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INNOVATIVE UNDERGROUND EARTHQUAKE ISOLATION SYSTEM GEO-ISOLATOR

Samyar SARRAF[1], Sadyar SARRAF[2], Kiarash DOLATSHAHI[3], Reza RAFIEE[4]

ABSTRACT

Seismic waves propagate through interior of the earth from earthquake focus to ground surface. The final portion of this traveling is often through the soil that can greatly influence the nature of shaking on the surface. Herein, a new isolation system is introduced to mitigate seismic waves before entering into the structure by changing the soil nature of underlying ground aggregates, named by the authors as geo-isolator. Rubber-Soil Mixture (RSM) is the target material used as the isolator ingredients. Moreover, because of geomaterials sensitivity to plasticity, nonlinearity and cyclically stress-strain modeling, this research utilizes Manzari-Dafalias advanced constitutive law and nonlinear soil response modeling. The main target of this research is to find the design spectra for isolated soil plus evaluation and comparison between isolated soil, pure ground soil and ASCE design spectra for site response analysis. Therefore, seven known excitation records, considering peak ground values, duration and frequency content, are chosen and scaled to be assigned as the uniform base displacement over the bottom of the numerical model. Results, in the form of response spectra, for superstructure period ranges between 0.0 to 4.0 seconds are obtained and finally are smoothed and formulated for 84.1% statistical consideration to find codes design curve template form. The results show the average reduction ability of 30~35% for geo-isolator while this magnitude is comparable to conventional methods such as base-isolation system.

Keywords: Geo-Isolator; Design Spectra; Rubber-Soil Mixture; Isolation System;

1. INTRODUCTION

From the beginning of the world, earthquakes have been occurred and will continue happening in the future. The most dramatic and memorable images of earthquake damages are indeed those of structural collapse (Kramer 1996). There are two fundamental approaches to mitigate earthquake damages on structures. The first approach is fortifying the structural lateral resistance system, using structural elements, in order to tolerate exerted earth motion forces. These systems include moment resistance frames, shear walls and braces. The first approach which is also known as conventional method is well-known, constructor-accepted and it has been widely used within the engineering practice; however, this method increases dead load of structure which can be undesirably costly. Designing usual elements and structural systems deals with whole arise earthquake energy exerting to the structure during ground motions. Diminishing earthquake forces by utilizing instrument named quake-attenuating systems before entering into the structure is known as the second approach. The second approach is less practiced in the literature and needs to be more explored.

The main goals of quake-attenuating in buildings are to absorb energy and to attenuate the exerted forces into structures as a result of ground motions; therefore, it makes considerable subsidence in story acceleration and story drifts that overall result is visible in designing forces carried by each elements. Quake-attenuating systems are divided into two main categories of Dampers and Isolators. The main factor distinguishing between dampers and isolators is operation fields. In fact, dampers are considered as structural elements in structure design procedure; moreover, dampers discharge a portion of available structure energy imposed by ground motion. Although isolator also partake into structure design procedure, isolator is located outside of structure

[1] Correspondent Author, Sharif University of Technology-Kish campus, Tehran, Iran, sarraf@kish.sharif.edu
[2] Civil Engineering Department, Sharif University of Technology-Kish campus, Tehran, Iran, sadyar.sarraf@gmail.com
[3] Civil Engineering Department, Sharif University of Technology, Tehran, Iran, dolatshahi@sharif.edu
[4] School of Civil Engineering, University of Tehran, Tehran, Iran, rezarafiee@ut.ac.ir

and in the series form. In controversy to dampers, Isolators filter a portion of passing earthquake energy before entering into structure. Notwithstanding achievements and developments in the field of dampers and isolators production, applying of them in structures is proportional to following complicated technology and subtle engineering; furthermore, installation and initiation depend on educated and expert crew and finally such attenuating systems need maintenance and repair during the useful structural life time. The aforementioned reasons lead to limitation and high-cost of utilizing such system especially in developing countries.

Nowadays civil engineering suffers from the lack of such quake-attenuating systems to be able to respond simply but applicable mechanism at the same time for almost all types of structure. Inspired by Patent No.: US 6,862,848B1, year 2008 Tsang published an article and introduced new system of isolation (Tsang 2008). This system is formed from rubber and soil mixture located in the base ground under structure foundation. Tsang showed the ability of mitigation of earthquake energy and isolation wave transition of this system for a ten story building. Afterward Kaneko conducted pseudo-dynamic response test and concluded that this system is effective for both seismic isolation and to prevent liquefaction and Xiong proposed that seismic isolation performance of rubber soil mixture is inferior to that of a foundation underlain by pure-sand, carried out by shaking table tests with a 1/3 scale rubber–soil mixtures model. All these evaluations prove the isolation ability of rubber-soil mixture as an isolator system. Therefore, researches over this new idea has begun and researches such as Senetakis et al. has started to find the behavioral parameters of rubber-soil mixture.

