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Seismic response investigation of retaining structures by using lightweight mixtures as backfill material

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ABSTRACT
The aim of this paper is the study of the strength parameters and the stress-strain properties during cycling loading of saturated mixes of natural volcanic coarse material (pumice) with granulated rubber derived from recycled used tires, and the application of the aforementioned mixtures in the seismic response of a rigid quay wall structure. On this framework, a set of laboratory tests comprising of monotonic triaxial tests, resonant column tests and cyclic triaxial tests were performed on identical saturated specimens of high density ($D_r \approx 90\%$) with varying percentage of rubber in the mixtures between 0% and 30% by mixture weight. The effect of non-linearity of the aforementioned mixtures as material of the counter-supported soil layer on the dynamic response of a wall/soil system is also investigated using finite element analysis with the code ABAQUS, along with the question of how that response can be differentiated by the use of G/G_0-γ-DT_o curves for volcanic materials with or without the addition of grained rubber.

1 INTRODUCTION

The mixture of non-cohesive soils with granulated rubber display satisfactory natural, mechanical and dynamic properties (low specific weight, high strength, high flexibility, high ability to absorb vibrations and high level of permeability). The above characteristics render them, in the last few years, suitable in a number of Civil Engineering works, i.e. artificial embankments and slopes, retaining walls and quays walls, as a material for layers of draining and as a material for construction insulation against earthquakes (Humphrey et al. 1993, Lee et al. 1999, Edeskar 2006, Xiong et al. 2011, Hazarika et al. 2012, Ravichandran et al. 2014 and Pistolas 2015).

The mechanical and dynamic properties of various materials comprising the mixtures have been extensively studied in the last few years (Edil et al. 1994, Masad et al. 1996, Feng et al. 2000, Zornberg et al. 2004, Hazarika et al. 2011, Anastasiadis et al. 2012, Nakhaei et al. 2012, Senetakis et al. 2012 and Pistolas et al. 2015).

However, looking back in international bibliography, one finds a relatively small amount of research into the mechanical and dynamic behavior of volcanic soil, as well as mixtures of volcanic soils and rubbers (Anastasiadis et al. 2010, Senetakis et al. 2012 and Senetakis et al. 2013).

The objective of this study was the determination of the static/dynamic properties of volcanic soil (pumice) through a series of tests carried out at the Laboratory of Soil Mechanics, Foundations and Geotechnical Earthquake Engineering of Aristotle University of Thessaloniki, Greece. The granular material of volcanic origin concerns vitreous rhyolites from the area of Nissyros island (Greece) which, after extraction and mechanic processing of the natural rock, can be found in the form of granular fractions, yet with a high percentage of fine-granule fraction (about 15% to 25%) passing through the N^{o}200 sieve. The synthetic materials (rubber) is derived from recycled used tires and, after appropriate processing, can be also found in the form of various sizes.

The effect on the dynamic response of the wall/soil system by the implementation of granular soil/rubber mixtures as backfill material added in the mass of the embankment is investigated using a fine element analysis with the code ABAQUS. The dynamic response of the material improvement is non-linear and occurs from the experimental results in the present study. In this way, an attempt is made to control the dynamic response of the structure/soil system through the monitor and improvement of the dynamic characteristics of the retaining soil. Therefore, it is possible a direct assessment of the influence of the proposed method of treatment on the dynamic response of the structure.

2 MATERIALS TESTED AND TESTING PROGRAM

The present work is part of a dynamic test program carried out at the Laboratory of Soil Mechanics, Foundations and Geotechnical Earthquake Engineering of Aristotle University of Thessaloniki, where there have been performed a great number of tests (>300) on soil/granulated rubber mixtures, including Resonant Column Tests, Cyclic Triaxial Tests, Monotonic Triaxial Tests and Direct Shear Strain Tests. As regards the specific series of tests, there were carried out three tests for each sample of pure fraction or soil/rubber mixture in order to eliminate uncertainties during the preparation and the perform of the test.

2.1 Materials

One uniform coarse pumice fraction of mean grain size D_{50} equal to 7.08mm was studied as primary physical material (LW), whereas one granular fraction of rubber of mean grain size D_{50} equal to 3.38mm was studied as primary synthetic material (R). The specific gravity of soil solids, G_s, was found equals to 1.72gr/cm^3 for the pumice fraction and, respectively, 1.15gr/cm^3 for the rubber fraction. Table 1 summarizes physical the characteristics of the natural soil and the synthetic material used in this research.

Table 1. Properties and classification of natural and synthetic examined materials.

