

REDUCING THE FORCES CAUSED BY EARTHQUAKE ON RETAINING WALLS USING GRANULATED RUBBER-SOIL MIXTURE

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Abstract In recent years, various studies have been undertaken on how to use waste materials in civil engineering projects. Among waste materials, waste rubber has been highlighted to be used for different purposes such as reinforcing of soil and making of reinforced slopes. To investigate the properties of granulated rubber-soil mixture and its application in making of slopes behind retaining walls, some series of cyclic triaxial tests and numerical analyses were carried out. In the former, dynamic properties of granulated rubber-soil mixture such as shear modulus and dynamic behavior were obtained and in the latter the effect of using granulated rubber-soil mixture on dynamic pressures and displacement of retaining walls during earthquake was investigated. The results of the present study showed that for all the confining pressures, with an increase in rubber percentage, shear modulus decreases while for any percentage of rubber inclusion, shear modulus increases as the confining pressure increases. In addition, new relations were introduced to define maximum shear modulus (G_{max}) and Normalized shear modulus as functions of confining pressure and granulated rubber percentage. Regarding the dynamic analyses of the retaining wall, with an increase in rubber percentage, a decrease in dynamic pressure and residual displacement was observed.

Keywords Retaining walls, Dynamic properties, Horizontal forces, Granular soil, Granulated rubber, Earthquake.

چکیده در سالهای اخیر مطالعات مختلفی بر روی استفاده از مصالح ضایعاتی در پروژه های مهندسی عمران انجام شده است. از میان مصالح ضایعاتی، مطالعه بر روی لاستیک های فرسوده برای مواردی همچون تسلیح خاک و مسلح نمودن شیروانی ها چشمگیر بوده است. در این مقاله برای بررسی مشخصات مخلوط های خاک-خرده لاستیک و کاربرد آن در شیروانی های پشت دیوارهای حائل، چند سری آزمایشات سه محوری در مقیاس بزرگ همراه با تجزیه و تحلیل عددی انجام گرفته است. در مرحله اول، خصوصیات و رفتار دینامیکی مخلوط های خاک-خرده های لاستیک مانند مدول برشی مورد مطالعه قرار گرفته و در ادامه تاثیر بکارگیری مخلوط های خاک-خرده های لاستیک بر روی فشارهای دینامیکی و تغییر مکان دیوارهای حائل در حین زلزله بررسی شده است. نتایج تحقیق حاضر نشان داده است که برای هر فشار محدود کننده ای، با افزایش درصد لاستیک، مدول برشی کاهش میابد درحالیکه برای هر درصد خرده لاستیک، با افزایش فشار محدود کننده، مدول برشی افزایش میابد. در ادامه جهت تعیین مدول برشی بیشینه (G_{max}) و مدول برشی نرمالیزه شده بصورت توابعی از فشار جانبی و درصد خرده های لاستیک مدل هائی ارائه شده است. همچنین بر اساس تحلیل دینامیکی دیوار حائل، نتایج نشان داده است که با افزایش درصد خرده لاستیک، کاهش محسوسی در فشار دینامیکی و تغییر مکان باقیمانده بوجود می آید.

1. INTRODUCTION

Highly destructive earthquakes damaging geotechnical structures such as transportation routes, retaining walls, high rise structures and other infrastructures plus their side effects on social and economical crises are matters of concern for authorities. All the above has encouraged

researchers to pay due attention on reducing the earthquake caused damages on geotechnical structures.

The problem of waste materials such as waste tires of airplanes, trucks, and other motor vehicles and how to deal with them have been primarily concerned by people all around the world. In the recent years different studies have been undertaken

by many researchers to tackle this problem.

In these studies, some key parameters such as shear modulus, bearing capacity, permeability, shear strength, Poisson ratio, compaction characteristics, swelling and compressibility have been considered [1-13].

Various studies have been also conducted concerning the high applications of these mixtures in making of geotechnical engineering structures. Trevor et al. [14], Youwai and Bergado [15] carried out researches on granulated rubber as filling materials behind retaining walls in active and passive states using numerical analysis. These showed that there would be a reduction in residual displacement and the earthquake caused forces while using reinforced soil. Edil and Bosscher [16], Benson [17] and Edincliler et al. [18] carried out some large scale direct shear and cyclic triaxial tests on rubber-soil mixture. The results showed that shear modulus and damping ratio of the soil reinforced by granulated rubber increased. They suggested that the stated mixture can be used as light filling material on constructing of the fillings of highway subbases and those behind retaining walls.

To investigate stress-strain relation and to determine the strength of the shredded rubber-sand mixture, a triaxial test was undertaken by Lee et al. [19]. They modeled a retaining wall using the related literature of the obtained results, and numerical method with and without geosynthetics. The results regarding the shredded tire, especially the one mixed with sand showed that this mixture can be used behind the retaining wall effectively.

Cristine Castro Fontenla Sieira [20] in his research made a retaining wall with the length of 60m and the height of 4m of waste tires tied together filled with compacted alluvial soil and then investigated the behavior of the wall. The results showed the existence of tire reduced not only the displacement but also the expenses. Meanwhile, Tweedie et al. [21] made a retaining wall with the height of 4.88m using soil- shredded rubber mixture and reached this result that the horizontal stress during the wall rotation is 35% less than that of the traditional walls.

Naik and Siddique [22] and Cao [23] added shredded tire to concrete slurry and asphalt respectively and found that despite a reduction in compressive strength and concrete density, its

flexibility, durability and torsion strength increased.

Hazarika et al.2008 [24] performed a series of large-scale underwater shaking table test on a gravity type model caisson protected by a cushioning technique using tire chips. The results showed that the seismic load against, and the residual displacement of the caisson quay wall reduced using the proposed technique.

A review of the literature regarding lateral forces on the retaining walls caused by earthquake shows that there have been considerable theoretical and practical studies in this respect. Despite all the various researches undertaken and the theoretical and practical data concerning the properties of the soil located behind the retaining walls and its influence on the lateral forces created by earthquake, the authors of this article have not found large scale experiments on the mixture of soil and granulated rubber. So any large scale experiments may be fruitful for dynamic analysis of soil-granulated rubber mixture which is behind the retaining walls, railways, around buried pipes, foundation of vibrating equipment, and foundation of the structures at risk of earthquake, and soil slopes. In addition, the new findings may be helpful in understanding the dynamic behavior of these materials especially in engineering projects in which these granular materials are used.