2. GEO-ISOLATOR

2.1 Idea Inspiration

Seismic waves travel from the source of an earthquake to the ground surface. The final portion of this traveling is often through soil and characteristic of the soil can greatly influence the nature of shaking at the ground surface. Soil acts as a filter for seismic waves by attenuating and amplifying the motion frequencies to the others. Inspired by this natural phenomenon, herein, it is aimed to propose a new idea that involves changing soil nature of under base by materials with known specifications to mitigate, deviate, refract and reflect seismic waves before entering into structure, named by the authors as *Geo-Isolator*.

2.2 Materials

Base-isolators is made from two parts of resistant section (lead) and mitigating section (rubber). Geo-isolator system categorizes in the same manner; however, allowable range of material stresses decrease from steel power to soil power by transferring isolator system from column-foundation junction to underground position. This changing over range of stresses help to consider more types of material as isolator aggregates. Appropriate choice for resistant section of geo-isolator is the same soil which not only accessible but also economical. For mitigating section, materials with high damping features, considerable hysteretic curve, low stiffness and reasonable ultimate stress is intended. Thus, although material used by past researchers was rubber, other materials with those four specific features have to find this chance to be considered. Such material may be named as elastomers, soft polymers, oil derivatives and etc. In spite of this consideration, this research, similar to past researches, utilizes the mixture of rubber and soil as geo-isolator material. In geotechnical engineering, the mix of shredded tires and sand is known as rubber-sand mixture or RSM. ASTM D6270 − 08 (Reapproved 2012) standard approve applicability of this material and determines some rules for the manner of being used in civil engineering project such as lightweight retaining wall backfill, drainage layers for roads, thermal insulation to limit frost penetration, vibration damping layers for rail lines, lightweight embankment and replacement for soil or rock in other field applications. One of the important rule which is relevant to this project states that RSM layer cannot be buried more than of 3 m depth.

2.3 Constitutive Law: Stress-Strain Relation

Choosing proper constitutive modeling has great influences on the geo-isolator results; in fact, initial evaluations conducted by Tsang (2008) considered elastic-linear behavior which led to depth of 10 m of isolation system that not only seems unreasonable, but also it is against ASTM rules. This result shows the sensitivity of geo-isolator system to nonlinear and plastic consideration of stress strain modeling. Based on this feature, researchers started to obtain geo-isolator experimental parameters. Senetakis et al. (Senetakis et al. 2012) offered cyclic nonlinear modeling of hyperbolic method and afterward Pitilakis et al. (Pitilakis et al. 2015) used advanced constitutive model of Von-Mises criteria to model behavior of geo-isolator. Finally, S. Brunet et al. (Brunet et al. 2016) succeeded to prove that geo-isolator layer is completely efficient for depth lower than 3 m which is in accordance to ASTM rules. Therefore, recognition and selection of constitutive modeling is one of the majority of this research.

Geotechnical engineering science classifies material stress-strain cyclic behavioral modeling into three types (Kramer 1996). As shown in Figure 1, the simplest method is equivalent linear modeling that only two constant coefficient values are needed. Cyclically nonlinear method improves reality of material behavior by using curves instead of constant coefficients and by considering Massing rules. The highest accuracy rate is observed in advance constitutive modeling which considers variety of complexity of real material features (Desai et. al. 1984). Simplicity of the first two modeling leads these methods to be very common between engineers. Despite of recent popularity of advance constitutive method, reasons such as complexity, computational cost and variety of input parameters are made this method not to be an attractive method between engineers. However, because of necessary accuracy needed for this research, advance constitutive modeling type is targeted. In 2004 Manzari-Dafalias (Dafalias & Manzari 2004) introduced a constitutive model which has the best compliance to sand behavior. This method considers a wider range of soil behavioral features as plastic and anisotropic hardening, changing size and translation of yielding surface, bauschinger effects, cyclic and hysteresis consideration (Desai et. al. 1984). Not only Manzari-Dafalias shows good compliances to sand behavior, but also Mashiri et. al. (Mashiri et. al. 2015) offered a constitutive law for RSM material which shows great similarity of RSM behavior to Manzari-Dafalias modeling.

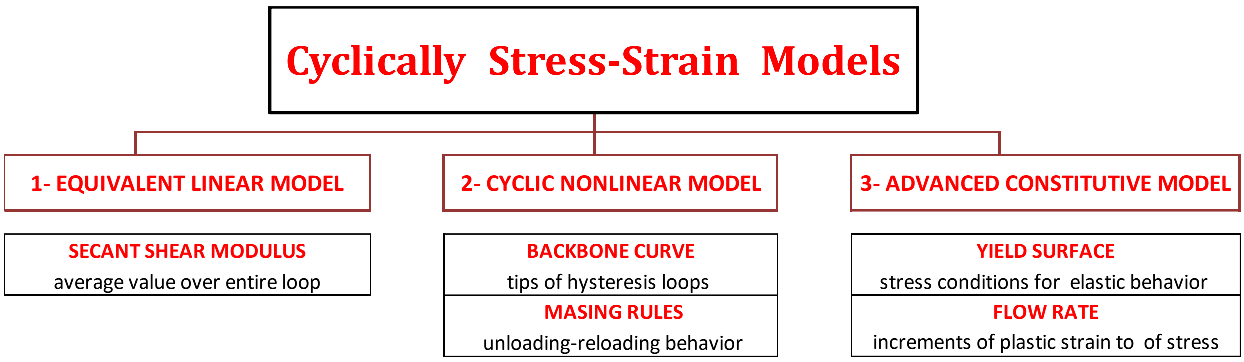

Figure 1. Classification of Soil Constitutive Modeling

2.4 Soil Response Modeling

Soil response modeling is another important factors; in fact, choosing proper soil modeling for full compatibility with the chosen Manzari-Dafalias constitutive law, low range nonlinearity and plastic behavior of soil is in great majority. Regarding to the three types of ground response modeling methods shown in Figure 2, the best suit response modeling is nonlinear approach specified by implicit time domain analysis. The other approaches, linear or equivalent modeling analyzed in frequency domain, are ignored because of relying on superposition rule that results to linear assumption and unfollowing of mentioned majorities.