Properties	Pumice	Rubber
Material code	LW	R
G_s (gr/cm^3)	1.72	1.15
D_{50} (mm)	7.08	3.38
D_{max} (mm)	9.28	4.71
D_{min} (mm)	4.89	2.04
C_u	1.47	1.68
e_{max}	2.009	1.636
e_{min}	1.866	0.726
$\gamma_{d,max}$ (kN/m^3)	6.00	6.40
$\gamma_{d,min}$ (kN/m^3)	5.72	4.20
USCS Classification	GP	Granulated Rubber

2.2 Testing program

The present work is part of a dynamic test program carried out at the Laboratory of Soil Mechanics, Foundations and Geotechnical Earthquake Engineering of Aristotle University of Thessaloniki, where there have been performed a great number of tests (>300) on soil/granulated rubber mixtures, including Resonant Column Tests, Cyclic Triaxial Tests, Monotonic Triaxial Tests and Direct Shear Strain Tests. As regards the specific series of tests, there were carried out three tests for each sample of pure fraction or soil/rubber mixture in order to eliminate uncertainties during the preparation and the perform of the test.

In total, twenty saturated specimens of a mixture of pumice with granulated rubber at a percentage of 0-10-20-30% per weight were examined in the present research. The basic characteristics of the specimens are presented in Table 2. Twelve cylindrical specimens with dimensions of about 100mm in height and 50mm in diameter were tested in the monotonic triaxial apparatus, four cylindrical specimens with dimensions of about 140mm in height and 70mm in diameter were tested in the resonant column apparatus, and four cylindrical specimens with dimensions of about 100mm in height and 50mm in diameter were tested in the cyclic triaxial apparatus.

In dynamic loading (RC and CTRX) the specimens are tested under undrained conditions while in static loading (TRX) under drained conditions. The TRX tests were performed under drained conditions since during a CD test the specimen is slowly charged allowing the pore water drainage during the loading step, so the pore water pressure remains constant while it is possible to estimate the strength parameters with their active values (c', φ') as well as to measure the volume change of the specimen in order to estimate the dilation angle of the examined sample. On the other hand, the Cyclic TRX and the RC tests were performed under undrained conditions since the loading speed should be high as it simulates a cycling (seismic) loading in order to estimate the stress-strain properties of the samples.

Due to the high porosity of the solid soil granules of pumice it was not easy to completely saturate the corresponding specimens for the tests, so the pumice sands were first boiled in water in order to remove the entrapped air from the grains. That means all pumice specimens, including pumice/rubber mixtures, were prepared in saturated conditions. All specimens were compacted at the same number of layers of equal mass, as well as the same number of tips reaching values of relative density varying from D_r≈90%, while the ratio of the mean diameter of their granules is $D_{50,s}/D_{50,r}=2.10$.

Table 2 shows, as it is expected, that the specific gravity of soil solids, G_s, and the initial dry unit weight, γ_d, of the tested specimens decrease as the rubber content increases. On the other hand, it is noticed that for the specific rubber percentages, for the given relative density, the initial void ratio, e_o, of the tested specimens and the equivalent void ratio e_{eq}, as proposed by Feng et al. (2000) increase as the rubber content increases.

Table 2. Specimens features study in Monotonic Triaxial, Resonant Column and Cyclic Triaxial device.

Specimen Code	Rubber[1] (%)	G_s (gr/cm^3)	γ_d (kN/m^3)	e_o	e_{eq}
LW/R-100/0	0	1.72	5.99	1.87	1.87
LW/R-90/10	10	1.66	5.73	1.86	2.34
LW/R-80/20	20	1.61	5.43	1.88	2.96
LW/R-70/30	30	1.55	5.23	1.86	3.70

[1] by mixture weight

The void ratio is estimated through Equation 1, while the equivalent void ratio is estimated through Equation 2, assuming that the volume of solids rubber granules is part of the total volume of voids of the mixture and does not participate in soil stiffness.

$$e_o=V_v/(V_s+V_r) \qquad [1]$$

$$e_{eq}=(V_v+V_r)/V_s \qquad [2]$$

In order to study the behavior of the aforementioned specimens from small to medium shear strains levels ($10^{-5}\%<\gamma<3*10^{-1}\%$), a resonant column (RC) device of free-fixed end (Drnevich, 1967) was used. Both, the dynamic small-shear modulus (G_0) and the dynamic small-strain damping ratio (D_0), as well as the variation stiffness and material damping with shear strain were examined in the RC apparatus (denoted as G/G_0-γ-DT_o curves) under sinusoidal torsional loading and undrained conditions. For greater levels of shear strain ($10^{-2}\%<\gamma<3\%$) undrained cyclic loading tests by means of applied strain control conditions were performed by using a cyclic triaxial device.

In the cyclic triaxial test the strain frequency is defined instead of the strain rate. That means that the strain rate varies, even within one load cycle. The applied strain frequency in the current study was 0.5Hz. The effect of cyclic strain frequency on the rubber/sand mixtures was presented in a previous study by Pistolas et al. (2014). It is evident that the load frequency effect on the small-strain shear modulus and damping ratio diminishes as the rubber content increases.