One of the main objectives of this research was to determine the dynamic properties of the granular soil-rubber mixture using the cyclic triaxial tests. Then, we use the found properties as a lightweight fill in performing of the fills of the retaining structures and the same goals. In other word, due to the special features of the mixture such as flexibility, and energy absorbing capacity, this research aims at offering a suitable method to strengthen the retaining walls against the forces. These forces caused by earthquake which are themselves because of changes in dynamic properties of the soil behind the wall.

Generally, due to the difficulties of the experiments, researchers have not undertaken large scale tests. Accordingly, the large size particles have to be separated from the base material and the experiments are performed on the materials that are finer than the base ones and as a result show a different behavior. Considering all the above, it seems that large scale experiments cause more

logical results.

To this end and in order to determine the dynamic properties of granular soil mixed with granulated rubber, in this research a series of cyclic triaxial tests have been carried out on samples with 15 and 30 cm diameter and height, respectively. Then with respect to the found properties, these materials were used as a lightweight fill behind the retaining wall. To analyze the performance of this wall, the applied pressure and displacement of the wall were considered under the effect of forces caused by earthquake using FLAC software. This study is of two main parts: the first part contains the results of cyclic triaxial tests, and the second part includes modeling of the retaining wall using the results of the first part.

2. EXPERIMENTAL PROGRAM

A series of large scale cyclic triaxial tests were undertaken to get the dynamic properties of granular soils mixed with granulated rubber. The explanation is as follows:

2.1. Material Properties The soil materials were river granular soil obtained from a huge mine situated in Ekhtiar Abbad, Kerman site and were sieved based on ASTM D 422 - 63 (Reapproved 2002) [25]. The particle size distribution curve is shown in Figure (1). This curve shows that 100% of the soil materials are of a diameter less than 25mm. Accordingly, with respect to the samples dimensions (diameter: 150mm and height: 300mm) the clause No. 7.1 of ASTM D 3999 - 91(Reapproved 2003) [26] has been observed. The sand equivalent, plasticity index and classification of the tested soil were determined based on ASTM Test Methods of D 2419-02, D 4318-00 and D 2487-10 respectively [27- 29]. The soil characteristics obtained are specified in Table (1). The granulated rubber used in the test samples was supplied by Behzist Factory located in Orumieh City, north-west of Iran. Based on ASTM D 6270 - 08^{e1} [30], it was composed of waste tires that had

been mechanically chopped using multiple chopping steps and were sieved with mesh numbers of 3/8", No.4, No.10, No.40 and No.100. The particles which passed sieve 3/8" and remained on sieve No.100 were used. These particles had nonspherical shapes with dimensions, from 0.15mm to 9.5mm. The particle size distribution curve for the granulated rubber is shown in Figure (1). A magnet was used to extract the steel wires from granulated rubber. The specific gravity of the granulated rubber was determined 1.10 based on ASTM Test Method for Specific Gravity of Soils (D 854 - 02) [31].

2.2. Specimen Preparation Procedure Based on the standard laboratory procedures ASTM D 4253 - 00 [32] and ASTM D 4254 - 00 [33], relative density expresses the degree of compactness of the tested mixture with respect to the loosest and densest conditions. ASTM D 4253 - 00 [32] suggests that, for some soils containing between 5 and 15% fines, the use of impact compaction (Test Methods ASTM D 698 - 00a^{e1} [34] and ASTM D 1557 - 02^{e1} [35]) may be useful in evaluating appropriate maximum unit weight. By this consideration, the soil was mixed with 0%, 8%, 10% and 14% granulated rubber by weight with the same grain size distribution. Then, to determine

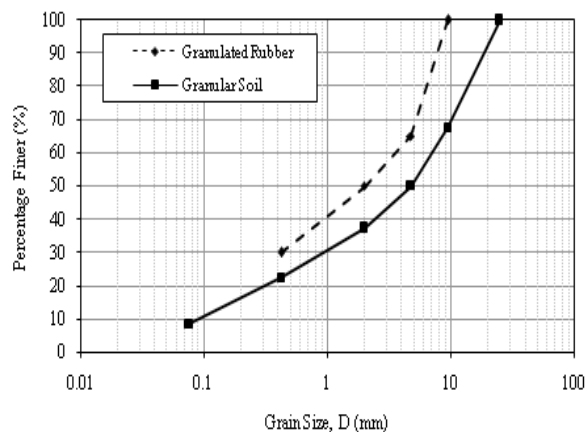


Figure 1. The Particle Size Distribution for Granular Soil and Granulated Rubber

TABLE 1. The tested soil properties

	Coefficient of uniformity (c_u)	Coefficient of curvature (c_c)	Passed sieve No. 200 (%)	Specific gravity	Sand equivalent (%)	Plasticity index (%)	Unified classification
Soil	77.77	1.29	8.5	2.65	51	4	GW-GC

the maximum dry unit weight and optimum water content, the compaction tests were carried out based on ASTM D 1557 - 02^{e1}, method C [35]. The optimum water content, maximum and minimum dry unit weights, and specific gravities of the mixtures are presented in Table (2).

The test specimens were prepared in such a way that, the cyclic test results will be consistent, repeatable, and less influenced by the specimen preparation. In the specimen preparation first the amount of granular soil and granulated rubber plus the required water were determined based on the specimen volume and optimum water content. To prepare test specimens, undercompaction method developed by Ladd [36], provides a highly uniform specimen. This method was also used by Feng and Sutter [5]. was applied. The samples were sequentially compacted in eight layers from the bottom to top of the mould. Each layer was compacted to a selected percentage of the required dry unit weight of the specimen. This procedure differs from the application of a constant compactive effort to each layer required by ASTM Tests for Moisture-Density Relations of Soils, using 5.5-lb (2.5-kg) rammer and 12-in. (304.8-mm) drop [35] and ASTM Tests for Moisture-Density Relations of Soils, using 10-lb (4.5-kg) rammer and 18-in. (457-mm) drop [36]. The

compaction of each layer was initiated using Harvard tamping device [37], having a spring force of 18-kg (40-lb) and with a compaction foot having a diameter equal to about 1/2 the diameter of the specimen. Finally, the split mould was removed, and the sample was placed in a triaxial cell and covered with rubber membrane. The prepared sample properties are presented in Table (3).