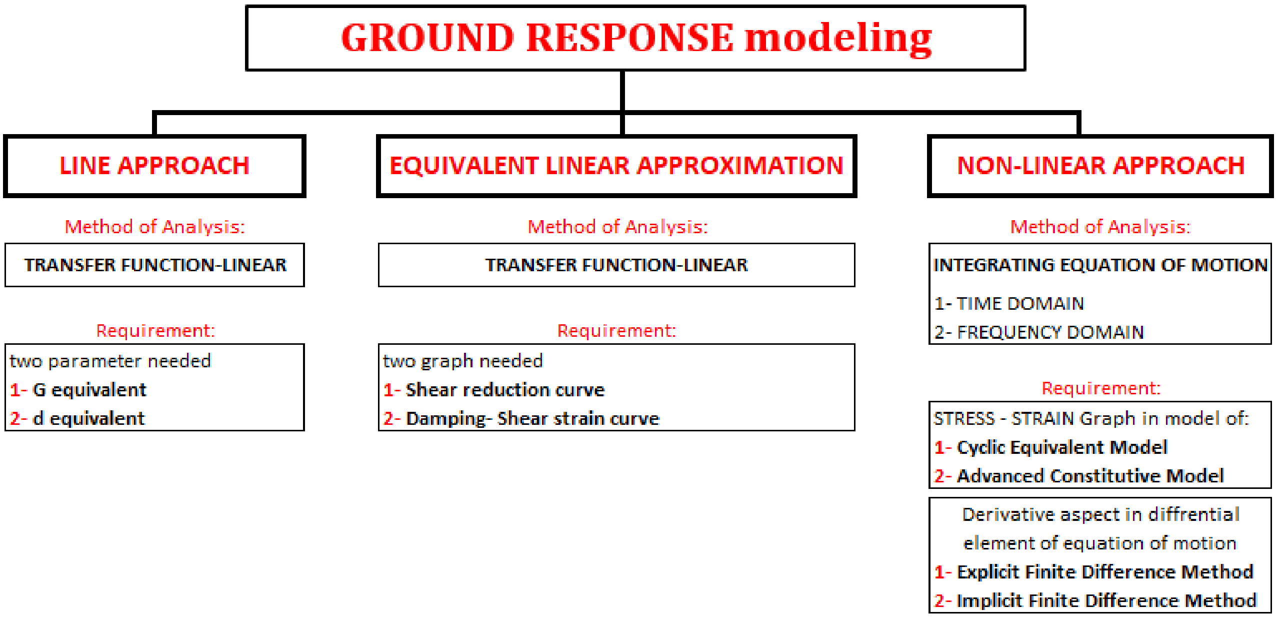

Figure 2. Soil Analytical Modeling Types

3. MODELING

3.1 FE Modeling Specifications

Analytical element modeling is considered in 2D plane strain condition for a rectangular shape of ground simulation with the dimension of 50m width to 30 m depth, while units are in metric tons, second and meter. Imposed materials follow Manzari-Dafalias constitutive modeling over all elements specified as 1x1 m^2 quad four noded four Guass integration points 2 DOF single phase, schematic details are shown in Figure 3. FE calculation is performed on OpenSees software framework which is one of the powerful FE application and is the only software that supports Manzari-Dafalias law. 10x3m^2 area under structure is replaced by the geo-isolator materials and is located between superstructure and pure ground soil. Foundation is considered mass-less in the purpose of not participation into dynamic response of superstructure, while top surface nodes are tied to center node connected to superstructure node. Superstructure performs in elastic isotropic small strain material behavior for period ranges between 0.0 to 4.0 seconds and constant damping coefficient of 5%.

