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Experimental study on sand-tire chip mixture foundations acting as a soil liquefaction countermeasure

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Abstract
Soil liquefaction is a phenomenon associated with strong earthquakes and it can affect large areas. High-rise and low-rise buildings, residential structures typically of 1–2 storeys, may be equally prone to the destructive consequences of liquefaction. For the case of high-rise buildings, expensive solutions like well-designed piles with ground improvement can be used. However, in the case of smaller residential structures, this is not economically viable. To this purpose, the current research explores the effectiveness of a novel proposed low-cost liquefaction protection technique, where the soil underneath the foundation is replaced by a sand-tire chip mixture base reaching down to a certain depth. Series of triaxial and shaking table tests were performed for a range of parametric scenarios to, mainly mechanistically, assess the effectiveness of such a mitigation technique, since similar previous studies are extremely limited. The tests have shown that the closest the considered base is to the surface, the thicker it is and with higher tire ratio, the more effective it can become on controlling the pore pressure rise that leads to liquefaction.

Keywords Vibration-liquefaction mitigation solutions · Triaxial tests · 1 g shaking table tests · Sand-tire mixtures · Soil-structure interaction

1 Introduction

Every year approximately 1 billion of waste tires are generated around the world and this number is steadily increasing by around 2% on an annual basis (Ramarad et al. 2015). The disposal of such waste brings up major environmental and economic concerns, since tires are mostly non-degradable (Sathiskumar and Karthikeyan 2015). Landfilling has been one of the earliest and more popular ways to dispose waste tires. However, this method nowadays is the most undesirable one because it contributes directly to soil and water pollution, it poses a significant fire hazard, and it is a waste of valuable land (Alsaleh and Sattler 2014). In recent years, active research investigates new ways to recycle waste tires focusing

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on either the potential energy that can be extracted out of them or the material properties they can contribute for engineering applications (Oikonomou and Mavridou 2009).

Typically, before waste tires can be reused, they are shredded into smaller pieces. By this shredding process, the volume of the material is decreased, which can result into considerable reductions in handling and transportation costs (Nikitas 2016). As a material, tire shreds possess interesting mechanical properties, such as low density, large elastic deformation capacity, low stiffness, high drainage and thermal insulation capacity due to the high percentage of rubber included within them. Because of these properties, tire shreds can be creatively utilized in a variety of civil engineering projects. The most common usage of these so-called tire chips is as lightweight fill material, replacing conventional natural materials such as crushed stones, which cost considerably more. Related research on this, can be found since the late 1980s (Ahmed 1993; Bosscher et al. 1997; Tanchaisawat et al. 2008). Also there has been extensive research for the use of tire chips as backfill material (Cosgrove 1995; Cecich 1996; Tweedie et al. 1998; Lee et al. 1999; Lee and Roh 2007; Abdullah et al. 2022) and several studies using them in drainage and thermal insulation applications (Humphrey and Eaton 1993; Chaney et al. 1998; Warith et al. 2004; Pérez et al. 2012; Vila et al. 2012). Another very popular application field for tire chips is the replacement of aggregates within the concrete mix is (Eldin and Senouci 1993; Toutanji 1996; Huang et al. 2004; Issa and Salem 2013). However, all these fields are outside the scope of the current study and only a few notable references are given.

When tire chips are used in geotechnics, especially in the area of foundation engineering, large displacements/settlements may be induced due to the high compressibility of rubber material. Therefore, compaction is needed first for the reduction of such initial compression and later creep. One other way to reduce the post-construction settlements arising from the low bearing capacity of tire shreds alone is their composite use within mixtures of tire chips together with soil. The output mechanical properties of such mixing soil, typically sand with rubber, mainly focusing on ultimate strength, stiffness and damping, and how these can be influenced by the different selection parameters, such as tire content, sand and tire particle size, shape and densities (Fonseca et al. 2019), have been a topic of extensive research for many years now. Previous research on the monotonic behaviour of sand-tire mixtures, has proved that the size and shape characteristics of the tire chips used in the mixture can have a major impact on its shear strength. A distinction of scrap tire chips into different sizes and shapes can be found in Bernal-Sanchez (2020), based on ASTM D6270. Numerous studies have demonstrated that when the waste tires are added in the sand as tire derived aggregate (tire chips or shreds), the overall shear strength of the mixture can increase for up to certain tire ratio, which in most cases is below 30% (Edil and Bosscher 1994; Foose et al. 1996; Tatlisoz et al. 1998; Wu et al. 2002; Zornberg et al. 2004; Ghazavi and Sakhi 2005; Attom 2006; Rao and Dutta 2006; Kim and Santamarina 2008; Edincliler et al. 2010; Cabalar 2011; Mohamad et al. 2013; Balunaini et al. 2014; Fu et al. 2014; Mashiri et al. 2015). However, when the tires are used as particulate rubber (crumbs), it has been observed that the shear strength of the mixture drops (Masad et al. 1996; Youwai and Bergado 2003; Sheikh et al. 2012; Pasha et al. 2019; Tasalloti et al. 2021).

Unlike to the monotonic behaviour, the research in the dynamic properties of such mixtures presents a clearer image. An increase in the tire content within the mixture is associated to a reduction in the shear modulus and at the same time to an increase in damping ratio (Feng and Sutter 2000; Zheng-Yi and Sutter 2000; Youwai and Bergado 2003; Anastasiadis et al. 2012a, b; Senetakis et al. 2012; Nakhaei et al. 2012; Ehsani et al. 2015; Li et al. 2016; Pistolas et al. 2018; Rios et al. 2021; Liu et al. 2022).

However, when the focus of the research is on the liquefaction potential, things are getting more complicated, especially because of the limited research outputs. As soil liquefaction is caused by the rise of pore water pressure between the soil particles, it is expected that the addition of tire particles can generally dissipate this pressure due to their high compressibility. Research on the liquefaction potential of sand-tire mixtures have shown that tire inclusion can decrease the liquefaction resistance at small tire contents (Promputthangkoon and Hyde 2007; Hyodo et al. 2008Senthen Amuthan et al. 2018). Above a certain tire content within the mixture (30% of tires in Hyodo et al. 2008), the liquefaction resistance increases significantly. On the other hand, there is also research (Mashiri et al. 2016; Bernal-Sanchez 2020) that presents the exact opposite behaviour, that essentially even a small addition of tires in sand can increase the liquefaction resistance. All these studies are based on cyclic triaxial tests, however the conditions performed are different. In the first case, the reported triaxial test results come from stress-controlled tests, while in the latter case from strain-controlled. These different approaches in testing can influence how the excess pore pressure generates (Martin et al. 1975). Also mixing parameters, like particle size and shape of the two materials, have a significant contribution in this forementioned disagreement in results. Unlike the cyclic triaxial test results, shaking table results are more consistent, even though very limited, and show that the inclusion of tire mixtures inside the soil mass can reduce the generation of excess pore water pressure that leads to liquefaction (Uchimira et al. 2007; Yoshida et al. 2008; Hazarika et al 2008, 2020; Kaneko et al 2013; Nikitas et al. 2014, 2016; Bahadori and Manafi 2015; Otsubo et al. 2016; Bahadori and Farzalizadeh).

Further to the study of the properties of these mixtures, per se, a significant part of research is focused on implementing optimum sand-tire mixtures into engineering applications. A significant application of such mixtures is to seismically isolate structures in low middle income countries (LMIC), by providing a flexible sub-surface for the foundation of a light structure (referred also as Geotechnical Seismic Isolation) at a low cost. The research conducted on the area of seismic isolation, has shown that the inclusion of rubber underneath a structure can work efficiently to protect structures against earthquakes, mainly through activating some efficient detuning-type mechanism. This is an outcome from numerical and analytical results (Tsang et al. 2008, 2009, 2012, 2019, 2022; Xu et al. 2009; Pitilakis et al. 2015; Brunet et al. 2016). The results from numerical studies are backed up by physical testing, including shaking table tests (Xiong et al. 2011; Xiong and Li 2013; Kaneko et al. 2013; Nikitas et al. 2014, 2016; Bandyopadhyay et al. 2015; Tsiavos et al. 2019; Yin et al. 2022) and centrifuge tests (Tsang et al. 2021).

However, in almost every large earthquake, soil liquefaction occurrence is also evident, with relative examples the 2011 Tohoku and 2016 Kumamoto earthquakes in Japan (Bhattacharya et al. 2012, 2018). Many successful soil improvement methods for liquefaction mitigation have been developed throughout the years and have been adopted by construction industry. Most of these techniques are mostly based on three principles, these being: compaction (increase the liquefaction resistance of the ground by densifying sandy soil with vibration or impact, i.e. dynamic compaction, vibro-flotation), pore water dissipation (reduce the excess pore water pressure generated in sandy soils by installing permeable drains, i.e. gravel drains) and cementation (solidify the soil by mixing a stabilizing material in sandy soil, i.e. grouting). The selection of an appropriate method depends on factors such as the applied depth and the influence on the surroundings (Nikitas 2016). However, such methods tend to be best fit for relatively bigger projects having a cost which is typically prohibitive for domestic houses (typical 1–2 storey houses).