The results of the two set of tests were combined to form the complete dynamic behavior of the examined mixtures by means of G/G_0-γ-DT_o curves in a wide range of strains. The effect of the rubber content in the mixtures, r(%), the mean effective confining stress, σ'_m, and the shear strain amplitude, γ, were examined in all cases. The amplitude of the applied confining pressure, σ'_c, was 25, 50, 100 and 200 kPa, while the applied consolidation time between the four levels of mean effective stress was 60'. The imposed loading frequency in the cyclic triaxial test was 0.5Hz with an amplitude of the applied vertical deformation that ranges between 0.00001 and 2.0 mm, while the maximum number of cycles for each level of strain was 10 cycles.

The behavior of the mixtures at values of high deformation reaching the point of failure was studied by using a monotonic triaxial (TRX) apparatus in order to estimate the elastic modulus and the strength parameters of the mixtures in axial deformation levels up to 20%. The consolidation stress, σ'_m, in the present research ranged from 100kPa to 300kPa, while the consolidation time depends on the type of the stiffness of the specimen and the amplitude of the applied consolidation stress. Finally, after the consolidation the soil samples are submitted under drained conditions in an axial compression with a loading speed around 0.005mm/min.

3 EXPERIMENTAL PROCEDURE RESULTS

3.1 Strength parameters of mixtures

Figure 1 shows the variation of deviatoric stress, q, with the axial strain, ε, of the examined mixtures LW/R in relation to the mean effective stress, σ'_m, and the rubber percentage, r(%), as those resulted from the monotonic triaxial device, for a level of effective confining stress equals to 100kPa and 300kPa respectively.

It is noticed that the increasing of the mean effective stress leads to an increase of the specimen's developed maximum diaviatoric stress. However, as the rubber percentage in the mixture increases the influence of the envelope stress is limited, since for greater levels of rubber content the increase of the maximum diviatoric stress is lower compared to the pure soil specimens. it appears that the addition of the rubber causes a reduction of the developed maximum diviatoric stress with simultaneous increase of the axial deformation which leads to a reduction of the elastic modulus of the specimens.

It is also seen that the response of specimens with rubber percentage equals to 20% by mixture weight, exhibit an intense linear behavior for the examined level of axial strain (up to 20%). This tendency is expected for high percentages of rubber, despite the granular nature of the rubber fraction, since the sample soil tissue maintains its elasticity due to the flexibility of the rubber granules which receive the load with their deformation and not with their rearrangement in the mixture.

The experimental results show that in the range of the axial deformation of the present study, the specimens of pure pumice fraction as well as the mixtures of pumice with rubber content present a shrinkage behavior with a tendency of reduction as the axial deformation increases. However as the rubber percentage in the mixture increases or as the level of the applied envelope stress increases the specimens exhibit a more intense shrinkage behavior, which means that the addition of the rubber in the mixture leads to a reduction of the dilation angle values.

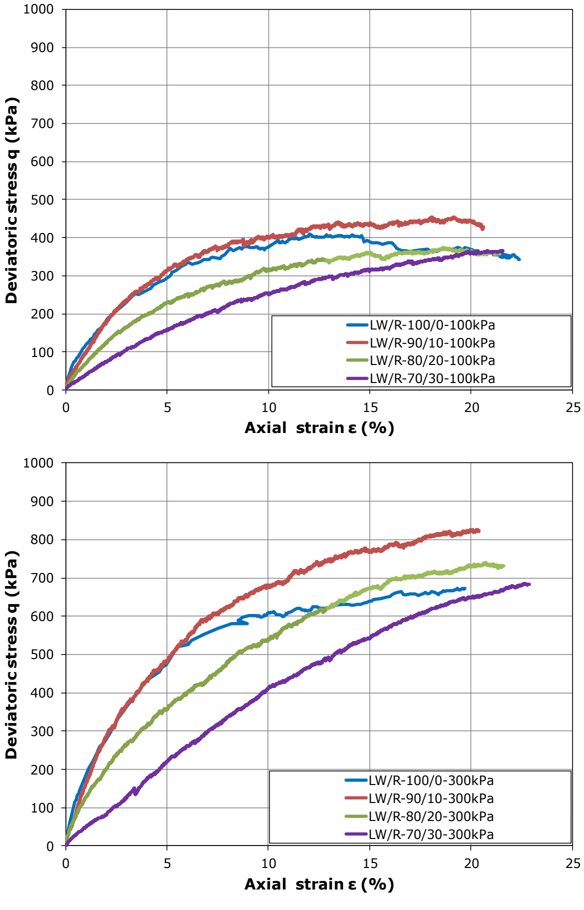

Figure 1. Variation of deviatoric stress, q, with the axial strain, ε, of pumice/rubber mixtures (LW/R) at σ'_m=100kPa (up) and σ'_m=300kPa (down).