2.3. Test Procedure All the samples were tested with a large-scale cyclic triaxial apparatus manufactured by Wykeham Farrance in United Kingdom. The samples diameters and heights were 15 cm and 30 cm, respectively.

Based on ASTM D 3999 - 91 (Reapproved 2003) [26], clauses 10.3, 10.4, and 10.5, all the samples were saturated, and pore water pressure parameter, B , ($B = \Delta u / \Delta \sigma$) reached over 95%. Then each sample was consolidated isotropically under 50, 100, 200 and 300 kPa pressures.

Then the consolidated undrained cyclic triaxial tests (CU) with 1^{Hz} frequency and under stress controlled condition with 40 cycles were undertaken.

As suggested by Kokusho [38], the 11th cycle output data was used for calculation and diagram layout.

TABLE 2. The specifications of soil-granulated rubber mixtures

Granulated rubber (%)	Optimum water content (%)	Maximum dry unit weight (kN/m ³)	Minimum dry unit weight (kN/m ³)	Mixture specific gravity
0.0	6.6	21.68	13.63	2.65
8.0	7.8	19.42	12.85	2.38
10.0	8.4	19.03	11.38	2.32
14.0	9.2	18.05	10.98	2.21

TABLE 3. The prepared sample properties

Granulated rubber (%)	Moisture unit weight (kN/m ³)	Dry unit weight (kN/m ³)	void ratio, e	Relative density, D_r (%)
0.0	22.00	20.64	0.259	91.47
8.0	20.14	18.68	0.250	92.25
10.0	19.47	17.96	0.266	91.14
14.0	18.67	17.10	0.267	91.37

2.4. Test Results and Discussion The shear modulus-shear strain amplitude curves for the soil-granulated rubber mixtures are presented in Figure (2) for the confining pressures of 50, 100, 200, and 300 kPa and 0.0, 8, 10, and 14% of granulated

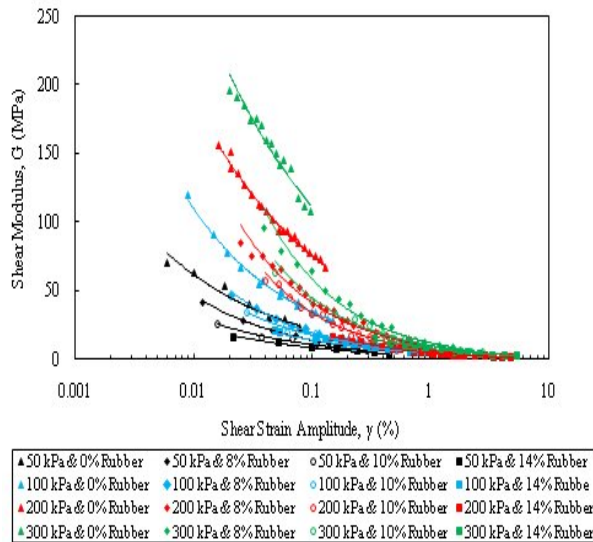


Figure 2. Shear Modulus versus Shear Strain Amplitude for the Confining Pressures of 50, 100, 200 and 300 kPa and the Variation of Granulated Rubber Percentages.

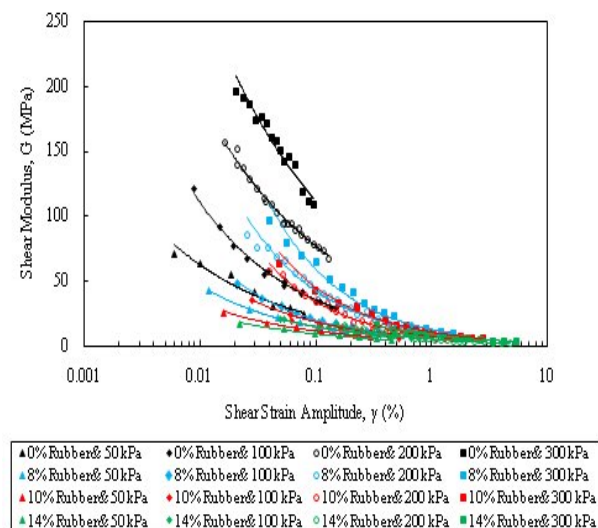


Figure 3. Shear Modulus versus Shear Strain Amplitude for 0.0, 8, 10 and 14% Granulated Rubber and the Variation of Confining Pressures.

rubber additive. The results indicate that at a constant confining pressure, with an increase in granulated rubber percentage, shear modulus decreases. This result was predictable by comparing the stiffness of rubber and soil grains. Also, by replacement of the soil grains with granulated rubber the mixture becomes more softer and the shear modulus decreases.

The shear modulus-shear strain amplitude curves for the soil-granulated rubber mixtures are presented in Figure (3) for addition of 0.0, 8, 10, and 14% granulated rubber and the confining pressures of 50, 100, 200, and 300 kPa. It can be observed that, for the soil with or without rubber, with an increase in confining pressure, shear modulus increases. This phenomenon is due to increasing intergranular friction as a result of an increase in confining pressure which leads to an increase in stiffness.

Figure (3) also shows that, with an increase in granulated rubber percentage, the effect of the confining pressure on shear modulus decreases. This coincides with the results obtained by Feng and Sutter [5], who worked on sand-granulated rubber. They showed that, in soil-rubber mixtures containing high percentage of rubber, the material tends to behave more elastic, and also the influence of confining pressure on the material's stiffness is insignificant.

2.5. Maximum Shear Modulus (G_{max}), Reference Shear Strain (γ_r) and Normalized Shear Modulus (G/G_{max}) The general trend observed in Figures (2) and (3) shows that the stated curves follow the well-known Hyperbolic model used by Hardin and Drnevich in 1972 [39].

$$\frac{G}{G_{max}} = \frac{I}{I + \frac{\gamma}{\gamma_r}} \quad (1)$$

where G_{max} is the maximum shear modulus and γ_r is known as the reference shear strain.