The current study focuses on the research of a low-cost liquefaction mitigation technique, aimed at small low-rise domestic buildings, through the re-use of rubber, from waste tires, as foundation material and drastically expands on the pilot work previously presented by Nikitas et al. (2014). That study has experimentally, exploiting 1 g shaking table tests, shown that the addition of a tire base underneath a small residential building can be an effective mitigation technique against soil liquefaction and at the same time an effective seismic isolation system amenable to optimal tuning. It has to be added that the research on this twofold action of such a foundation, is limited in the literature.

Namely, in the study to follow, the analysis delves in the scaled schema indicatively depicted within Fig. 1, where shredded tire chips are used to minimize earthquake and liquefaction impacts by being embedded inside the foundation material, and by acting within the projection envelope of a building. In more detail, shredded tires together with soil are packed, within perforated containments in order to form an elastic base, on which the structure will be founded upon. Due to the increased permeability of this resulting tire-base and its high compressibility, it is expected that it could effectively block the generation of excess pore water pressure in the area right below the structure. Further, the added damping and modified elasticity of the new foundation type could work towards reducing the transmission of the shear waves from the underlying layers, and therefore filter down the acceleration transmitted to the structure.

For further verifying the above almost intuitive hypothesis, and mostly for exploring the range of good tuning possible, a series of 1 g shaking-table physical experiments were conducted with the intention to provide experimental evidence that could validate and scrutinize the performance characteristics of the developed technique while inspiring routes towards some full-scale solution application development. The replacement of the rubber base with sand-tires mixtures is being investigated through a parametric study affecting the most important of the design characteristics of this liquefaction

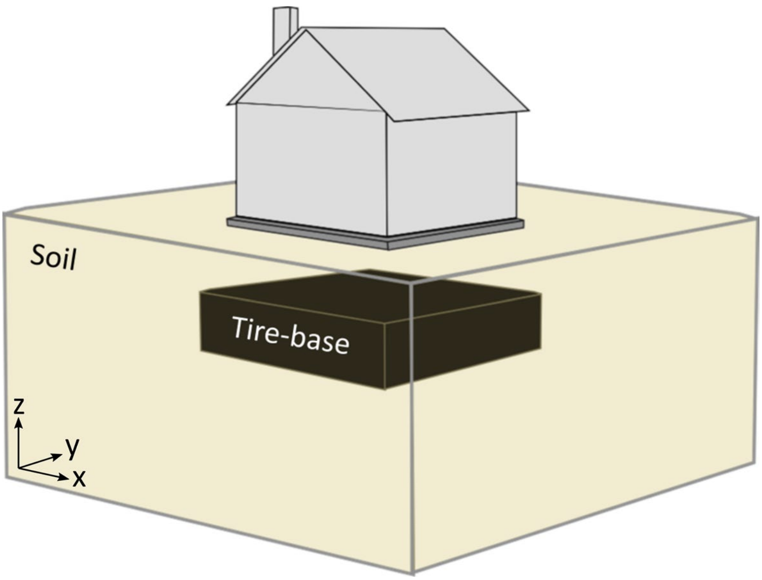

Fig. 1 Schematic outline of the proposed ground improvement technique

Table 1 Summary of the monotonic triaxial tests in the current study

Test ID	Material	D_r	σ_3'	Test conditions
Test 1MT	Redhill 110 Sand	45%	100 kPa	Consolidated undrained
Test 2MT	70% Sand + 30% Tire chips *(by volume)*	*		
Test 3MT	30% Sand + 70% Tire chips *(by volume)*	*		
Test 4MT	Tire chips	70%		

*45% for the sand and 70% for the tire chips, of their accounting volume in the mixture

Table 2 Summary of the cyclic triaxial tests in the current study

Test ID	Material	D_r	σ_3'	q	Frequency
Test 1CT	Redhill 110 Sand	45%	100 kPa	Sinusoidal (− 50, 50) kPa	0.1 Hz
Test 2CT	70% Sand + 30% Tire chips *(by volume)*	*			
Test 3CT	30% Sand + 70% Tire chips *(by volume)*	*			
Test 4CT	Tire chips	70%			

*45% for the sand and 70% for the tire chips, of their accounting volume in the mixture

mitigation solution. These include the tire-soil composition fraction, the depth of the engineered sub-base and its thickness.

In what follows, Sect. 2 will present the experimental programme carried out in this study, while Sects. 3 and 4 will present and discuss the element testing and the shaking table tests results, respectively. Lastly, Sect. 5 will summarize this study and discuss the key findings from the experimental work.

2 Experimental programme

The experimental campaign carried out in this study focuses in better understanding the effect of adding tire chips inside a soil foundation mass and more specifically in providing proof of concept for the ability to inhibit liquefaction development. The current experimental endeavor is divided into two different testing procedures, consisting of triaxial element tests and scaled 1 g dynamic shaking table tests. Details on both are given below.

2.1 Triaxial testing programme

The purpose of these tests is to find and compare the strength characteristics of the materials used also within the later 1 g shaking table tests. In order to attain directly comparable results, all the cases are tested in exactly the same conditions, such as applied stress rate and confining stress. Both monotonic and cyclic tests were conducted. The monotonic triaxial tests provide details about the stiffness and the strength of the material, while the cyclic triaxial tests provide details on the liquefaction propensity. An overview of the experiments that will be presented in the following sections, alongside their naming convention is listed below in Tables 1 and 2. The values presented in the tables and relate to the sample preparation and test specifications are relative density (D_r), effective confining stress (σ_3') and deviator stress (q).

For the case of cyclic triaxial tests, all tests were performed in undrained conditions to experimentally replicate the liquefaction phenomenon. In order to evaluate the liquefaction potential of soil deposits, there are two approaches mainly used in practice, the cyclic stress approach (Seed and Idriss 1971) and the cyclic strain approach (Dobry et al. 1982). When it comes to soil testing, these approaches translate to stress-controlled and strain-controlled tests respectively. Out of these two methods, the cyclic stress approach is the most widely used procedure for evaluating liquefaction (Rodriguez-Arriaga and Green 2018). For this reason, this study adopts the stress-controlled approach, where the cyclic stress ratio ($CSR = q/2\sigma_3'$) is kept constant for a value of $CSR = 0.25$. Strain-controlled approach for cyclic triaxial tests can be further used to assess the change of dynamic properties such as shear modulus (G) and damping ratio (ξ) for a specific strain level, similar to Mashiri et al. (2015). Another important parameter in these tests is also the selection of loading frequency, which can have an immediate effect on the test results. The current study uses a frequency of 0.1 Hz, based on the literature and on practice. Most studies on the liquefaction resistance of sands are conducted at a loading frequency of 0.1 Hz (Nong et al. 2020), since this frequency can be considered the upper limit in order to maintain quasi-static conditions, in order to minimize any inertial effects during testing. On top of that, when using higher frequencies, the available travel distance of the actuator on the triaxial apparatus significantly decreases.

The densities for the triaxial tests were selected so that they are close to the densities achieved in the shaking table tests, which are achieved through wet pluviation. The different mixing ratios of sand and tire chips were selected in order to cover a wide range of tire ratios, in order to better see the different behaviors with the variation in tire content, sand-like and rubber-like (Kim & Santamarina 2008; Senetakis & Anastasiadis 2015). It has to be noted that most of the studies in literature are focusing on tire ratios up to 40% (Promputthangkoon and Hyde 2007; Mashiri et al. 2016; Bernal-Sanchez 2020). Also, Hyodo et al. (2008), has shown that the addition of tires can be effective against liquefaction above 30% tire content. A major issue that has to be discussed during sample preparation, is the segregation of the two different materials used as it has been seen in literature (Kim and Santamarina 2008; Pistolas et al. 2018). In order to avoid this inherent problem and achieve homogeneity in the mixture, the samples were prepared using the moisture tamping method is added, where moisture was added during the mixing process. Further details on the equipment used and the sample preparation can be found in Nikitas (2016).

2.2 1 g Shaking table testing programme

Physical modeling is a tool for studying complex interaction problems (Bhattacharya et al. 2021). In this case, a parametric study is carried out in order to investigate how different variables related to the design of the tire base can affect its overall performance as a mitigation technique focusing mainly against soil liquefaction and vibration suppression. The 1 g shaking table tests were conducted at the BLADE facilities of University of Bristol on the 3 m × 3 m, 6-axis and 30 t capacity shaking table (Nikitas 2016). Overall, 6 different configurations of the tire-base were tested under different dynamic stimuli. An overview of the below presented experiments done, alongside mapping to a naming convention is given in Table 3.