Table 3 summarizes the elastic modulus values for each examined mixture group under different values of effective confining stress. It is observed that the increasing of the mean effective stress leads to an increase of the specimen's elastic modulus, as it is expected, while as it is mentioned above the increasing of the rubber percentage in the mixture leads to a reduction of the elastic modulus. However, it should be noted that the above reduction is accompanied by a more stable-linear behavior of the specimens response due to the high elasticity of the rubber grains and their interaction (friction and mechanical engagement) with the soil grains.

Table 3. Elastic modulus, E, in MPa of pumice/rubber mixtures (LW/R) under drained loading conditions.

σ'$_3$ (kPa)	Rubber percentage (%) per mixture weight			
	0	10	20	30
100	7.5	7.3	4.7	2.8
200	10.8	7.6	5.0	4.7
300	11.6	10.6	6.4	5.1

Figure 2 shows a representative image of the Mohr circles and the adjustment of the Mohr - Coulomb failure criterion on the experimental results of the examined mixtures LW/R with rubber percentage equals to 0% and 30% by mixture weight under three different levels of effective stress (100-200-300kPa).

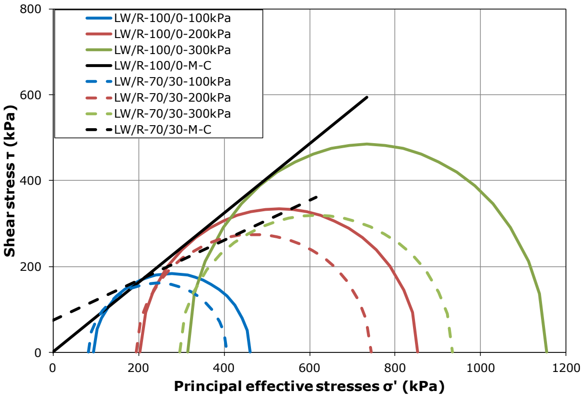

Figure 2. Mohr circles and Mohr - Coulomb failure envelope of pumice/rubber mixtures (LW/R) for various percentage in rubber.

As mentioned in previous research (Zomberg et al. 2004, Edeskar 2006), in order to achieve a better adjustment of the Mohr - Coulomb failure envelope stress on the experimental results of granular soil mixtures with granulated rubber it is necessary to estimate an "apparent" cohesion value for those materials. However, the addition of the rubber in the mixtures does not change the nature of the tested materials since the estimated cohesion has numerical character and does not offer resistance against tensile or repulsion between the soil grains.

According to the experimental results, as also seen in Table 4, it is noticed that the pure soil fractions have zero cohesion and exhibit higher values of friction angle compared to mixtures, while the addition of the rubber in the mixture mass leads to a reduction of the friction angle and at the same time it increases the cohesion of the examined materials.

Table 4. Friction angle, φ', and cohesion, c, of pumice/rubber mixtures (LW/R) under drained loading conditions.

	Rubber percentage (%) per mixture weight			
	0	10	20	30
φ'(°)	39	31	28	25
c' (kPa)	0	50	60	75

As mentioned by Kikkawa et al. (2013), the pumice particles are highly crushable under loading because of the combination of their high porosity and their angular shape. According to the laboratory test of the present study, it is seen that pumice particles are highly crushable under loading conditions since the comparison of the grain size distribution curves before and after the CD triaxial tests shows that for high levels of the applied load the fine fraction produced from the particle crushing increases, while the addition of the rubber in the mixture mass can improve the above behavior.

3.2 Small-strain response of mixtures

Figure 3 shows the dynamic shear modulus, Go, and the dynamic damping ratio, Do, of mixtures LW/R of the present paper, as those resulted from the resonant column device.

According to the experimental results, it is notice that as the rubber content increases, the specimens exhibit lower shear stiffness and higher damping ratio, since the additional rubber does not contribute in any way to the stiffness of mixtures due to the low stiffness of the solid rubber granules, compared to the pure pumice specimens, and gives the mixture a more intense linear behavior. Additional, the increase in the dumping ratio can be attributed to the friction coefficient developed between the rubber and soil granules, compared to the corresponding one between two soil granules, and also to the local deformation of the rubber granules in their contact with soil granules.

Those shifts become more noticeable with the increase of the rubber percentage per mixture weight as there is also an increase in the rubber percentage per mixture volume, resulting in the behavior of the mixture being influenced by the existence of the rubber fraction.

By increasing the mean effective stress, regardless of the rubber content, an increase in the values of maximum shear modulus is observed and respectively a reduction in the values of the minimum damping ratio of the examined materials. This is attributed to the fact that resistance to strain is increased as a result of the higher forces of friction developed among the granules.