Using regression analysis on obtained laboratory experimental data (G and γ), and Equation (1), the values of G_{max} and γ_r are evaluated and the results are plotted in Figure (4) and Figure (5).

Figure (4) shows that as rubber percentage increases, both the values of G_{max} and difference

between its values in different confining pressures decrease. This result is compatible with the results obtained by Feng and Sutter [5].

Figure (5) shows that, with an increase in rubber inclusion, the reference shear strain (γ_r) increases. This can be explained that, as the rubber inclusion increases, the mixture becomes more flexible and softer. Therefore, the slope of stress-strain diagram decreases and causes an increase in γ_r values.

It seems that the predicted values for maximum shear modulus and reference shear strain follow a logical and acceptable trend. So in the absence of experiments in low strains (e.g. resonant column test), the predicted values presented in Figures (4) and (5) may be used as maximum shear modulus and reference shear strain for the tested material in this study, and as a result these values will be used for calculations.

To reach a continuous and experimental relation between physical and mechanical properties and stress conditions applied to soil-granulated rubber mixtures, Equation (2) has been used. It is the experimental relationship which predict the G_{max} values and offered by Kokusho [40].

$$G_{max} = A.F(e).(\sigma_3)^n \quad (2)$$

where $F(e)$ is known as the void ratio function, [41], and is determined as follows:

$$F(e) = \frac{(2.17 - e)^2}{1 + e} \quad (3)$$

By replacing $F(e)$ in Equation (2) with that of Equation (3), Equation (4) is obtained.

$$G_{max} = A. \frac{(2.17 - e)^2}{1 + e}. (\sigma_3)^n \quad (4)$$

Investigation into the properties of rubber/sand mixtures carried out by Feng and Sutter 2000 [5] suggests that the rubber inclusion may be approximated and equated to the void ratio of the soil (i.e., $R \sim e$).

In this research, further studies were carried out to clarify the approximation, to examine the applicability and suitability and to present a new model. Considering Equation (4), the current

model is suggested to predict G_{max} values as follows:

$$G_{max} = A \times \frac{(a - R)^2}{b + R} \times \sigma_3^n \quad (5)$$

Equation (5) is the same as Equation (4) making us to approximate G_{max} values continuously based on rubber percentage and confining pressure. The constants A , a and b as well as n in Equation (5) are obtained by

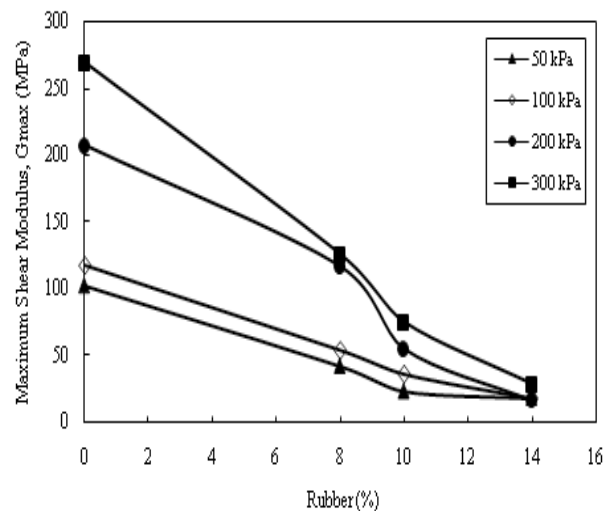


Figure 4. Maximum Shear Modulus versus Granulated Rubber Percentage for the Variation of the Confining Pressures.

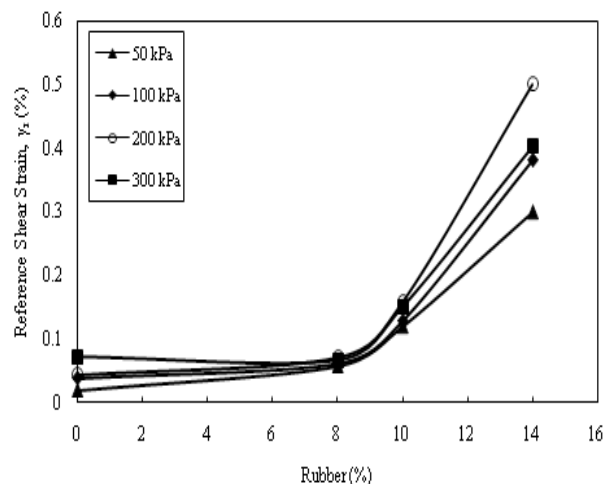


Figure 5. Reference Shear Strain versus Granulated Rubber Percentage for the Variation of Confining Pressures.

regression analysis and are presented in Table (4).

Figure (6) shows the graphical comparison of variation of G_{max} predicted by Hyperbolic model (Equation 1) and those obtained by Equation (5) using constant values presented in Table (4).

It is understood that the values of G_{max} obtained from Equation (5) have an acceptable correlation with those values predicted by Hyperbolic model. So the maximum shear modulus of the soil-granulated rubber mixture can be calculated using Equation (5) and constants stated in Table (4).

Considering the values of G_{max} predicted by Hyperbolic model (Equation 1), the non-dimensional values of G/G_{max} are determined in terms of R and σ_3 as functions of γ . It is understood that γ_r , itself, is dependent on R and σ_3 ; hence, Equation (1) was expanded to examine such dependency. Trial and error functions were used to reach the following relation:

$$\frac{G}{G_{max}} = \frac{1}{1 + [A \times \sigma_3^n \times (1 + R)^m] \times \gamma} \quad (6)$$

Using the values of G/G_{max} and γ and regression analysis, the constants of A , m and n are calculated and presented in Table (5).

It may be noted that Equation (6) is in fact the expansion of Hyperbolic model (Equation 1), so the term in bracket in Equation (6) is equated to an equation for γ_r . Therefore,

$$\frac{1}{\gamma_r} = A \times \sigma_3^n \times (1 + R)^m \quad (7)$$

Figure (7) shows the graphical presentation of reference strain values (γ_r) against rubber inclusion predicted by Hyperbolic model (Equation (1)) and those defined by Equation (7) using constant values presented in Table (5).

Considering Figure (7) it is understood that, there is a good correlation between reference strains predicted by Hyperbolic model and those predicted by Equation (7). So Equation (7) can be used to calculate the reference shear strain of the soil-granulated rubber mixture.