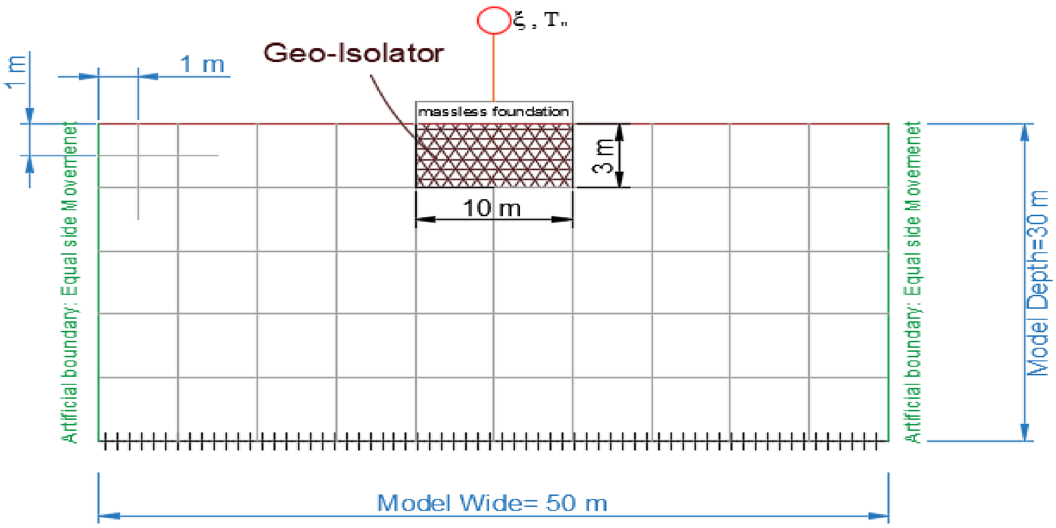

Figure 3. Schematic Modeling of Geo-Isolator FE Modeling

Finite Element Method can only model a finite portion of soil although real ground is unbounded. Thus, FE dynamic analysis involves reflection of wave propagation and disturbances at artificial boundaries of cutting sides of model. To transmit waves outside of model, Artificial boundary is used over cutting edges. Among available artificial boundaries such as Lysmer's dampers, spring damper and others, because of permanent displacement of earthquake excitation which leads to final residual displacement of whole model and simplicity consideration, equal boundary which is equal side displacement of FE modeling is the best suit boundary applied to FE modeling (Towhata 2008).

Numerical analysis is performed on the software framework of OpenSees which is one of the open source application software in the fields of soil, structure and soil-structure interaction. Model has been passed through error optimization of element size and time step by procedure of error estimation and Adaptivity methods of FEM (Khoei 2014), which is suggested in literature to choose element size less than 0.10 wave length (Semblat & Brioist 2000).

3.2 Soil Specifications

3.2.1 Soil Parameters

Two types of material are assigned for soil: ground soil is considered as Toyoura sand and geo-isolator is considered as RSM 35%. Parameters for Toyoura sand is offered from Manzari-Dafalias (Dafalias & Manzari 2004) article and parameters relevant to isolation layer is obtained from experimental results of Mashiri (Mashiri et. al. 2015), Tsang (Tsang et. al. 2012), Sheikh (Mashiri et. al. 2015) and Senetakis (Senetakis et. al. 2012 and 2016). These results are collected from different examination of cyclic triaxial apparatus, monotonic apparatus, resonant column apparatus and bender element apparatus. The reasons of utilizing variety of experimental devices are allowable strain ranges and types of outputs results of each device, while selected constitutive law contain 18 parameters which is offered in table 1.

Table 1. Manzari-Dafalias Material Parameters [metric ton, m, s]

Parameter	Soil	Geo-Isolator
G_0	125	50
υ	0.4	0.4
e_{init}	0.8	0.33
e_0	0.934	0.534
λ_c	0.019	0.25
ξ	0.7	0.4
P_{atm}	100	100
c	0.712	0.8
m	0.01	0.01
M_c	1.25	1.36
n_b	1.1	8.4
n_d	3.5	1.0
h_0	7.05	10.70
C_h	0.968	0.4
A_0	0.704	0.495
z_{max}	4	4
c_z	600	600
ρ	1.42	1.35

3.2.2 Soil Damping

Damping modeling over numerical analysis contain two parts of uncounted loads and hysteretic damping. Hysteretic damping is accounted by nonlinear-plastic stress-strain modeling of material behavior and uncounted damping forces such as temperature or other source of loading which is not considered in modeling.

Soil material, especially sands, shows rate independent behavior. This is why each soil has only one specific damping-strain curve. However, FE modeling of time domain is established by following of rate dependent damping modeling. In fact, this happened because of simplicity of rate dependency compare to rate independent over modeling and acceptable relative error results between them. Therefore, one of the benefits of Manzari-Dafalias law is to eliminate the damping coefficient and considering it as the hysteretic damping made by constitutive law. Newmark (Newmark 1982) evaluation revealed that materials show two different damping behaviour due to their range of strain. To clarify reasons why each damping value is assigned to each part of modeling, it is important to notice that although ground modeling parts follow Manzari-Dafalias model, hypo-elastic section of constitutive model is assigned for soil part and only isolation layer is controlled by elasto-plastic response. Consequently, no damping coefficient is considered for isolation layer while the value of 7% damping is imposed for remaining soil. In addition, 12% damping ratio is assumed for pure ground case.

3.2.3 Soil Layering

Reasons of soil layering may be discussed as capturing trapped shear waves known as love waves and considering different soil wave velocity in the depth of soil profile. Soil modeling in 2D plane strain condition causes blocking out of plane displacement. This leads that love waves do not have a chance to appear in such modeling. This condition allows in plane wave propagation which has higher rate of priority in earthquake engineering. Moreover, imposing soil weight due to geostatic procedure of analysis leads to relative changes in soil density over depth that results to soil wave profile variation. Top of them, uniform hypo-elastic ground soil is assumed for the purpose of not considering a specific soil conditions and generalize results of this research.