Table 3 Summary of the tests in the current study

Test ID	Input motion	Description
Test 1	Low intensity White-noise along X axis	Without the tire sub-base
	High intensity White-noise along X axis	
Test 2	Low intensity White-noise along X axis	With 100% tire sub-base (40 mm thick and 0 mm under the surface)
	High intensity White-noise along X axis	
Test 3	Low intensity White-noise along X axis	With 100% tire sub-base (40 mm thick and 40 mm under the surface)
	High intensity White-noise along X axis	
Test 4	Low intensity White-noise along X axis	With 100% tire sub-base (120 mm thick and 0 mm under the surface)
	High intensity White-noise along X axis	
Test 5	Low intensity White-noise along X axis	With Soil-Tire Mixture, as in Test 4 (70–30% respectively)
	High intensity White-noise along X axis	
Test 6	Low intensity White-noise along X axis	With Soil-Tire Mixture, as in Test 4 (30–70% respectively)
	High intensity White-noise along X axis	

Due to the early-state of the research and the complexity of the whole approach, the dynamic experimental protocol employed is primarily targeting qualitative results, by means of acquiring some better understanding of the mechanics of the observed earthquake resistant performance. Therefore, the focus is mainly on trends and relative rather than absolute numbers. A quite rudimentary, experience-driven quasi-geometrical scaling was employed. The scaling laws adopted in this study are proposed by Iai (1989) and they are presented in Table 4, where N = 20. Alternative scaling approaches and possibly other type of complementary scaled dynamic experiments would be further pursued in a follow-up study, similar to Antoniou et al. (2020).

For the test setup, a rigid plastic container (1120 mm × 920 mm × 600 mm) was rigidly mounted centrally on the top of the shaking table. Because of the rigidity of the walls the wave propagation is not able to dissipate with distance and therefore the energy is erroneously contained within the soil mass, distorting any physical resemblance (Antoniou et al. 2020). For this reason, absorbing boundaries (polystyrene foam) of 6 cm thickness were mounted on all sides of the container to minimize the wave back-reflection which could be rather distorting, due to the limited dimensions of the container (Kim et al. 2020). This is a typical practice performed both in physical and numerical geotechnical experimentation. Also, the model was placed as far as possible from the walls. No further investigation is made on the effect of boundary conditions.

Inside the container, the sand was poured in using the method of wet pluviation to combine the saturation of the soil at the same time and it was dropped from a constant height of 30 cm inside water in order to achieve density homogeneity in the soil deposit. The excess of any water was removed before the actual test. The relative densities achieved were measured through a sampling and testing process in the range of 45%. The tire chips were packed inside a permeable containment to form the sub-base and to keep them from floating and/or washing away during testing. For the case of sand-tire mixtures, some moisture is added during mixing before they are finally placed in the containment. The use of containment and the addition of moisture during mixing can reduce the segregation of the two materials which can be a problem when using sand-tire mixtures. The base was later placed in the soil mass during the pluviation stage at the corresponding locations. On top of the soil finished surface a model of a rigid square foundation was used, to form a uniform base for the model house to stand, with an overall weight of 11 kg which translates to approximately 1.2 kPa of stress. Figure 2 illustrates in detail the top and side views of the different model arrangements tested, as

Table 4 Scale factors for 1 g Shaking Table tests (Iai 1989)

Physical quantity	Dimensions	Scaling factors (prototype/model)
Length (L)	L	N
Density (ρ)	ML^{-3}	1
Strain (ε)	–	$N^{0.5}$
Stress (σ)	$ML^{-1}\,T^{-2}$	N
Time (T)	T	$N^{0.75}$
Acceleration (α)	LT^{-2}	1
Displacement (δ)	L	$N^{1.5}$
Velocity (u)	LT^{-1}	$N^{0.75}$

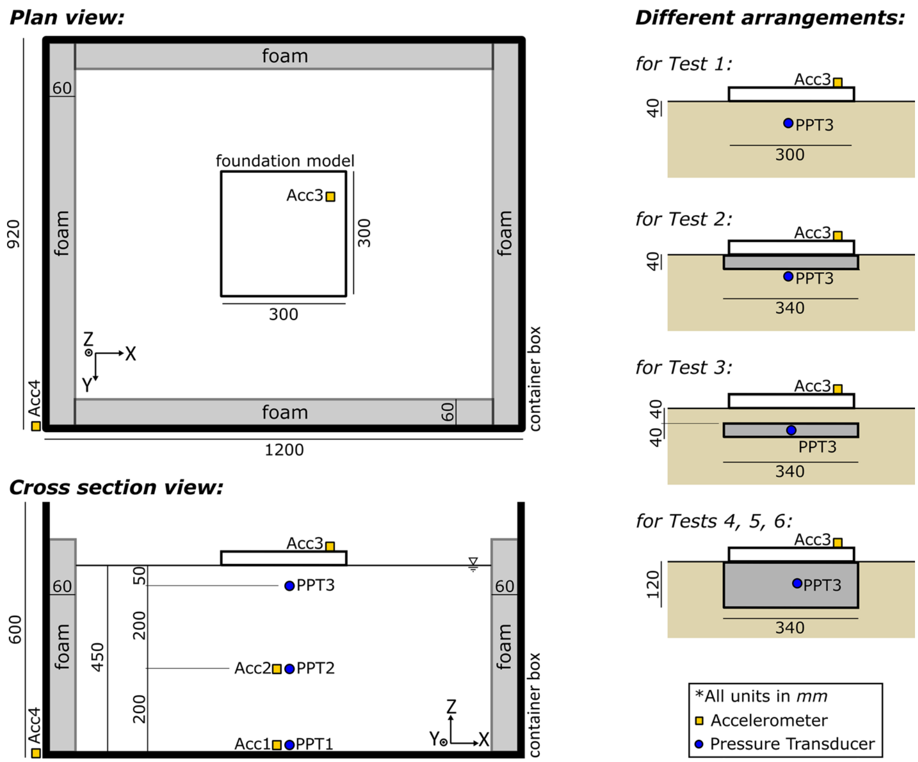

Fig. 2 Model arrangements for 1 g shaking table tests

these were included in Table 3. The locations of the transducers used along with every relevant dimension are designated in the associated figures, for allowing reproduction of the test setup.

All the models are first shaken with relatively low intensity white-noise (bandwidth frequency 0.01–80 Hz; intensity of around 0.002 g) along the X axis (see Fig. 2 for axis designation) alone in order to retrieve through simple inverse analysis (Welch's power spectral density estimate) the relevant modal characteristics. This should yield identical results as with shaking along the Y axis. From previous study (Nikitas et al. 2014) it was found that dynamic characteristics change during the shaking largely in the horizontal plan, rather than vertical. By knowing these measured dynamic characteristics of the models, it is possible to evaluate and assess the response during any other input action. The low amplitude of the shaking is expected to produce minimal densification of the soil so that the sequential form of the shaking will not produce distorting artefacts for the dynamic characterization. After the application of the low intensity white-noise input, a stronger white-noise variant was applied, unlike the study of Nikitas et al. (2014) where the shaking input also consisted of real earthquake accelerogram(s). The main aim of the input motion, for this set of tests, was to be able to cause the liquefaction of the soil yet retain the analysis simplicity. By using as a higher intensity white-noise as signal input for the main test, it would help to assess how the dynamic attributes are changing during the test without the need to revert to Frequency Response Function (FRF) calculations.

Table 5 Physical properties of Redhill 110 sand

Material	D_{50} (mm)	e_{min}	e_{max}	γ_{dmin} (kN/m^3)	γ_{dmax} (kN/m^3)	Cu	Gs	φ
Redhill 110	0.12	0.547	1.037	12.76	16.80	1.63	2.65	36°

Table 6 Physical properties of tire chips

Material	D_{50} (mm)	e_{min}	e_{max}	γ_{dmin} (kN/m^3)	γ_{dmax} (kN/m^3)	Cu	Gs
Tire chips	1.20	1.60	2.32	4.92	7.75	2.31	1.15

2.3 Materials and instrumentation used

In order to measure the different physical quantities that are critical for the tests (acceleration and pore pressure), appropriate sensors were deployed at the positions shown in Fig. 2 aiming to provide a full-field picture of response distributions. Identifying the liquefaction phenomenon necessitates of keeping track of the water pressure and its subsequent rise inside the saturated soil body. For measuring the water pressure along the different depths indicated, three Druck PDCR 811 Pore Pressure Transducers (PPTs) were employed. Acceleration is strongly correlated to the pore pressure rise and needs to be recorded accurately during the dynamic testing. For such measurements four ADXL335 MEM accelerometers (3-axis, ± 3 g), which were specially modified for underwater use, were employed. Such instruments were found to produce quality measurements, comparable to much more expensive uniaxial low-noise instruments for a wide band of frequencies. Namely, the used accelerometers were calibrated against force balance Setra 141A (± 8 g) sensors as reference, during a dedicated calibration study (Nikitas 2016). To monitor the displacements and very importantly distorting tilts of the model during the tests, a Qualisys motion capturing system was used. The system was recording the displacements of specific points, which were marked on the model. Measurements of the motion capturing system will be presented in what follows, when these are genuinely adding information relevant to the accelerometer equivalent ones.

The sand that was used for the shaking table tests, but also in the triaxial tests, is Redhill 110 sand. The physical properties of the specific sand are listed in Table 5. These properties include the average size particle (D_{50}), the void ratio (e), the dry unit weight (γ_d), coefficient of uniformity (Cu), specific gravity (Gs) and angle of friction (φ). Redhill 110 sand is a fine-grained silica type of sand with an average particle size of approximately 120 µm (Kelly et al. 2006). A soil typically consists of particles with different sizes and shapes. The gradation of a soil is probably the most important factor that defines the behaviour of the soil, because it can affect important engineering properties such as the density, permeability and shear strength. Redhill 110 sand is a well-documented soil and prone to liquefaction, and that is the main reason it was selected. Further information on the shear properties of the specific sand used can be found in Nikitas et al. (2017).