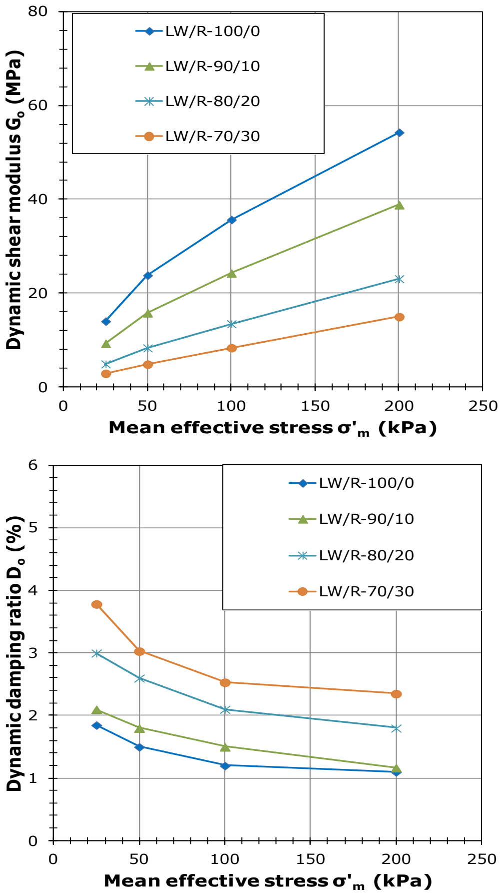

Figure 3. Effect of rubber content on G_o and D_o of pumice/rubber mixtures (LW/R).

3.3 Medium to high strain response of mixtures

Figure 4 shows representative experimental G/G_o-γ-DT_o curves, as those resulted from the combination of the two dynamic loading test devices used in the present study, of pumice/rubber mixtures of high density and radial stress equals to 50 and 100kPa respectively.

It is noticed that the increase of the shear strain amplitude leads to a reduction of the shear modulus and to an increase of the damping ratio, regardless the rubber percentage in the mixture. However, as the rubber content increases the aforementioned behavior is less intense since the dynamic response of the specimen is affected by the rubber existence.

With the increase of the implemented shear strain, the presence of rubber brings about an increase of the normalized shear modulus, in a direct antithesis to the reduction observed in small shear strains, which becomes more intense with as the percentage of rubber increases. That is because the G/G_o-γ-DT_o curves become more linear due to the linearity of the elastic material fraction, and as a result the reference strain, γ_{ref}, which corresponds to the value of G/G_o=0.5 is increased.

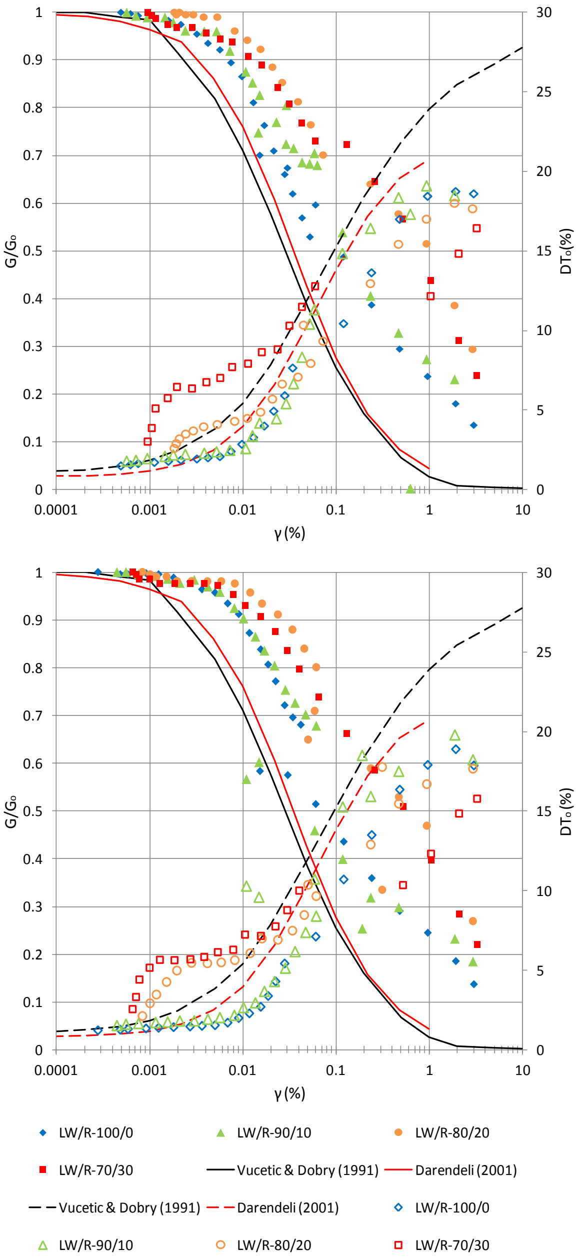

Figure 4. Effect of rubber content on G/G_o-γ-DT_o curves of pumice/rubber mixtures (LW/R) at σ'$_m$=50kPa (up) and σ'$_m$=100kPa (down).