3.3 Earthquake Excitation

Seven well-known earthquake records, Table 2, are applied for this research evaluation. Variety of these records have been chosen based on frequency content, duration features, frequency contents, the number of vibration which is in higher magnitudes and according to FEMA-440a and FEMA-P695. Even though ASCE code determined at least 5 records for site response analysis, this research choose 7 earthquake of table 2.

Table 2. Ertquake Excitation Record (PEER Strong Motion Database)

Event	Date	Recording station	Frequency range
Chi-Chi (Taiwan)	September 20, 1999	TCU045	0.02-50.0 Hz
Friuli (Italy)	May 06, 1976	TOLMEZZO (000)	0.1-30.0 Hz
Imperial Valley (USA)	October 15, 1979	USGS STATION 5115	0.1-40.0 Hz
Kobe (Japan)	January 16, 1995	KAKOGAWA(CUE90)	0.1-unknown
Landers (USA)	June 28, 1992	000 SCE STATION 24	0.08-60.0 Hz
Loma Prieta (USA)	October 18, 1989	090 CDMG STATION 47381	0.1-40.0 Hz
Northridge (USA)	January 17, 1994	090 CDMG STATION 24278	0.12-23.0 Hz

3.3.1 Effective Duration

High numerical cost of advance plasticity modeling and earthquake consideration motivate for using effective duration of each record. Hence, determining effective duration of this research is followed by Trifunac-Brady (1975) method. This method modifies duration by excitation energy intensity accounting and choosing time period between 5% to 95% energy intensity as record duration. All records are modified by this method.

3.3.2 Scaling

Peak acceleration of records is scaled to the magnitude of 0.35g which is known as a high value of bed-rock acceleration for structural design procedure. In addition, since excitations are imposed over bedrock of the model, the peak values rise while waves travel from base to ground surface.

3.3.3 Excitation Types

Excitation of soil dynamic analysis are usually imposed in two main approaches: uniform displacement and force excitation. Uniform base displacement excitation is chosen for this research which is an analytical modeling for soil located over bedrock in nature. The excitation is assigned by horizontal shear wave, SH-wave, applied to base; but, to capture more realistic results compare to nature, by considering Poisson ratio of ground, model experiences 2D wave propagation with higher priority of SH wave, since plasticity modeling makes unavailable utilizing superposition rule.

3.3.1 Outcrop

The records which have been used are those available in global seismic center data base and the conversion between surface to base rock of each one is ignored and all records are considered as outcrop excitation. This decision is based on not applying specific conversion for a specific soil, lack of ground site parameters for each record and stiff soil assumption for records based on FEMA695. Furthermore, evaluating on these records over own frequencies are conservative because transferring from surface to bottom is a decreasing procedure over record values. Additionally, comparison between pure soil and isolated model is excluded from outcrop issue.

4. DESIGN SPECTRA

Finding proper design spectra for isolated ground is the target goal of this research; indeed, this design curve is added to available codes design curve for isolated soil consideration. Therefore, without setting any limitation through superstructure shape, use and dimension, isolated ground can analyze and design in conventional codes procedure by utilizing geo-isolator design curve. This point is the major superiority of this isolator type compare to others available method.

To evaluate reliability of this research results, pure soil ground and isolated ground responses are compared with design curve of ASCE-Minimum Design Loads for site-specific ground motion seismic design. By considering soil material used in this research, ASCE soil classification type D for stiff soil is determined as ground specification and ASCE Deterministic Lower Limit on MCE_G Response Spectrum is applied for this purpose.

4.1 Response Spectrum

Seven earthquake records response analysis for superstructure period range between 0 to 4 and modeling without superstructure is evaluated and results reveal over Figure 5 for pure ground soil and Figure 4 for isolated buildings are offered. To obtain design spectra of each one, mean values (μ) curve for 50% consideration of responses and mean value plus one standard deviation ($\mu+\sigma$) curve for 84.1% consideration of responses are plotted in Figure 4 and Figure 5. Variety range of response spectrum prove the workability of selected earthquake records.