Finally, the values of G/G_{max} were calculated using Equation (6) and regression analysis constants presented in Table (5) and were plotted in Figures (8) to (11).

In Figures (8) to (11), the symbols are the

TABLE 4. Determined regression analysis constants A , a , b and n for Equation (5)

Constant	Value
A	39847.7
a	0.275
b	0.53
n	0.67

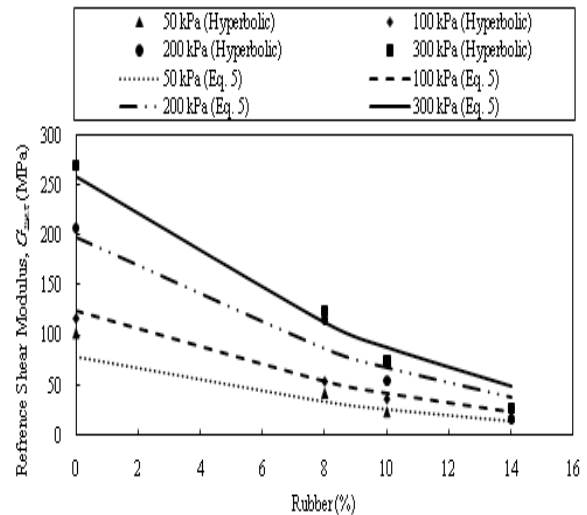


Figure 6. Maximum Shear Modulus versus Granulated Rubber Percentage Obtained from Hyperbolic Model (equation 1) and Equation (5)

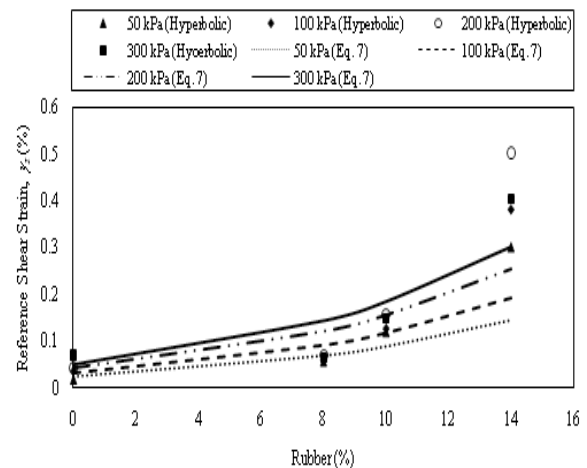


Figure 7. Reference Shear Strain (γ_r) versus Granulated Rubber Percentage Obtained from Hyperbolic Model (equation 1) and Equation (7).

values of G/G_{max} in which the maximum shear modulus is predicted by Hyperbolic model (Equation (1)), and the curves represent the values of G/G_{max} calculated by Equation (6) and constants in Table (5).

The effect of the confining pressure on G/G_{max}

TABLE 5. Determined regression analysis constants A , m and n for Equation (6)

Constant	Value
A	207.65
m	-13.70
n	-0.41

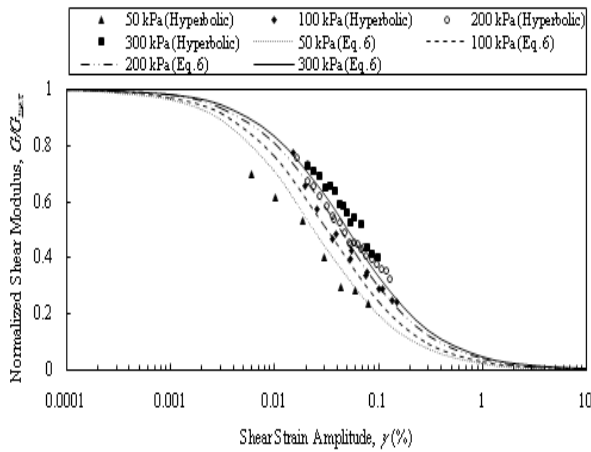


Figure 8. Normalized Shear Modulus versus Shear Strain Amplitude for 0.0% Granulated Rubber and the Variation of the Confining Pressures.

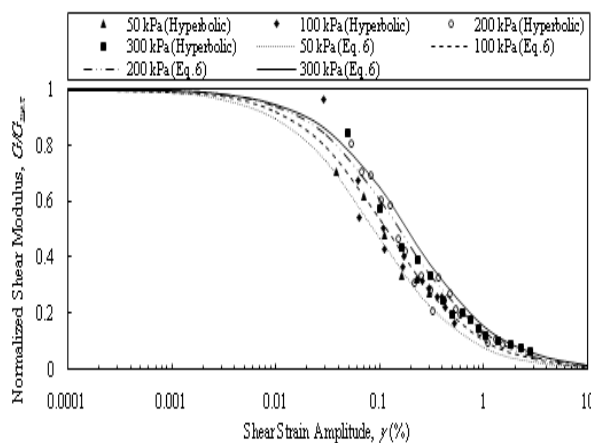


Figure 9. Normalized Shear Modulus versus Shear Strain Amplitude for 10.0% Granulated Rubber and the Variation of the Confining Pressures.

values for the various rubber inclusion percentages is presented in Figures (8) and (9). It can be observed that, for a given percentage of rubber, as confining pressure increases, the values of G/G_{max} increases. This phenomenon results from an increase in material stiffness due to an increase in confining pressure.

Figures (10) and (11) show the impact of rubber inclusion on G/G_{max} for the variation of confining pressures. It can be observed that, at a given confining pressure, the values of G/G_{max} increase with an increase in rubber percentage. This phenomenon shows more elastic and flexible behavior (uniform behavior) of the mixture by increasing the rubber percentage.

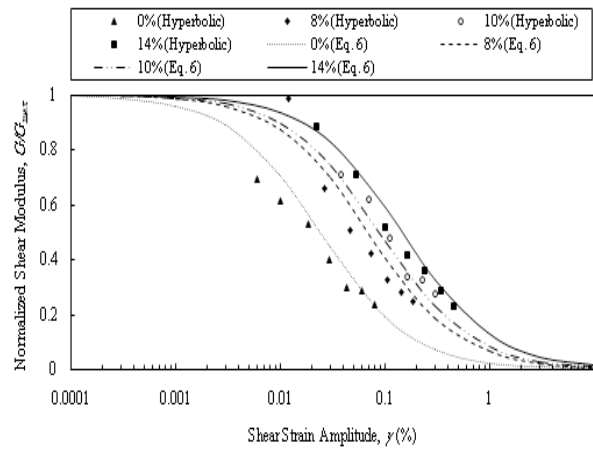


Figure 10. Normalized Shear Modulus versus Shear Strain Amplitude for the Confining Pressure of 50 kPa and the Variation of Granulated Rubber Percentages.