Due to different mechanism of damping activated with the increase of the implemented shear strain, two areas of behavior can be detected as far as the damping ratio of mixtures and the level of strain. The latter becomes more intense with the increase of the rubber content. In the area of linear strain ($\gamma \leq 10^{-3}$%) the friction between the grains plays a very important part, as the strain is small and the imported energy is consumed more by the friction between grains and less by their rearrangement in the specimen. Therefore, the reason why the mixtures compared to the fraction of pure pumice present higher torsional damping is the higher friction between soil and synthetic granules compared to that between granules of pure pumice. In the area of non-linear strain ($\gamma > 10^{-3}$%) the consumption of imported energy in the specimen happens primarily through the rearrangement of grains and to a lesser degree through the friction between them. At this level of strain the opposite image is presented, as the damping ratio of the mixture appears lower than that of pure pumice because of the flexibility of the rubber granules which receive the load with their deformation and not their rearrangement in the mixture.

4 MODEL GEOMETRY AND INPUT MOTIONS

A 2D plane-strain finite element model was constructed using the ABAQUS commercial code in order to investigate the seismic response of a rigid quay wall, through 2D equivalent linear analyses, where the embankment consists of a mixture of coarse volcanic material (pumice) with a percentage of granulated rubber (tires) in various rates.

For practical reasons (including the implementation in ABAQUS) in order to control shear behavior consistent with the laboratory derived data the abovementioned method of analysis was chosen, despite the fact that according to Figure 2 a non-linear envelope will seem appropriate for mixed materials. The major reason for that choice is that the Mohr-Coulomb (M-C) model is just as limited as the linear elastic model for strains in the linear elastic range and can only simulates shear modulus reduction and damping when the soil enters a failure state, which is known not to be the case for real soil behavior.

The simulated model, Figure 5, concerns a concrete quay wall with dimensions of about 14.0m in height and 5.0m to 8.0m in width, located at the Port of Thessaloniki, and its behavior is presumed to be elastic. The discretization consists of four-noded quadrilateral, plane-strain elements. The simulation of the behavior of the composite soil material is carried by the equivalent linear method and plane strain conditions using appropriate G/G_o-γ-DT_o curves determined from laboratory tests. Table 5a and 5b summarized the wall and soil properties used in the present research. In table 5a, the layer numbering is from the top to bottom.

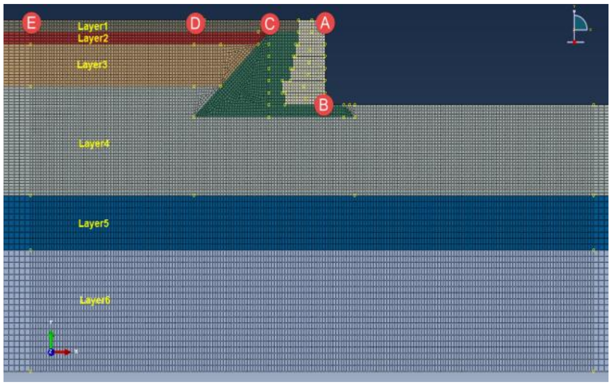

Figure 5. 2D fine element mesh (in ABAQUS) of simulated wall/soil system.

In order to consider the soil-structure interaction during the dynamic analyses, all soil-wall interfaces are tensionless with potential for sliding.

The model includes two identical walls, one opposite to the other, to render the model symmetrical, and hence to minimize boundary effects (Garini et al. 2015). The geometrical limits of the model are 200m behind each wall, while to avoid any interaction between the two walls, they were placed at a distance of 200m. Horizontal and vertical viscous dashpots with free field boundaries were added to absorb the radiated energy from the P and S waves.

Table 5a. Wall and soil properties.

Name	USCS	h(m)	Vs (m/s)	ρ (tn/m^3)	E_o (MPa)
Wall	-	-	-	2.50	300000
Layer1	GW	2.0	400	2.14	856
Layer2	SM	2.0	278	1.88	362
Layer3	CH/CL	7.0	174	1.66	126
Layer4	SM	18.0	239	2.08	297
Layer5	SC	9.0	424	2.12	952
Layer6	CL	20.0	410	2.059	865
Bedrock	CL	-	600	2.20	1980

Table 5b. Backfill soil properties.

Material	h(m)	Vs (m/s)	ρ (tn/m^3)	E_o (MPa)	v
LW/R3-100/0	12.0	242	0.61	104	0.46
LW/R3-90/10	12.0	203	0.59	70	0.44
LW/R3-80/20	12.0	156	0.55	38	0.39
LW/R3-70/30	12.0	125	0.53	18	0.13

Two earthquake strong motions records, applied at the base of the model (at -58.0m depth), were used as input excitations. Table 6 summarized the characteristics of each record.

Table 6. Strong motion records used.