The tire chips that were used in all testing procedures are coming from shredded waste tires, mainly containing high percentage of rubber. The average particle size is approximately 1.20 mm. The properties of the tire chips used in this study are listed in Table 6. Figure 3 shows the particle size distribution curve of the tire chips, as a result of a sieve

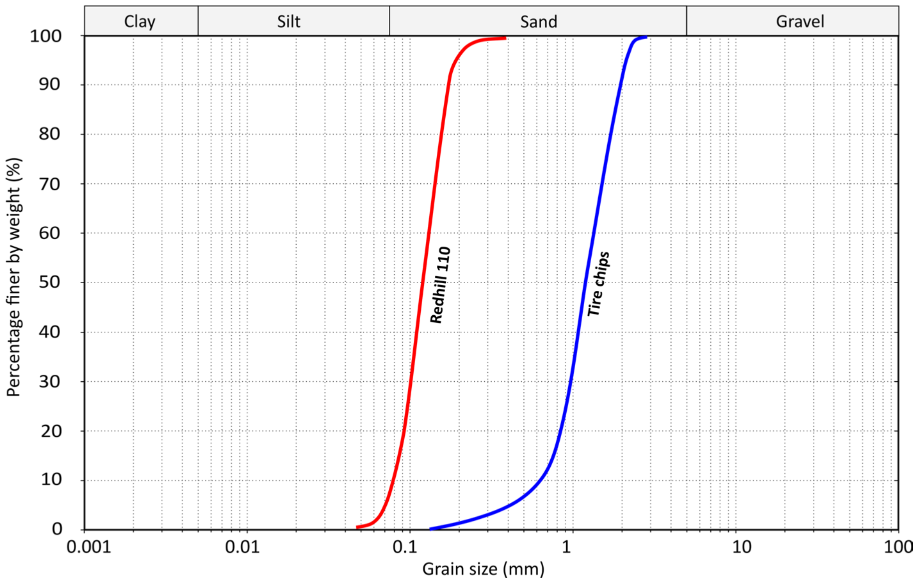

Fig. 3 Particle size distribution curve of tire chips compared to Redhill 110 sand (BS 1377–2:1990)

analysis (BS 1377–2:1990) and it also compares it with the particle size distribution curve of the Redhill 110 sand in order to have a better view of the mixture equivalent distributions.

Tires can be used in different sort of forms, including tire derived aggregates (TDA), i.e. tire shreds and rubber chips, or particulate rubber, i.e. granulated/ground rubber and rubber fibres. The size ratio between sand particles and tire chips, as well as the shape and type of tires can massively influence the strength and stiffness characteristics of the sand-tire mixtures (Bernal-Sanchez 2020). Very simplistically it can be picked from Fig. 3 that the average sand particle is approximately ten times smaller than the average tire chip. A comparison of the size along with the shape characteristics of the average sand and tire particles is illustrated in Fig. 4.

3 Triaxial test results

The results from a series of undrained triaxial tests are presented in the following section. These tests were performed on sand—tires mixtures, as indicated in Tables 1 and 2, and the results will establish how the inclusion of tire chips in the soil mass can change soil characteristics. In both types of testing, the analysis will be based upon the stress paths that will be drawn from the data acquired and the generation of excess pore pressure.

3.1 Monotonic

The results from the monotonic undrained triaxial tests are presented in Fig. 5, where the relationship between the deviator stress (q) and the axial strain (ε) for each testing case is shown. Such figures are necessary in order to estimate the strength and stiffness for each

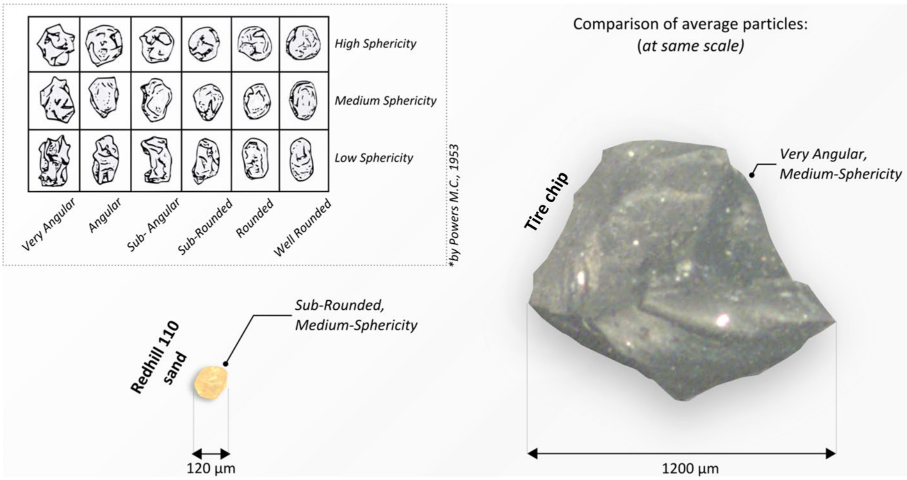

Fig. 4 Comparison of average particle for sand and tires in terms of size and shape

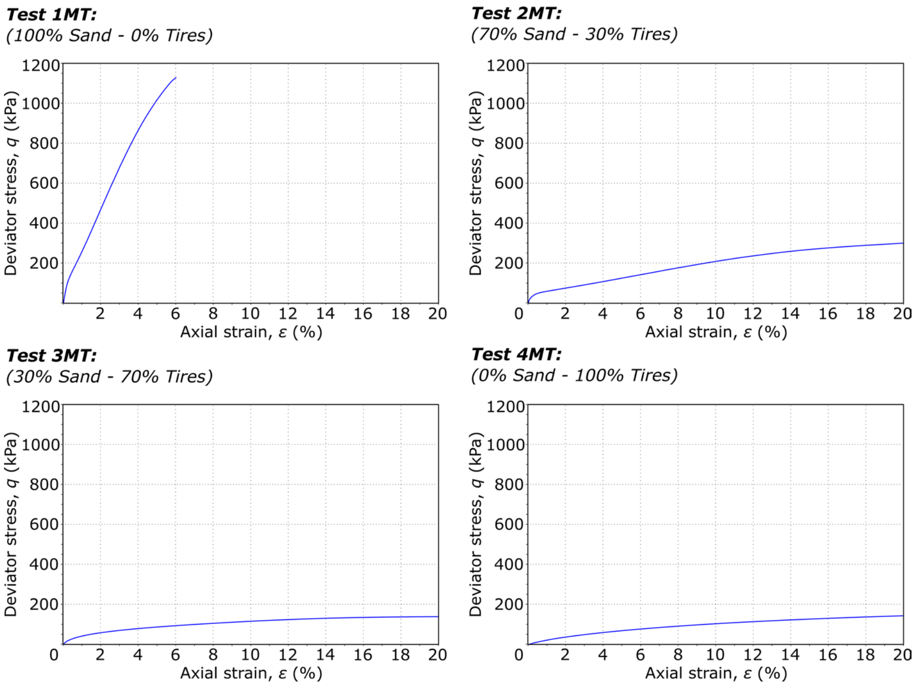

Fig. 5 Relationship between stress and strain

of the custom materials used. The strength of the specimen with 100% sand (Test 1 MT) was the highest among all the four and it even has to be noted that the test for this case has stopped due to the load cell reaching its limit. The specimen containing 70% sand and 30% tires (Test 2 MT) shows a considerably decreased strength capacity compared to the 100% sand specimen. This decrease contradicts the results from literature that show an increase in the strength of such mixtures (Zornberg et al. 2004; Mashiri et al. 2015). As it was mentioned before, a reason for this disagreement with the literature is due to the different mixing parameters and testing conditions. Quite intuitively strength has decreased even more for the next specimen containing 30% sand and 70% tires (Test 3 MT). Interestingly, the strength of the specimen containing purely tires (Test 4 MT) has not reduced any further denoting that the strength of it as well as that of the mixture with 30% sand have probably converged to a lowest plateau value. Such a plateau value can be also seen in the literature (Youwai and Bergado 2003; Kawata et al. 2008).