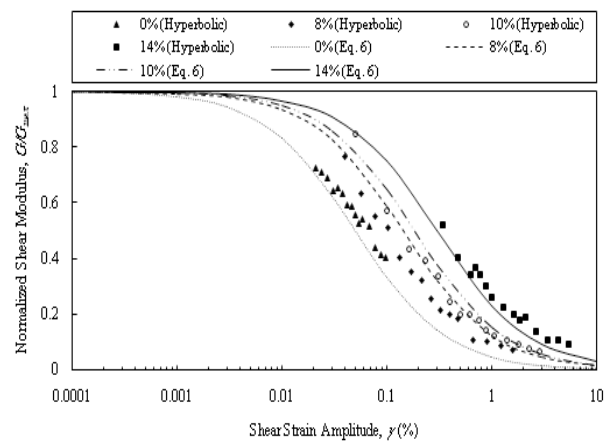


Figure 11. Normalized Shear Modulus versus Shear Strain Amplitude for the Confining Pressure of 300 kPa and the Variation of Granulated Rubber Percentages.

The summary of the test results for Shear modulus and Normalized shear modulus are presented in Table (6).

TABLE 6. The summary of test results for shear modulus and Normalized shear modulus

	Increase in Confining Pressure	Increase in Rubber Inclusion
Shear Modulus	increase	decrease
Normalized Shear Modulus	increase	increase

3. THE RETAINING WALL ANALYSIS

Using the experimental results and relations reached in the first section and in order to investigate the influence of using these mixtures as a lightweight fill behind the retaining wall on the horizontal pressure and displacement during earthquake, a retaining wall was modeled using FLAC software.

The dimensions of the model are presented in Figure (12). In this model the properties of the natural soil and fill behind the wall were in accordance with the properties specified in Table (7).

3.1. Static Analysis In order to make the loading conditions in the model more real, 100 kPa uniform load was applied to the earth on the two sides of the wall. After static analysis, the values of the stress in the three main directions were obtained for each element. So the confining pressure for each element was defined using the Equation (8).

$$\sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \quad (8)$$

3.2. Dynamic Analysis The Hysteresis damping

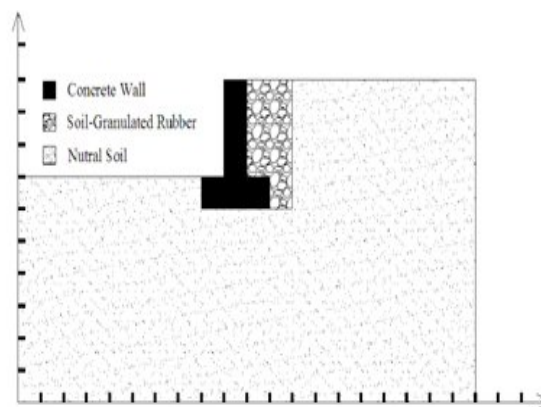


Figure 12. The Retaining Wall Model

was used for dynamic analysis. Different models such as Default model, Sigmoidal models and Hardin/Drnevich model have been defined for this kind of damping in FLAC software. And considering the relations obtained in the first section, the Hardin/Drnevich model was used to determine the dynamic behavior of the material. In Hardin/Drnevich model in FLAC software, reference shear strain (γ_r) is used as Hardin number to determine the dynamic behavior of the material. In the present study, for the natural soil, only the changes in the confining pressure were viewed, and for the soil behind the wall, the changes in confining pressure and granulated rubber percentage were taken into consideration.

To analyze and determine dynamic response of the model the basic parameters G_{max} and γ_r are required. So, these parameters have to be defined as continuous functions of confining pressure and rubber percentage for the natural soil and the fill behind the wall.

3.2.1. Determination of Max. Shear Modulus and Reference Shear Strain for Natural Soil

To define the value of G_{max} for the natural soil, the characteristics stated in Table (7) and Equation (9) offered by Braja M. Das in 1993 [42] are used.

TABLE 7. The Soil Characteristics

Soil	PI	e	G_s	γ_d (kN/m ³)	γ_{sat} (kN/m ³)	v	E_{static} (kN/m ²)
Natural	20	0.7	2.77	17.9	19.33	0.35	8622
0%	4	0.2	2.65	21.68	23.3	0.30	70884
10%	-	0.286	2.495	19.03	21.21	0.40	11940
14%	-	0.322	2.433	18.05	20.44	0.40	4135

$$G_{max} = \frac{3230}{1+e} (2.97-e)^2 (OCR)^k (\sigma_m)^{1/2} \quad (9)$$

where e is void ratio, OCR is over consolidation ratio, and σ_m is the average confining pressure in kPa. By applying the characteristics of Table (7) to Equation (9), this equation is summarized to Equation (10) which defines max shear modulus according to confining pressure for natural soil.

$$G_{max} = 9790.5(\sigma_m)^{1/2} \quad (10)$$

To determine the reference shear strain (Hardin No.) for the natural soil as a continuous function of confining pressure, the Hyperbolic model (Equation (1)) is used. In Equation (1), the reference shear strain can be expressed as Equation (11).

$$\frac{1}{\gamma_r} = A \sigma_m^n \quad (11)$$

So the Hyperbolic model (Equation (1)) changes to Equation (12) as follow:

$$\frac{G}{G_{max}} = \frac{1}{1 + A \sigma_m^n \cdot \gamma} \quad (12)$$

To get the constants, A and n, in Equation (12), the relations offered by Darendeli in 2001 [43] are used in a way that G/G_{max} and γ_r were obtained for the different confining pressures, and then the above stated constants presented in Table (8) were determined using Equation (12) and regression analysis.

TABLE 8. Equation (12) Constants

Constant	Value
A	84.394
n	-0.337

Figure (13) shows the comparison between the values obtained from the relation offered by Darendeli [43] and those determined using Equation (12).

