depicted by the negative displacements in the graph of Figure 9, which correspond to movements of the abutment towards the center of the bridge. For the conventional backfill (black line), the abutment has a maximum displacement of 10.0 mm towards the center of the bridge, while the corresponding displacement is 9.0 mm and 6.0 mm for the backfills 90-10 and 70-30, respectively. The residual displacements on the top of the abutment, are found equal to 7.0 mm, 6.0 mm and 3.0 mm towards the center of the bridge in the conventional, 90-10 and 70-30 backfills, respectively. Similar results were obtained for the five seismic motions used in the analyses, indicating that displacements introduced to the deck are efficiently reduced with use of rubberised backfill materials. For these cases, the gap between the abutment and the backfill is expected to be smaller during, and at the end of, an earthquake. Such behaviour indicates a structure that is expected to sustain smaller damages, and consequently is more resilient.

260 Figure 10a shows the mean plus and minus one standard deviation of the residual horizontal displacements
 261 along the abutment for the analysed earthquake motions. For the conventional backfill, the abutment has a
 262 residual displacement towards the center of the bridge, ranging from 10.0 mm to 12.0 mm on average along
 263 the abutment (black curve), leaving a gap from the backfill. In the long term, soil flow to fill the gap develops
 264 (England et al. 1995) leading to irreversible deformation of the abutment and a gradual increment of the
 265 passive pressures acting on it. On the contrary, the application of the rubberised backfills leads to a larger
 266 residual deformation of the abutment towards the backfill, ranging from 5.0 mm to 30.0 mm on average along
 267 the abutment (green and red curves), eliminating the gap in between. Moreover, the shape of the curves in
 268 Figure 8a, indicates that in the rubberised backfills the translational response of the abutment is governing,
 269 while the rotational and bending deflection of the abutment is smaller. Figure 10b, c and d show an example
 270 of the residual displacement and rotation of the abutment in the conventional and improved schemes.

271 **Figure 9.** Absolute horizontal displacements of the top of the abutment during the Parnitha (Greece) seismic motion.
 272

Figure 10. (a) Mean plus and minus one standard deviation of horizontal residual displacements along the height of the abutment for the five earthquake records. Deformed shape of the abutment and the conventional (b), 90-10 (c) and 70-30 (d) backfills at the last step of the analysis for Parnitha (Greece) seismic motion showing the residual rotation at the footing (θ_{res}^{foot} equal to 0.08% for b and 0.10% for c and d) and the displacement at the top ($U_{x,res}^{top}$) of the abutment.

4.3 Earth pressures on the abutment

Figure 11a presents the mean plus and minus one standard deviation of residual total pressures for the five records, i.e. the residual post-earthquake pressures acting on the abutment. The maximum pressure in the conventional backfill (black curve) is as high as 241.0 kN/m², whereas in the rubberised backfills 90-10 and 70-30 is 167.0 kN/m² and 108.0 kN/m², respectively (green and red curves). The maximum mean residual pressure is reduced by 31% and 55% for the backfills 90-10 and 70-30 respectively, with respect to the conventional one. The residual pressures in the conventional backfill have a maximum standard deviation equal to 126.0 kN/m² while in the backfills 90-10 and 70-30 they have 96.0 kN/m² and 56.0 kN/m², respectively. This implies relatively lower variation of the pressures in the rubberised backfills, thus, reduced design uncertainty, and a more controlled stress condition on the aftermath of an earthquake event.

The mean, plus and minus one standard deviation, of maximum pressures along the height of the abutment are shown in Figure 11b, in form of an envelope of the maximum pressures developed along the abutment during the seismic excitation. In the conventional backfill the maximum pressure is found equal to 502.0 kN/m², while it is 360.0 kN/m² and 234.0 kN/m² in the backfills 90-10 and 70-30, respectively. Therefore, the rubberised backfills achieve a reduction of pressures of the order of 28% and 53%, respectively. The distribution of the pressures along the height of the abutment shows a more uniform shape for the increasing rubber content (red curve, 30% rubber) compared to the conventional backfill (black curve). This trend is more pronounced in Figure 11c, which illustrates the mean pressures at the time step of the peak ground acceleration. An efficient reduction of the pressures is again achieved in the rubberised backfills, as opposed to the conventional one.

(a)

(b)

(c)

Figure 11. Mean plus and minus one standard deviation of pressures along the abutment for the five seismic motions (a) final residual pressures, (b) maximum absolute pressures during the seismic excitation, (c) total pressures at the time step of the peak ground acceleration.