When focusing on low (i.e., near zero) strains a comparison of the effective elastic modulus of the material is also possible. Figure 6 presents the elastic modulus for all the test cases at low axial strain. As probably expected, since the introductory part, the stiffness of the pure sand was the highest of all the four material variants, with the pure tires having on the other hand the lowest, despite the fact that strength-wise it was coinciding with the mixture of 30% sand and 70% tire. Regarding the stiffness of the material such results were expected based on literature, even though the focus there is the change in terms of shear modulus. (Feng and Sutter 2000; Zheng-Yi and Sutter 2000; Youwai and Bergado 2003; Uchimira et al. 2007; Anastasiadis et al. 2012a, b; Senetakis et al. 2012; Nakhaei et al. 2012; Ehsani et al. 2015; Pistolas et al. 2016, 2018, Li et al. 2016, Rios et al. 2021; Liu et al. 2022). As a simplistic rule, it can be stated that there is pure monotonicity where the higher the percentage of sand into the mixture, the higher the stiffness gets. Moreover, it can be seen in Fig. 6 that the elastic modulus in this testing seems to decrease exponentially, however such a trend cannot be backed up by the literature,

3.2 Cyclic

The results out of the cyclic triaxial tests that have been carried out in order to estimate the liquefaction propensity of the materials used are discussed below. More specifically, Fig. 7 presents the effective stress path (q, p′) for each testing case separately. For the specimens containing 100% and 70% sand, the pore water pressure builds up as the cyclic loading progresses, which results in a gradual decrease in the effective stress until it reaches zero. The complete loss of effective stress means that the specimen has reached a state of initial liquefaction. Both specimens liquefied in less than 10 cycles, indicating a behavior rather prone to liquefaction. It has to be noted that in the case with 70% sand the deviator stress seems to be reducing even though the tests are stress-controlled. The exact same issue can be found in Hyodo et al. (2008). The reason for this can be assigned to a necking failure,

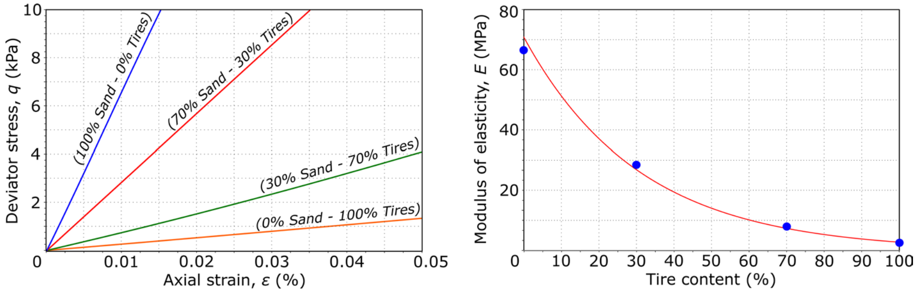

Fig. 6 Comparison of elastic modulus for all the cases at low axial strain

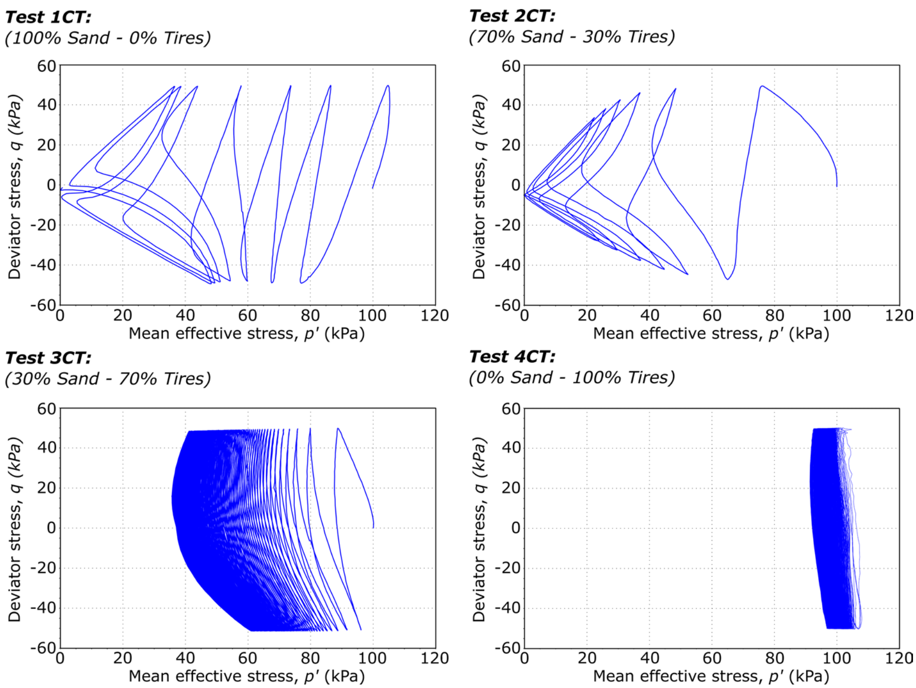

Fig. 7 Effective stress paths

which was probably caused by the segregation of the two materials, coming as a result of the different properties of them, such as the particle sizes, density, stiffness and shape characteristics (Kim and Santamarina 2008). For the specimen containing 30% sand, the effective stress decreases, but not to the point that it gets to zero even after 100 cycles of loading. As for the specimen with 100% tires, the decrease in effective stress was minimal even after 1000 cycles. Also, by looking at the first cycle in each case we can verify the findings from the monotonic tests that the specimen with 100% sand shows a dilative behaviour and that the one with 70% sand shows the most contractive behaviour which is decaying with the increase of tire percentage. Similar behaviours can be found in the results by Hyodo et al. (2008) and Kawata et al. (2008). However opposite results can be found in Lopera Perez et al. (2016), where the addition of tires enhances the dilative behaviour. Once again, the main reason can be attributed to the different testing parameters.

The most important aspect in studying liquefaction is the evolution of pore pressure. The pore pressure generation, for each specimen separately, can be seen in Fig. 8 in terms of time histories of excess pore water ratio (r_u) and for Test 3CT and Test 4CT also the moving average is plotted in order to better see the trend in the rise of pore pressure. For the cases of Test 1CT and Test 2CT, the excess pressure ratio reached 1 in less than 10 cycles proving that these materials can be quite easily liquefied. For the case of Test 3CT, the pore pressure has increased but nowhere near the liquefaction point and for the case of Test 4CT, pore pressure was hardly even generated. The reason for this is that as the tire's percentage in the specimen is increasing, the properties of the tires are dominating over the properties of the sand as a result the specimen is having a more elastic behavior as the tire's percentage is increasing. Due to the ability of tire chips deforming easily, when cyclic loading occurs, the load is not transmitted to the water inside the pores but instead is

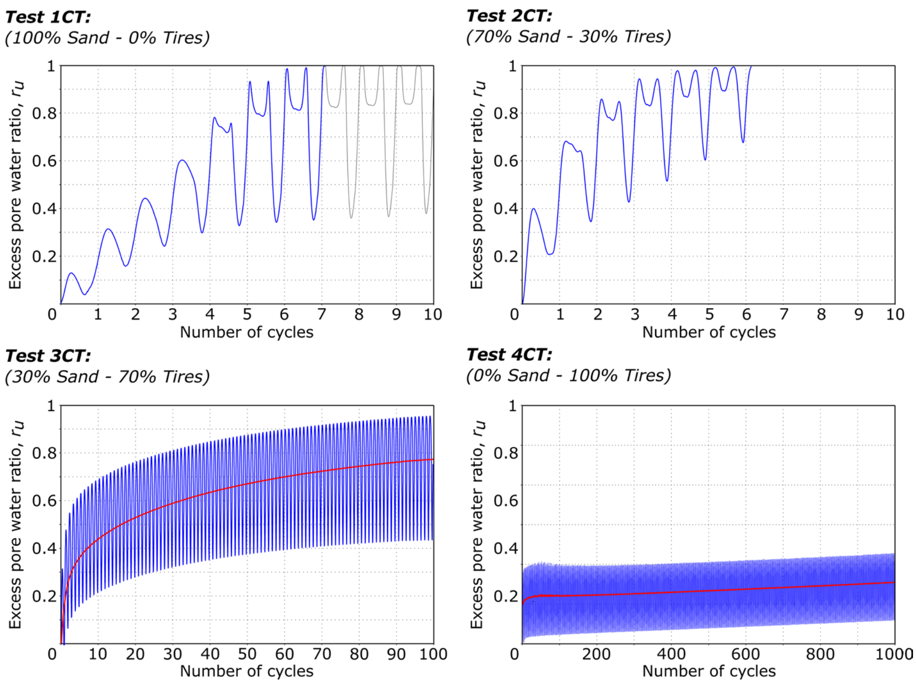

Fig. 8 Time history of excess pore water pressure ratio

deforming the tire chips and therefore no pore pressure can be generated. The results from this experimental endeavor agree with the results found in Hyodo et al. (2008) and Senthen Amuthan et al. (2018).

4 Shaking table results

To practically verify whether the proposed mitigation technique is effective against liquefaction at the structure level, 1 g shaking-table experiments were conducted as detailed earlier, on the grounds of simple rudimentary quasi-geometrical scaling considerations. These tests could act as the bridge, transitioning from the earlier reported foundation material change to a more insightful system change. Particularly modal frequency variations are targeted, which are customarily used in Structural Health Monitoring (SHM) practices to denote damage, degradation and influence of external parameters in a system (Xu et al. 2019). All the subsequent tests will be compared against the baseline unmodified soil foundation case (Test 1) in order to establish the tangible benefits coming from the parametric addition of custom-designed tire bases underneath the foundation. It has to be noted that.