Figure (13) demonstrates an acceptable compatibility between the two values stated above. Accordingly, the values of γ_r for the natural soil are determined using Equation (11) as a continuous

function of confining pressure.

As a result, after static analysis and determination of main stresses for each element, the values of G_{max} and γ_r are calculated using Equations (8), (10) and (11) and the constants of Table (8) and accordingly the properties of each element are also obtained.

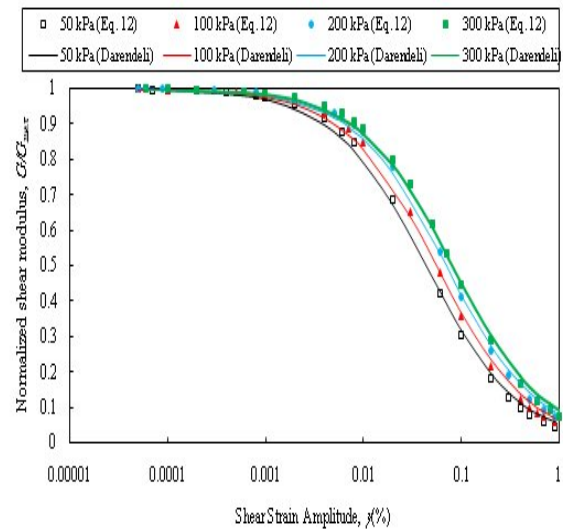


Figure 13. The Values of G/G_{max} obtained from the relation offered by Darendeli and those determined by Equation (12)

3.2.2. Determination of Maximum Shear Modulus and Reference Shear Strain for the Mixture of Soil and Granulated Rubber With respect to Equations (5) and (7) it is understood that the values of G_{max} and γ_r can be obtained as continuous functions of confining pressure and rubber percentage. So, after static analysis and determination of the main stresses, G_{max} and γ_r are determined for each element using Equations (5), (7) and (8) with due consideration of rubber percentage.

3.2.3. Input Motions Input motions include two strong earthquakes, El Centro (California, 1940) and Tabas (Iran, 1978). The acceleration of these two earthquakes is presented in Figures (14) and (15).

3.2.4. Dynamic Analysis Result To investigate the effect of using soil-granulated rubber mixture behind the retaining wall on its dynamic response during the earthquakes, the values of horizontal

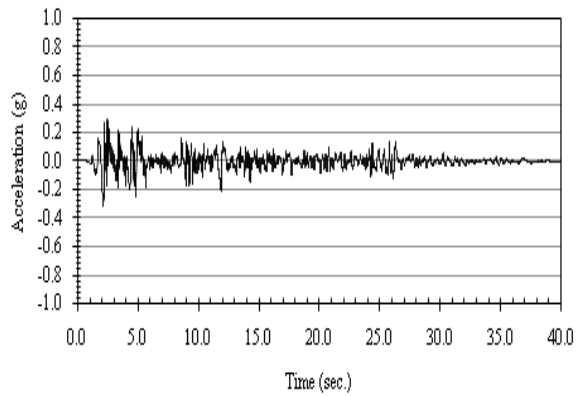


Figure 14. Acceleration-Time Diagram Earthquake (El Centro, 1940)

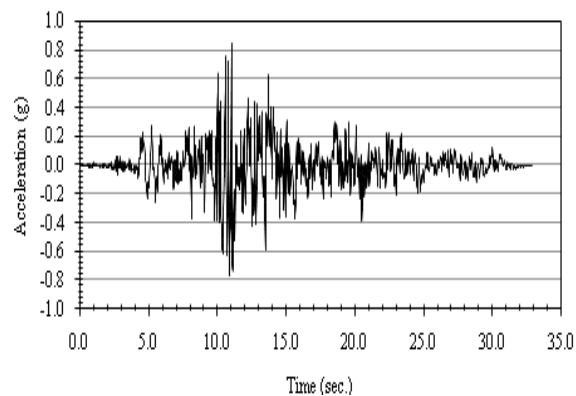


Figure 15. Acceleration-Time Diagram Earthquake (Tabas, 1978)

pressure and displacement were analyzed in three points of the wall (up, middle, down). The values in the following diagrams are just the results of the dynamic analysis, and static results are omitted.

Figure (16) is an output sample of the FLAC software for the displacement time history of the middle of the wall for different rubber percentages. This figure shows that the value of residual displacement in the wall after earthquake reduces with an increase in rubber percentage. In this figure, the negative and positive values are indications of the wall movement towards the fill and backwards, respectively.

Figure (17) is an output sample of the FLAC software for the pressure time history of the down point of the wall for different rubber percentages. This Figure shows that the values of Maximum horizontal pressure applied to the wall reduced as rubber percentage increased. In this Figure, the

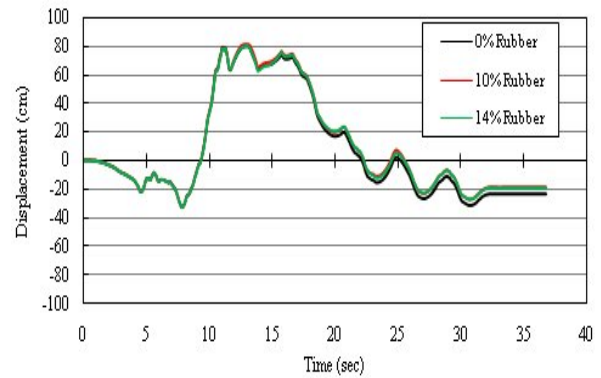


Figure 16. Displacement-Time History (middle point, Tabas)

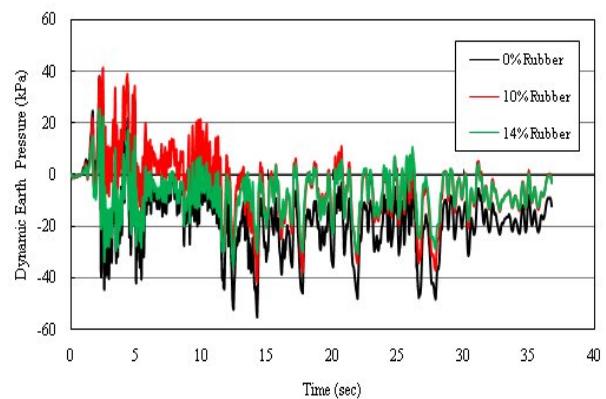


Figure 17. Pressure-Time History (down point, El Centro)

negative and positive values are indications of pressure and tension on the wall respectively.