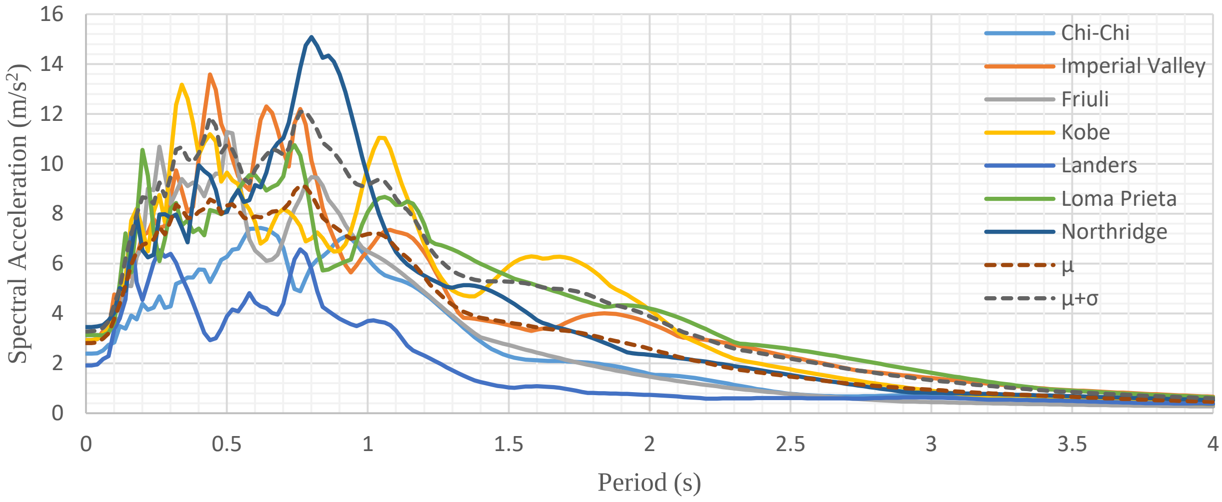

Figure 4. Isolated Ground Response Spectrum

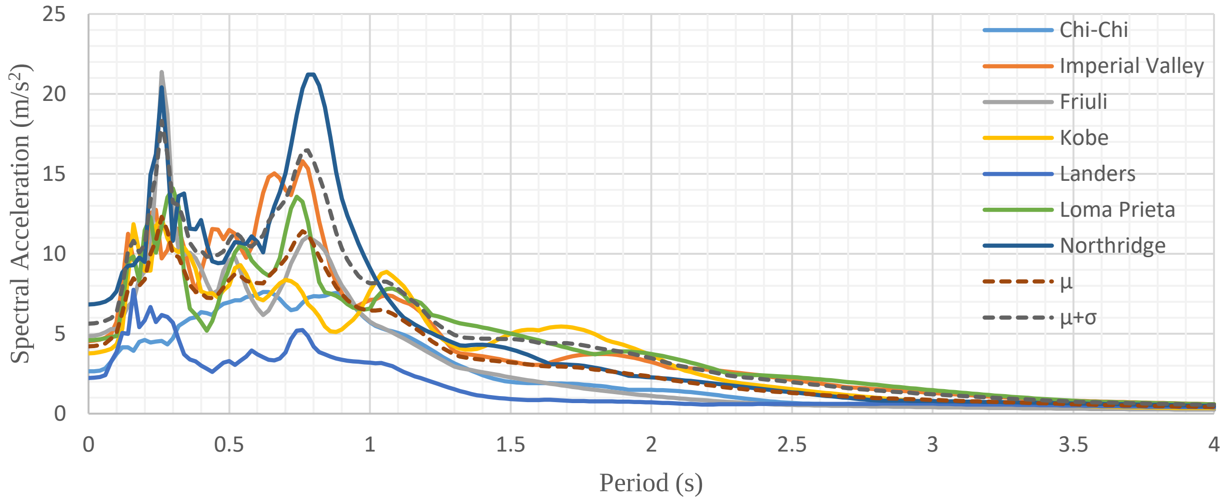

Figure 5. Pure Soil Response Spectrum

4.1.1 Response Evaluation

Evaluation over these results reveals that apart from base ground experience of 0.35g peak acceleration, for pure ground soil, ground surface feel higher magnitude as 0.7g peak acceleration in the worst case. Nonetheless, geo-isolator model does not experience more than of 0.35g acceleration in the worst case. Furthermore, geo-isolator system has great influences for vibration which are higher than 0.2g acceleration magnitude, as is mentioned over past research results by Brunet et al (Brunet et al 2016). This issue may consider that geo-isolator system may fail without superstructure and its interactional effects; but, results over free-field data prove the ability of 20% to 35% reduction for these cases.

4.2 Isolated and Non-Isolated Response Spectrum Comparison

To find design spectra and making a comparison between pure soil and isolated ground response, mean value plus one standard deviation (μ+σ) curve with 84.1% consideration of spectral responses are chosen to smooth in accordance to gain codes design curve shapes, as shown in Figure 6. In consequence, curves are divided into four section of equation: linear small period section, constant spectral acceleration section, inverse period function section and square inverse function of period for long period section.