4.4 Internal forces in the abutment

The seismic design of the abutment (i.e. geometry and reinforcement demand) can be either based on the internal forces or the deformations developed along its height, due to the abutment-backfill interaction under seismic loading. Internal forces (i.e. bending moment and shear) were calculated by derivation of the

304 **abutment's deflection.** In Figure 12, the mean plus and minus one standard deviation of the bending moments
 305 and shear forces are plotted at the time step of the maximum displacement of the abutment top towards the
 306 backfill for the five seismic motions. The values are given for the unit width in the transverse direction of the
 307 abutment up to the deck level (i.e. 7.0 m from the foundation). It is observed that the mean bending moment
 308 values do not vary significantly, while the standard deviation at the deck level seems to be quite important
 309 especially for the rubberised backfills. Similar observation applies to the shear forces. Generally, the more
 310 flexible the backfill soil the larger the displacements of the integral bridge, hence the displacements of the
 311 integral bridge with the rubberised backfill lead to larger longitudinal displacements of the deck.

312 **Figure 12.** Mean plus and minus one standard deviation of internal forces acting on the abutment at the time step of the
 313 maximum displacement of the abutment top for the five seismic motions: (a) bending moment, (b) shear force.

314 5 Conclusions

315 A coupled integral abutment-backfill system under earthquake loading is used to investigate whether the use
 316 of rubber-soil mixtures in the backfill would be beneficial for the performance of the system, by employing
 317 the unique properties of rubberised soil and at the same time promoting a solution for waste tyres
 318 management. Two mixtures with 10% (90-10) and 30% (70-30) rubber by weight and selected seismic ground
 319 motions corresponding to EC8-1 elastic spectrum were considered for the numerical analyses. The
 320 performance of the system was evaluated on the basis of comparisons against the performance of the
 321 conventional backfill soil that consists of sand. In particular, the residual displacements of the backfill, the
 322 displacements of the abutment and the pressures and internal forces on the abutment were evaluated. The
 323 **feasibility** study drew the following conclusions:

It was found that an improvement zone equal to twice the height of the abutment had a positive impact, which was more pronounced for the backfill 70-30 that contained larger amount of rubber content per weight.

With respect to a conventional backfill, the settlements were reduced on average by 50% in the backfill 90-10 and by 55% in the backfill 70-30, while they reached almost zero values near the top of the abutment. Hence, the ratcheting effect, which is likely to be developed due to the granular soil flow in the gap formed between the abutment and the backfill, is mitigated. In addition, the “bump-at-the-end-of-the-bridge” effect is mitigated efficiently, improving the post-earthquake functionality of the bridge. The displacement of the abutment, and therefore the loading and stresses introduced to the prestressed deck was successfully reduced when rubberised backfills were used in comparison to the displacements of the conventional one. On average, it was reduced by about 8% in the backfill 90-10 and by 18% in the backfill 70-30. Similarly, the residual horizontal displacement of the top of the abutment was effectively reduced by 20% in the backfill 90-10 and by 43% in the backfill 70-30. In this way the gap formed behind the abutment due to the subsidence of the backfill soil was eliminated, contributing to reduced maintenance or repair costs. The pressures acting on the abutment were dependent on the rubber content of the backfill, as an average reduction of 31% and 47% was observed for the backfills 90-10 and 70-30, respectively, against the soil pressures calculated for the conventional scheme. The analyses have shown that the internal forces of the abutment do not change significantly when the rubberized backfills were applied with respect to the conventional backfill. However, the dynamic response of the abutment is a complicated mechanism that includes material and geometrical non-linearities, thus, analysis of the entire bridge system with the backfill soil should be conducted to better understand the behavior of integral abutment bridges.

The conclusions of this feasibility study revealed that the application of sand-rubber mixtures in the backfill soil of integral abutments is a solution that can potentially mitigate the dynamic interaction effects under seismic loading, towards more resilient structures of minimal damage. However, further research in the direction of adopting more advanced constitutive models for soil-rubber mixtures, capable of reproducing more realistically their behaviour under dynamic conditions is needed. On-going research with more advanced numerical analyses including the simulation of the entire bridge and backfills as well as 3D models of the abutment-backfill system, will give comprehensive conclusions for the benefits of using rubber-soil mixtures. Finally, the optimisation of the rubberised soil properties and the efficiency of the rubberised backfill, should be validated by large-scale testing (i.e. shaking table, centrifuge tests). The performance of the new material under operating conditions should be also evaluated.

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