Strong Motion	Date	Magnitude	PGA (g)	T_p (sec)	F_p (Hz)
Duzce 1	12/11/99	7.2	0.11	2.92	0.34
Ano Liosia	07/09/99	6.0	0.27	0.25	4.05

5. RESULTS OF DYNAMIC ANALYSES

The results of the numerical analysis demonstrated that the addition of rubber to the mass of the embankment affects the seismic response of the system. Figures 6-8 and Table 7 show representative results from the numerical analyses for the left wall.

Figure 6 shows the distribution with depth of the static at rest earth pressure for different percentage of rubber content in the mass of the backfill material. It is seen that as the rubber percentage increases, for rubber content up to 20% per mixture weight, the applied on the wall geostatic pressures are reduced due to the rubber's smaller value of specific gravity of soil solids, G_s. But for greater percentage of rubber (≥30%) it is seems that the geostatic pressures start to increase again due to the high deformability of the elastic grains that effecting the soil tissue of the mass of the retained soil.

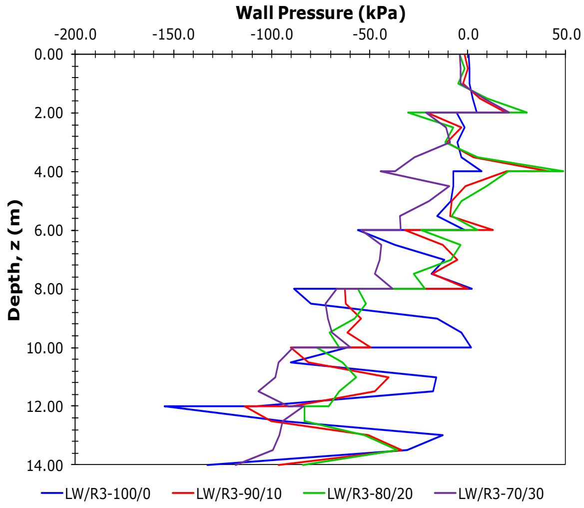

Figure 6. Static at rest earth pressure on the left wall for different percentage of rubber content in the mass of the backfill material.

Figure 7 refers to wall response to both ground motions and it shows the distribution with depth of the peak earth pressure for different percentage of rubber content in the mass of the backfill material. It is noticed that as the rubber percentage increases the applied on the wall earth pressures are greatly reduced by following a more uniform distribution with the depth due to the presence of the rubber content in the mass of the retained soil.

Figure 8 illustrates the distribution of plastic stain magnitude in the soil behind the wall for the strong motion record of Ano Liosia, for two different percentage of rubber, 10% (up) and 30% (down). It is evident that a failure wedge forms in the soil behind the wall, while small plastification is noticed beneath the outer corner of the wall base. The abovementioned behavior is more intense for greater percentage of rubber.

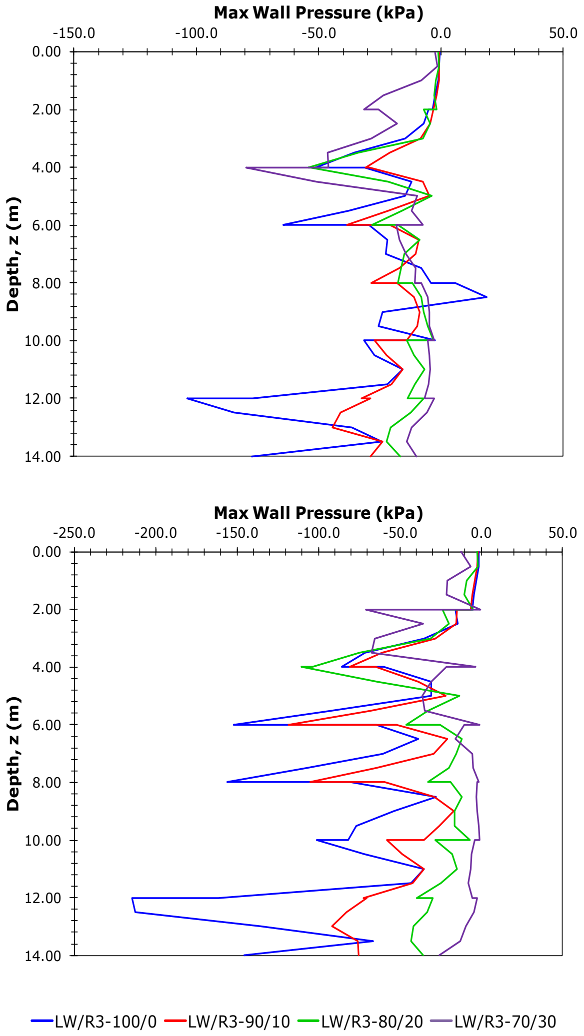

Figure 7. Maximum earth pressure on the left wall for different percentage of rubber content in the mass of the backfill material when subjected to Duzce (up) and Ano Liosia (down) record.