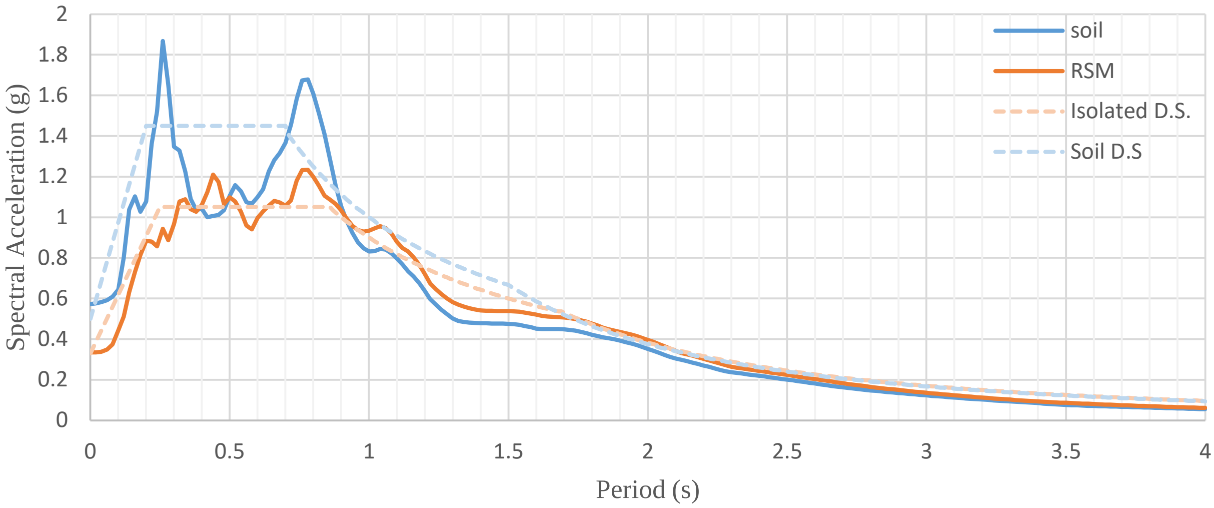

Figure 6. Isolated and Non-Isolated Comparison

4.2.1 Evaluation

Although response of soil is equivalent to isolated ground for high period values, geo-isolator system leads to considerable subsidence for structures. Despite that, pure soil curve shows lower values for high period magnitudes than isolated curve, following four section of codes equation for best suiting with response spectrum is the reason why design curve of pure soil is located above isolated curve partially. However, this problem does not significantly affect isolated design curve calculation, which is in priority, while the soil design curve is for comparison purposes.

4.3 Design Curves and Evaluation

The final practical results of this research are design curves which is shown in Figure 7. Differences between soil design curve and ASCE minimum design curve is less than 5% which is due to applied soil plasticity modeling. While design curves response in same limits for long period section, great impact of isolation system is outside of this ranges and for long period other mitigation method may be suggested. However, since design curve basis is the minimum design curve of ASCE, long period section of this design curve may change for different condition and different site properties.

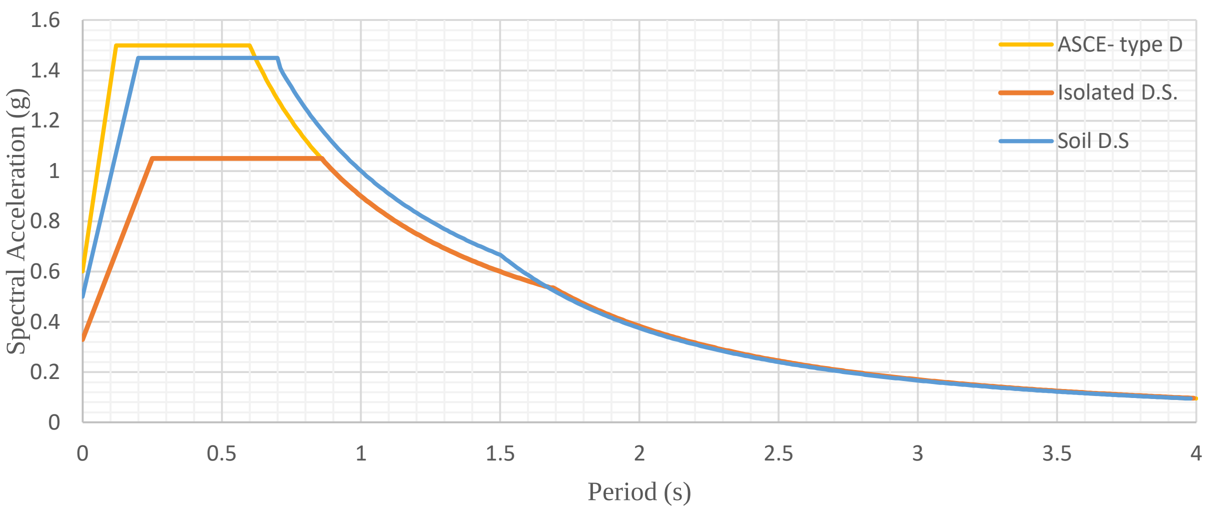

Figure 7. Design Spectra Curves

5. CONCLUSION

Geo-isolator is a new isolation system, which is located in the ground under the foundation. This system mitigates earthquake peak acceleration such that for the worst case of ground 0.7g excitation, isolated structure experiences 0.35g peak acceleration. Results of this research are offered in the form of design spectra, by evaluating seven scaled excitations soil response analyses. The important outcomes of this research are as follow:

- Based on frequency content, duration, peak values, number of high magnitude vibration and codes suggestion from FEMA-P695 and FEMa-440a, seven earthquake records are chosen and applied to a nonlinear plastic behavior model. Responses are in the form of response spectra that are changed into design curves for two types of pure ground soil and isolated soil.
- Geo-isolator shows the average reduction of 30~35% for seismic waves effect, while this value is remarkable compared to the base-isolator system. This reduction is due to the number of vibration exceed the minimum level of 0.2g acceleration; in fact, this system limits the maximum value of acceleration that ground surface can experience.
- Geo-isolator shows considerable reduction in low period range and equal values for high period domain. However, imposing weigh of real structure for high period range is forecasted to show notable reduction for those ranges too.
- Geo-isolator system has the ability of being utilized for any superstructure with different shape, usage, and dimension. In fact, geo-isolator is located outside of the structure that makes a series of function between the isolator and superstructure response.
- The great advantage of this new isolation system is the lack of requirement for making any changes into superstructure design procedure. Actually, since geo-isolator system changes the nature of ground motion, this system can be designed separately and the structure is designed via isolated design curve.
- Codes obtain minimum design criteria which maintain a level of non-destructive protection for building. Geo-isolator system not only maintain this feature, but it is able to guarantee performances of important building after earthquake excitation because of its reduction level.
- Although foundation has specific dimension, results can be expanded to conventional structures because of equal surface foundation node movement which is tied to the superstructure node.