4.1 Effect of depth and thickness (results from Test 1, 2, 3 and 4)

Tests 1, 2 and 4 address to the effect of the depth the tire base is positioned, while Tests 1, 2 and 3 focus on the effect of the tire base's thickness. In these tests each scenario is tested independently, with the models first being shaken with a low intensity white-noise unable to cause any observable change of the pore pressure in order to get the base undisturbed-state natural frequencies. For the latter, a simple peak picking of auto- Power Spectral Densities (PSDs) intuitive approach is employed. During this but also the main noise shaking, where the models are moved with the same input spectrum but only 10 times higher intensity for a duration of 60 s, along only one horizontal axis of the shaking table (X axis, the longer box in-plan dimension). The approximate changes in the most strongly excited (i.e., the fundamental) natural frequency for all the cases tested are presented within Fig. 8. In this figure, the acceleration response auto-PSDs, from the initial low intensity white-noise and the main high intensity one, are plotted together in order to be compared with one visualizing the change in natural frequency in the course of the main shaking. There is a tacit assumption that the change is exclusive to liquefaction type phenomena rather than an amplitude type effect. All response values are coming from the accelerometer placed on top of the foundation plate (Acc3 as shown in Fig. 2).

During the low intensity shaking, it would be expected that the less rigid foundations would show a lower natural frequency, due to their lower stiffness of the tire base underneath, Fig. 9 comes in contrast to those expectations by presenting similar natural frequencies for all cases, at least along the horizontal direction considered here. This similarity in the natural frequencies for low intensity shaking can also be seen in Kaneko et al. (2013) and it can possibly validate the outcome of Bandyopadhyay et al. (2015), which suggests that such a foundation can be ineffective as a base isolation for low amplitudes shaking motions.

Further to the application of the high intensity white-noise, changes in the relative dynamic characteristics of the different systems are expected. As it can be observed from the test acceleration auto-PSDs produced, there is a decrease in the natural frequency for all the different cases tested. When the tire base is not in place, there is the lowest decrease quantitatively, while the inclusion of the tire base has a much more pronounced effect in the

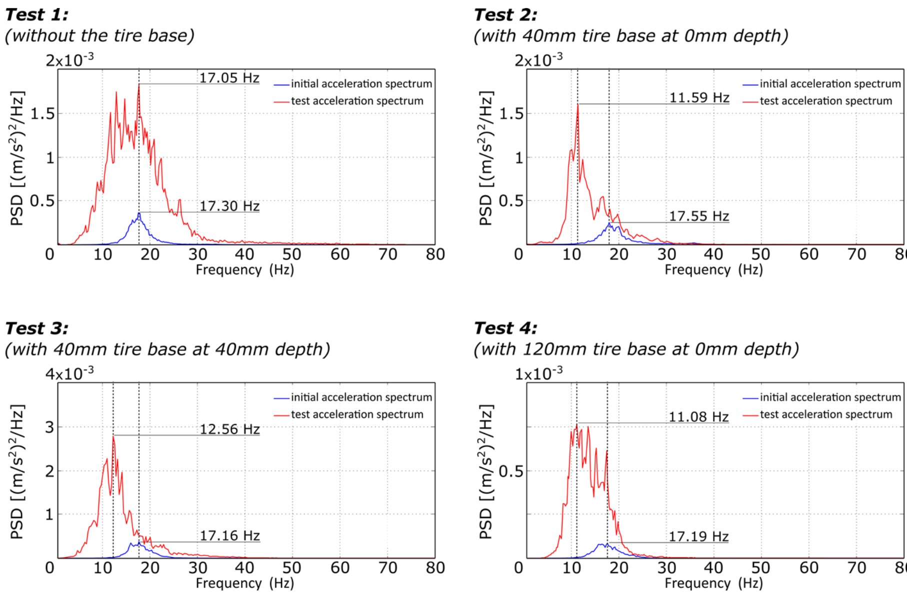

Fig. 9 Comparison of acceleration spectra between low and high intensity motions for tests 1,2,3,4

drop of the fundamental natural frequency. Such a softening effect was probably expected, due to the flexible nature of the tire chips as a material, yet not just during the main shaking. This significant drop of the natural frequency can be qualitatively similar to the behavior of base isolation systems and their earthquake protection function. Blindly assessing these results, one may well say that the sub-base founded systems should have experienced more damage post-shaking. Moreover, when the tire base was placed directly underneath the foundation, the drop in the natural frequency was pronounced even more than the case where the tire base was placed deeper in the soil mass. Also, when the 120 mm thick tire base was placed exactly underneath the foundation, there was only a marginal bigger drop in the natural frequency than the case where the 40 mm tire base was in place. This drop in the natural frequency can be seen in Yin et al. (2013). Simplistically, the closest the tire base is to the surface, and the thicker it is, the more significant is the effect towards the change in the dynamic characteristics of the structural response. The efficiency of a tire-based foundation, as a seismic isolation, when the thickness increases, has been seen in Kaneko et al. (2013) and Xiong and Li (2013), however both studies are not accounting the liquefaction phenomenon, which is the focus of this research. An interesting observation in Fig. 9 is that the acceleration content in the case where the tire base is not in place (Test 1), is lower than the cases where the tire base was in place (Test 2 and 3). This can be attributed to the fact that the structure was sinking within the liquefied soil, which essentially restricted the structures lateral movement, but also due to the drift of accelerometer on structure due to the progressive tilt.

The occurrence of liquefaction is better assessed in pore pressure rise terms, as such it is interesting to see how the pore pressure progresses inside the soil mass during the main test. First comes the pressure data from inside the soil mass of the case without any ground improvement technique. This case is, as earlier quoted, the reference, with all the subsequent pressure data compared against it and scaled to it, in order to prove the effect of the proposed technique into altering the pore pressure generation. Figure 10 presents the time histories of excess pore water pressure ratios (PPTs located at 0 cm, 20 cm and 40 cm from the bottom of the box) and the synchronous input acceleration on the X axis during the application of high intensity white-noise.

The pressure increase varies with different depth and as the depth increases, the rise in pressure gets smaller, justifying for once more the observation of inhomogeneous liquefaction in this sort of experiments. More specifically, it can be seen that as soon as the dynamic load is applied at 0 s, the pore pressures at different depths are increasing until they reach their maximum value near 10 s and after that the pressures are stabilized near that steady value, until the end of the of load application at 60 s. The pressure near the surface shows the highest values confirming the dominant occurrence of liquefaction at that level. It can be also observed that during the generation of excess pressure near the surface, there is a generation of negative excess pressure between 0 and 2 s. This possibly comes as a result to the tendency of the sand to dilate, which has been mentioned in the triaxial testing.

Having observed the pressure effect that the earthquake equivalent shaking has on the ordinary foundation it is time to examine it against the tire foundations. In Fig. 11 the closer to surface PPTs (i.e., PPT3) from all the cases presented in this section are plotted together. When the tire-based inclusion is in place the pore pressure does not rise as high as in the reference case. This is the best means of proving the effectiveness of such a foundation solution, which can effectively eliminate the liquefaction phenomenon.

In all cases, the pore pressure is increasing, but in rather different ways. In more detail, the case where the tire base is at 0 mm under the surface (the PPT is underneath the tire

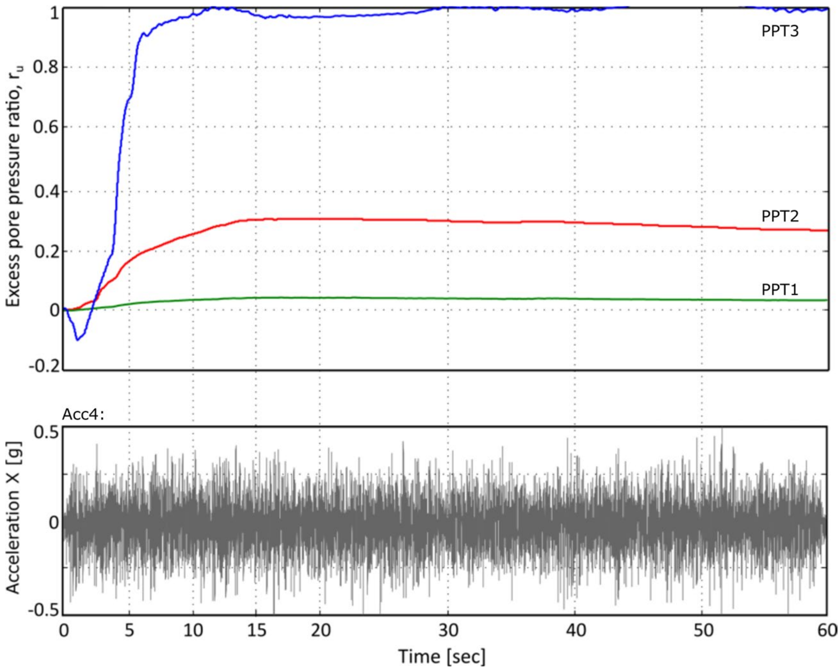

Fig. 10 Pore pressure rise during the high intensity white-noise for the case without tires