Acceleration time-histories were investigated at two points (A, B) on the wall, one at its top and one at its base, and at three points (C,D,E) behind the wall at soil surface at distance 2.5m, 16.5m and 47.0m from the wall (Figure 5). Table 7 summarized the above results for the strong motion record of Ano Liosia, for two different percentage of rubber (10% and 30%). It is clear that the rubber presence affects the seismic response of the system since as the rubber content increases it causes a reduction of the maximum horizontal acceleration at the top of the wall (point A), while the exact opposite behavior is noticed at the bottom of the wall (point B) regardless the frequency content of the excitation used.

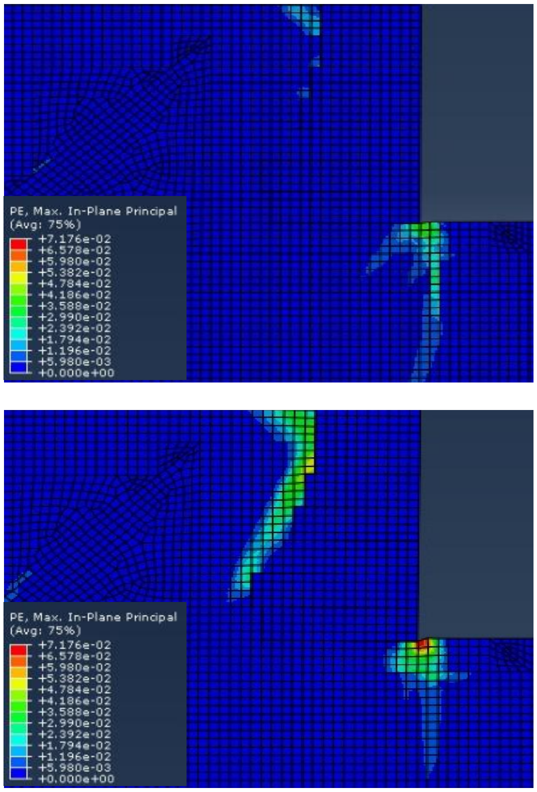

Figure 8. Plastic strain distribution due to strong motion record of Ano Liosia in the case of mixture of pumice with rubber at 10% (up) and 30% (down) per mixture weight.

Table 7. Maximum horizontal accelerations in the case of mixture of pumice with rubber at 10% and 30% per mixture weight for the strong motions of Duzce (left) and Ano Liosia (right).

Point	A_{max}^{1} (g)	A_{max}^{2} (g)	A_{max}^{1} (g)	A_{max}^{2} (g)
A	0.19	0.13	-0.44	-0.35
B	-0.09	0.12	0.23	-0.27
C	0.13	-0.14	0.37	0.39
D	0.12	-0.13	0.36	0.39
E	-0.12	-0.11	0.39	0.37

[1] backfill mixture with 10% rubber

[2] backfill mixture with 30% rubber

5. SUMMARY AND CONCLUSIONS

In the present study the effect of rubber content, r(%), on the mechanical and the dynamic small-strain shear modulus (G_o) and damping ratio (D_o), as well as the variation stiffness and material damping with shear strain (G/G_o-γ-DT_o) is investigated by means of monotonic CD triaxial, resonant column and cyclic triaxial tests, considering a wide range of shear strain amplitudes up to 3%.

The experimental results show that the rubber content affects the mechanical properties and the mechanical strength of saturated mixtures of high density since the sample's maximum deviatoric stress increases with the increase of the mean effective stress, but as the rubber percentage in the mixture increases the influence of the envelope stress is limited. It is also noticed that the addition of the rubber causes a reduction of the developed maximum deviatoric stress with simultaneous increase of the axial deformation which leads to a reduction of the elastic modulus of the specimens and gives them a more stable-linear behavior until the stage of failure.

Furthermore, the results from the dynamic tests show that the rubber content affects also the dynamic response of saturated mixtures of high density since the increase of the rubber percentage in the specimen causes a decrease of the initial shear modulus and an increase of the initial torsional damping ratio compared to the pure soil material. However, as the level of strain increases there is an increase in the normalized shear modulus in comparison with that of pure pumice, which generally presents a more linear behavior for bigger percentage of rubber, as well as an increase of the damping ratio in the area of small to medium strains. While for an even higher level of strain ($\gamma > 10^{-3}$%) this image is reversed as the mixtures present a lower damping ratio than that of pure pumice.

Finally, the results from the numerical analysis show that adding granulated tires in the mass of the retaining soil can improve the seismic response of the system soil/wall by significantly reducing the earth pressure (geostatic and earthquake) applied on the wall due to the low specific weight and the higher energy dissipation of the rubber on the embankment mass. However, it is noticed that there is a small increase concerning the values of the acceleration on and near the wall in relation with the increscent of the rubber percentage which can be attribute to the high flexibility of the rubber.

6. REFERENCES

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