Although 2D wave propagation is captured by considering evaluation conducted by imposing base shear wave excitation, the effect of love waves and independent surface motion sources are not involved. This field is suggested as future works while these effects may not be as much important.

Manzari-Dafalias parameters evaluation over numerical analysis reveals that there is a good chance to find other suitable materials such as soft polymers, elastomers and oil derivatives to show even better results for geo-isolator system.

6. REFERENCES

Anastasiadis, A., Senetakis, K., & Pitilakis, K. (2012). Small-Strain Shear Modulus and Damping Ratio of Sand-Rubber and Gravel-Rubber Mixtures. Geotechnical and Geological Engineering, 30(2), 363–382. https://doi.org/10.1007/s10706-011-9473-2

Brunet, S., de la Llera, J. C., & Kausel, E. (2016). Non-linear modeling of seismic isolation systems made of recycled tire-rubber. Soil Dynamics and Earthquake Engineering, 85, 134–145.https://doi.org/10.1016/j.soildyn.2016.03.019

Dafalias, Y. F., & Manzari, M. T. (2004). Simple Plasticity Sand Model Accounting for Fabric Change Effects. Journal of Engineering Mechanics, 130(6), 622–634. https://doi.org/10.1061/(ASCE)0733-9399(2004)130:6(622)

Khoei, A. R. (2014). Extended finite element method. extended finite element method: theory and applications. https://doi.org/10.1002/9781118869673.

Kramer, S. L. (1996). Geotechnical Earthquake Engineering. Prentice-Hall, Inc. http://doi.org/10.1007/ 978-3-540-35783-4, ISBN 0-13-374943-6

Lopera Perez, J. C., Kwok, C. Y., & Senetakis, K. (2016). Effect of rubber size on the behaviour of sand-rubber mixtures: A numerical investigation. Computers and Geotechnique, 80, 199–214. https://doi.org/10.1016/j.compgeo.2016.07.005

Mashiri, M. S., Vinod, J. S., & Sheikh, M. N. (2015). Constitutive Model for Sand–Tire Chip Mixture. International Journal of Geomechanics, 4015022. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000472

Mashiri, M. S., Vinod, J. S., Sheikh, M. N., & Tsang, H. H. (2015). Shear strength and dilatancy behaviour of sand-tyre chip mixtures. Soils and Foundations, 55(3), 517–528. https://doi.org/10.1016/j.sandf.2015.04.004

N. M. Newmark, and W. J. Hall, Earthquake Spectra and Design, Earthquake Engineering Research Institute, Berkeley, Calif., 1982.

PEER Strong Motion Database, https://ngawest2.berkeley.edu/

Pitilakis, K., Karapetrou, S., & Tsagdi, K. (2015). Numerical investigation of the seismic response of RC buildings on soil replaced with rubber-sand mixtures. Soil Dynamics and Earthquake Engineering, 79, 237–252. https://doi.org/10.1016/j.soildyn.2015.09.018

Semblat, J. F., & Brioist, J. J. (2000). Efficiency of higher order finite elements for the analysis of seismic wave propagation. Journal of Sound and Vibration, 231(2), 460–467. https://doi.org/10.1006/jsvi.1999.2636.

Senetakis, K., Anastasiadis, A., & Pitilakis, K. (2012). Dynamic properties of dry sand/rubber (SRM) and gravel/rubber (GRM) mixtures in a wide range of shearing strain amplitudes. Soil Dynamics and Earthquake Engineering, 33(1), 38–53. https://doi.org/10.1016/j.soildyn.2011.10.003

Towhata, I. (2008). Geotechnical Earthquake Engineering. Springer, ISBN 978-3-540-35782-7

Tsang, H. H., Lo, S. H., Xu, X., & Neaz Sheikh, M. (2012). Seismic isolation for low-to-medium-rise buildings using granulated rubber-soil mixtures: Numerical study. Earthquake Engineering and Structural Dynamics, 41(14), 2009–2024. https://doi.org/10.1002/eqe.2171

Tsang, H. H. (2008). Seismic isolation by rubber-soil mixtures for developing countries. Earthquake Engineering and Structural Dynamics, 37(2), 283–303. https://doi.org/10.1002/eqe.756

Wood, D. M. D., Britto, A. M., Gunn, M. J., Desai, C. S., Siriwardane, H. J., Roscoe, K., & Burland, J. (1984). Constitutive Laws for Engineering Materials: With Emphasis on Geologic Materials. Change. https://doi.org/10.4324/9780203477977