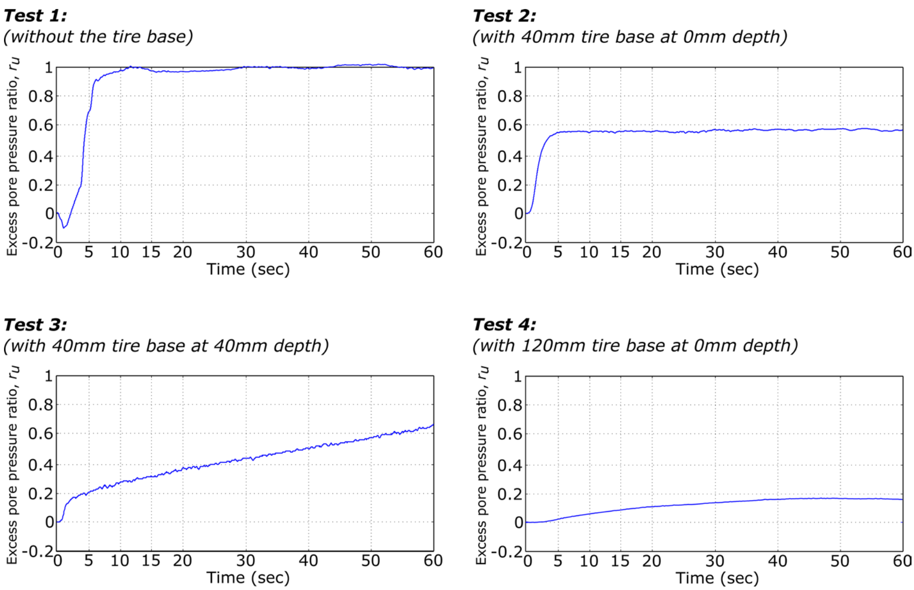

Fig. 11 Comparison of near surface pore pressure rise for Tests 1, 2, 3 and 4

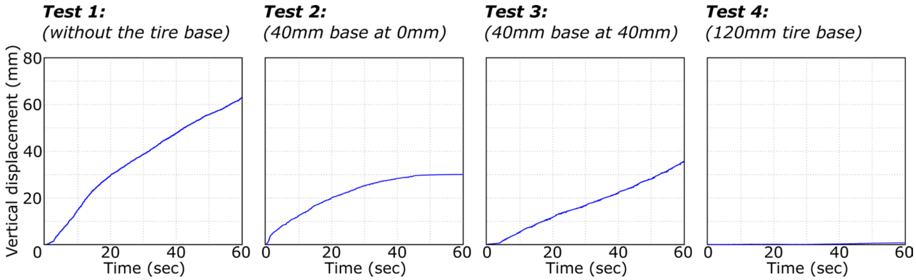

Fig. 12 Comparison of vertical displacement of the center of the foundation for Tests 1, 2, 3 and 4

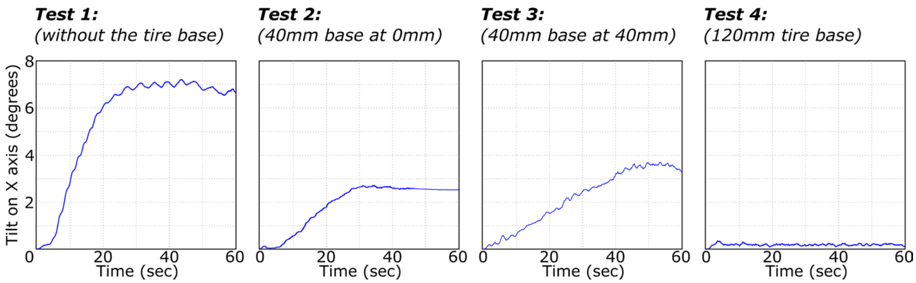

Fig. 13 Comparison of tilt in X axis of the foundation for Tests 1, 2, 3 and 4

base) shows the more radical initial increase up to 5 s and after that the pressure stabilizes near the maximum plateau reduced value. When the tire base is embedded at 40 mm below the surface (the PPT is inside the tire base) the pressure progresses slowly and steadily to its maximum non-plateau value until the end of the test and is similar to the pressure progression when the base is 120 mm thick (the PPT is again inside the tire base), but for this case the pressure increases only slightly in absolute magnitude compared to the baseline value of 1. The different patterns in pore pressure generation in Tests 3 and 4 are possibly related to the fact that the pressure transducer was inside the tire base. It has to be noted that the fact that each of these tests described were conducted independently inside the container, something that may well inflict some discrepancies in the results, particularly owing to subtle preparation changes.

The effectiveness of the tire base as a soil improvement technique can be expressed consequently in terms of the tilt and permanent displacement of the foundation at the end of the test as these are analyzed from the motion captured data. Figure 12 presents the vertical displacement of the center of the foundation in all cases, so a comparison is possible. The displacement for the case without the tire base shows the largest value of all cases (around 64 mm), while in the case with the 120 mm thick tire base, the vertical displacement at the end of the test was remarkably small (around 1 mm). When comparing Tests 2 and 3, the tire base directly underneath the foundation shows the smallest vertical displacement after 52 s until the end of the test (around 30 mm). However, the way displacement time histories developed, can be possibly attributed to the way the generation of excess pore pressure progressed in the soil mass.

The progression of tilt of the structure for all the different cases is presented in Fig. 13. The largest tilt, at the end of the test, was observed for the case without the tire base and by far the smallest for the case having the 120 mm thick tire base. When the same thickness tire base is placed right underneath the structure model the tilt is smaller than when the base is placed at 40 mm depth from the surface.

4.2 Effect of the sand-tire ratio (results from Test 1, 4, 5 and 6)

Tests 5 and 6 focus on the sand-tire mixtures and how the sand to tire ratio is affecting the response results. As before, in these tests each scenario is tested independently, and the models are shaken with high intensity white-noise along only one axis of the shaking table (X axis). Identically to before, all the models were first shaken with a low intensity white-noise in order to get their initial natural frequencies and compare them. Figure 14 shows the acceleration auto-PSDs along the X and Z axis respectively, during both the low and high intensity white-noise shakings. Interestingly, the dynamic characteristics seem almost identical regardless of the foundation type.

The addition of the tire chips into the soil mass has a big effect in the drop of the first natural frequency, as it was also pointed out previously. All of the cases presented a significant drop in the global natural frequency of their foundation systems, and even a small addition of tire chips into the soil mass can impact on how the dynamic characteristics of the superstructure will change during dynamic shaking. Therefore, the quantity of tire chips inside a soil-tire mixture will affect greatly the overall dynamic characteristics during an earthquake.

As in the previous section, in order to see the effect on the liquefaction process of the different sand-tire ratios, the surface pore pressure data are compared with the reference case, again exactly as before. Figure 15 presents the time histories of excess pore water pressure ratios for all cases. It can be seen that the addition of tire chips inside the soil under the model can effectively reduce the rise of excess pore pressure and therefore