The summary of the obtained values for residual displacement and maximum horizontal pressure applied to the wall during the two earthquakes, (Tabas and El Centro) for different rubber percentages in the three points of the wall are shown in Figures (18), (19), (20), and (21).

Figures (18) and (20) show that the residual displacement of the wall (backwards the fill) decreases with an increase in rubber percentage. This indicates that an increase in rubber percentage causes less displacement in the wall at the end of the earthquakes. This result is compatible with the results obtained by Hazarika et al. [24].

Figures (19) and (21) show that, with an increase in rubber percentage, the maximum horizontal pressure applied to the wall decreased. This coincides with the results obtained by

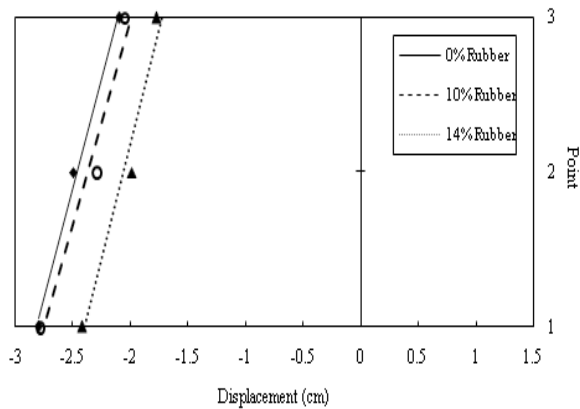


Figure 18. Residual Displacement Values in the Wall for Different Rubber Percentages in the El Centro Earthquake

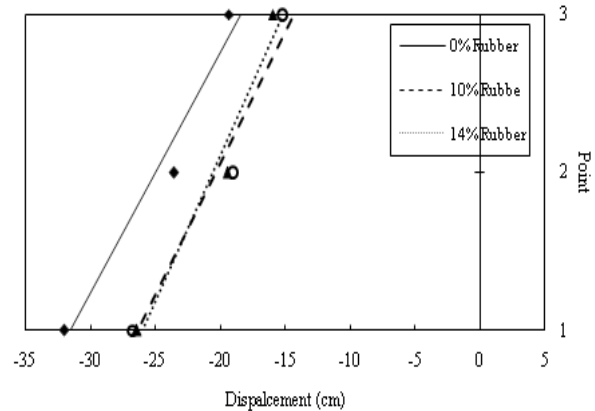


Figure 20. Residual Displacement Values in the Wall for Different Rubber Percentages in the Tabas Earthquake

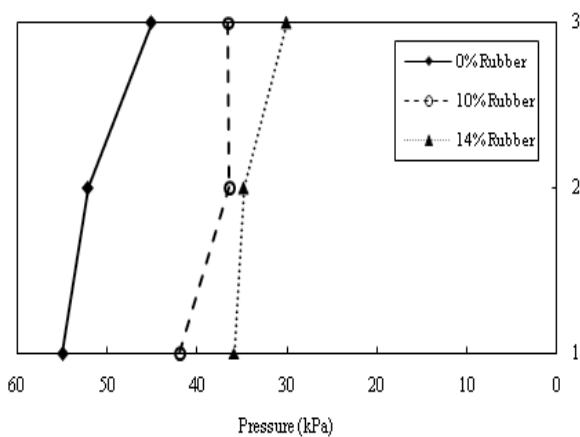


Figure 19. Maximum Horizontal Pressure Values Applied on the Wall for Different Rubber Percentages in the El Centro Earthquake

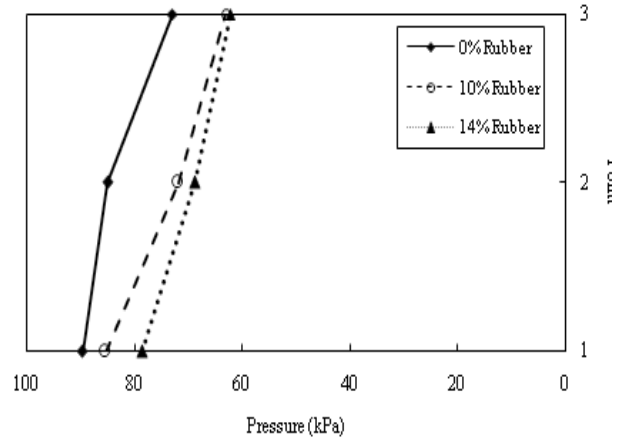


Figure 21. Max Horizontal Pressure Values Applied on the Wall for Different Rubber Percentages in the Tabas Earthquake

Hazarika et al. [24]. A decrease in the forces caused by an earthquake lead to a decrease in design forces applied to the retaining wall. This results in a decrease in wall dimensions and construction expenses which all optimize the wall building.

4. CONCLUSIONS

In the present research a series of large-scale consolidated undrained cyclic triaxial tests was carried out using granular soil-granulated rubber mixtures. Based on the tested materials, the following conclusions are made:

1. The residual displacement of the wall (backwards the fill) decreased with an increase in rubber percentage. This contribution indicates that an increase in rubber percentage causes less displacement in the wall at the end of the earthquakes.
2. The maximum horizontal pressure applied to the wall decreased with an increase in rubber percentage. A decrease in the forces caused by an earthquake lead to a decrease in design forces applied on the retaining wall.
3. Shear modulus decreased with an increase in rubber inclusion for all the confining pressures.

4. Shear modulus increased with an increase in the confining pressure for any percentage of rubber inclusion.
5. A model was introduced to predict G_{max} for the various confining pressures and rubber inclusion percentage.
6. A model was established to evaluate the Normalized shear modulus (G/G_{max}) versus shear strain amplitude (γ) for the various confining pressures and rubber inclusion percentage.
7. For a given percentage of rubber, with an increase in confining pressure, the values of G/G_{max} increased.
8. At a given confining pressure, the values of G/G_{max} increased with an increase in rubber inclusion percentage.

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