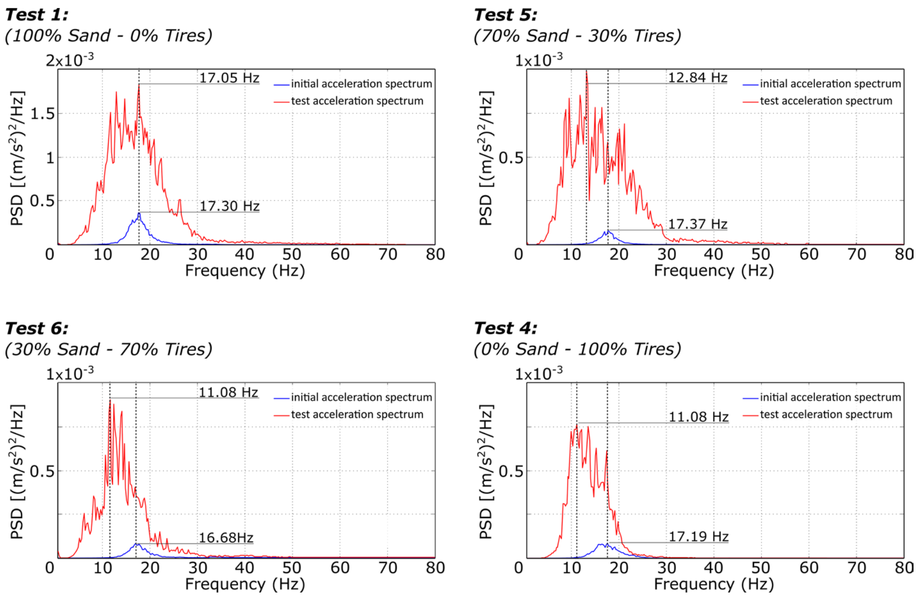

Fig. 14 Relationship between stress and strain

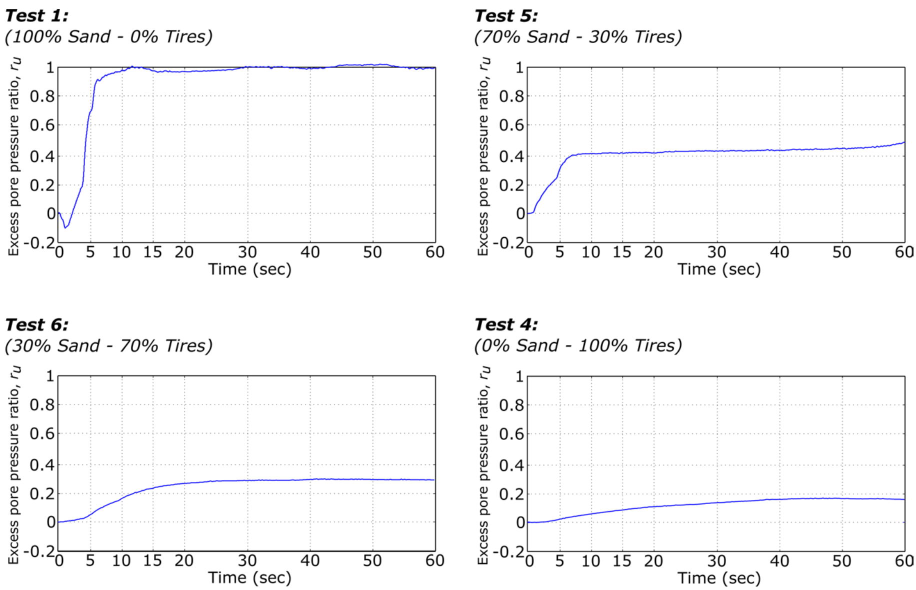

Fig. 15 Comparison of near surface pore pressure rise for Tests 1, 4, 5 and 6

eliminate the occurrence of soil liquefaction. Particularly the case with 30% tire—70% sand fractions, showed a significant decrease in the rise of pore pressure, which is almost equal to that for the case of 70% tire—30% sand. When a 100% tire base is placed underneath the foundation, the pressure rises slowly and in relative numbers it increases slightly, which eventually translates into smaller displacements and tilts for the foundation. The pressure in this case is the smallest out of all the cases tested. Therefore, it can be concluded that the addition of tire chips inside the soil can effectively reduce the risk of soil liquefaction, due to the decrease of pore pressure generation something though not evidently linked to observations as in Fig. 14.

The effectiveness of the tire base foundation will be finally assessed also by the data provided from the motion capture system. Figure 16 presents the vertical displacement of the center of the foundation in all three cases. The case where 100% tire chips are in place presented the smallest vertical displacement (1 mm) and as the amount of tire chips inside the mixture was decreasing, the vertical displacement of the foundation was increasing.

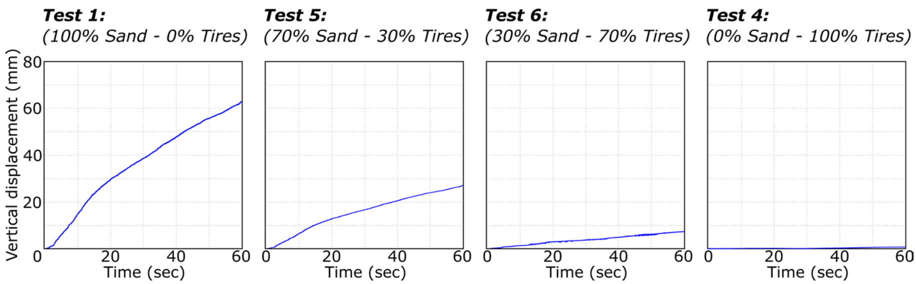

Fig. 16 Comparison of vertical displacement of the center of the foundation for Tests 1, 4, 5 and 6

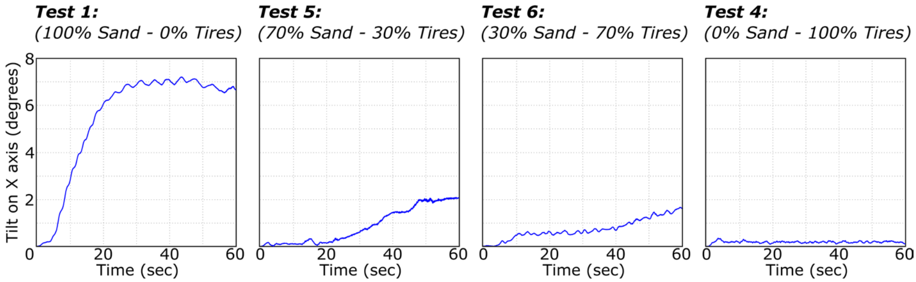

Fig. 17 Comparison of tilt on X axis of the foundation for Tests 1, 4, 5 and 6

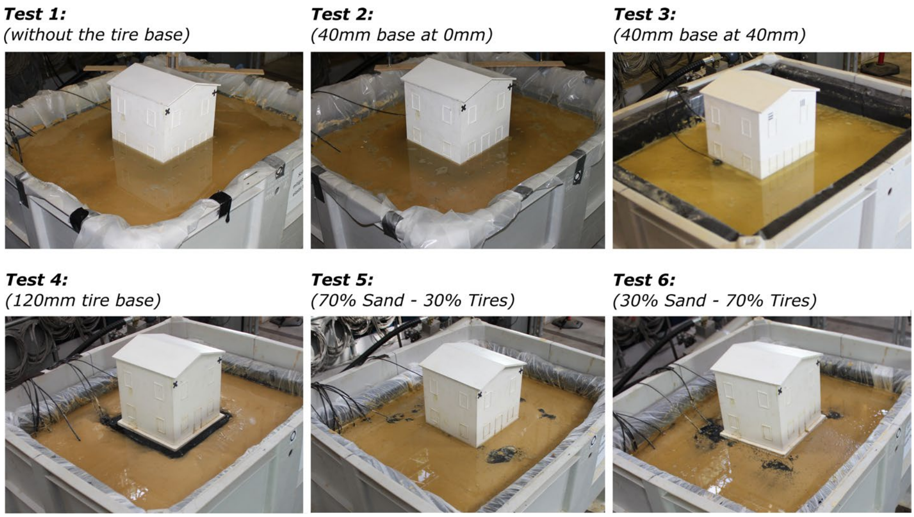

Fig. 18 Photos of all the test cases after the main shaking

Similar results can be seen in Fig. 17, where the time histories of tilt around the X axis, for all tire-retrofitted cases are plotted together. The largest tilt, at the end of the test and among retrofitted cases alone, was observed for the case of 30% tires—70% sand and the tilt was decreasing with the addition of tire chips into the mixture. It is interesting though that up to 20 s of shaking the tilt was similar for all case.

All the results about settlements and tilting can be further depicted by presenting the photographs of the test models after the test. For this reason, Fig. 18 presents the photographic documentation of all the shaking table test models used for all the different scenarios presented in this study. These photos present the state of the models after the application of high intensity white-noise, which agree with the data values presented earlier.

5 Conclusions

The current research work presents a novel soil liquefaction mitigation technique that can be applicable to small domestic buildings. It expands on the pilot work previously presented by Nikitas et al. (2014). According to this technique, tire chips, coming from shredded waste tires (thus being cost-effective and environmentally friendly), are placed underneath the foundation of the structure to minimize the effects of liquefaction by diminishing the excess of pore water pressure. In order to showcase the above philosophy, an experimental programme was conducted, including triaxial tests (monotonic and cyclic) and dynamic 1 g shaking-table tests. These tests provided experimental data necessary to better understand the proposed method. As it was shown in previous study (Nikitas et al. 2014), the dynamic characteristics of the structure change during the shaking largely in the horizontal plane, that is why this study focuses on just one axis.

Based on the collected data, the addition of tire chips underneath the foundation reduced the displacements and tilts of a low weight superstructure. Due to the properties of the tire chips, observed also previously in triaxial testing, the liquefaction phenomenon could not take place in the vicinity a retrofitted area. It is actually the influence on excess pore pressure generation that resulted in such reduced responses. On top of that, it was noticed (by analysing acceleration data) that the addition of a tire sub-base led to a reduction in the foundation's natural frequency. This proves that the proposed method can possibly also help in seismically isolating a structure against higher frequency inputs.

Further to these conclusions, the parametric study presented helpful results into the optimization of the proposed mitigation method. More specifically it was presented that the closest the considered tire base is to the surface and the thicker this base is, the more effective it can become. The sand-tire mixtures can also be effective against liquefaction, and it was noted that as the quantity of tire chips increases in the sand—tire mixtures, there is a significant decrease in permanent vertical deformation and tilt. Therefore, the sand-tire mixtures can be a good solution in order to minimize the settlement during the construction of the superstructure.

Due to the limited research on the combined action of such foundation as a liquefaction mitigation and as a seismic isolation, further investigation is necessary. Before this method can be deployed in the field with confidence in its liquefaction resistance capability, there are still many aspects to be investigated for future work:

- Additional tests should be performed with different size configurations in order to approximate any unforeseen size effects.
- Further a micro level study must investigate into the effect that the size and shape of the tire chips, in relation to the soil grain size, has to the overall performance of the soil improvement technique.
- The deployment of the proposed method in the field is another issue to be looked into. A full-scale structure with tire chip foundation when monitored adequately can provide a wealth of data that can become the testbed for any future scaled physical testing approaches.

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Declarations

Conflict of interest The authors have no financial interests to disclose.

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