# MITIGATION OF EARTHQUAKE HAZARDS OF MEDIUM-RISE BUILDINGS BY USING DIFFERENT SOIL IMPROVEMENT METHODS

by

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# ABSTRACT

## MITIGATION OF EARTHQUAKE HAZARDS OF MEDIUM-RISE BUILDINGS BY USING DIFFERENT SOIL IMPROVEMENT METHODS

Earthquakes can be hazardous to occupants and their assets, especially in some regions such as Turkey, Japan, Chile, and the United States of America etc. Nowadays, some regulations were published to mitigate the hazards occurring in buildings during earthquakes. Besides, the hazards can be mitigated by making use of different soil improvement methods such as Geotechnical Seismic Isolation (GSI) Systems which earthquake loads transferred from ground to structure are decreased using geotechnical materials. Gravel and Gravel-Rubber Mixtures (GRM) can be alternative materials for the GSI system because they provide more bearing capacity, less earthquake-induced settlements and high permeability. The aim of this thesis is to evaluate the effectiveness of the proposed Gravel and Gravel Rubber Mixtures (GRM) materials on the seismic performance of low-to-medium rise buildings by means of 1/10 scaled 3 and 5-story building models by shaking table tests. The shaking table experiments were conducted by considering different rubber content, thickness of GSI and the number of stories under various seismic motions. Within the scope of this thesis, all improved cases were compared with unimproved cases. This study showed that surrounding building foundations with Gravel or Gravel Mixtures plays a key and favorable role in the mitigation of earthquake hazards by dissipating earthquake energy inside the soil.

# ÖZET

## ORTA KATLI BİNALARIN DEPREM HASARLARININ FARKLI ZEMİN İYİLEŞTİRME YÖNTEMLERİ KULLANARAK AZALTILMASI

Depremler, özellikle Türkiye, Japonya, Şili ve Amerika Birleşik Devletleri gibi bazı bölgelerde bina sakinleri ve onların malları için tehlikeli olabilir. Günümüzde, depremler sırasında binalarda meydana gelen hasarları azaltmak için bazı yönetmelikler yayınlanmıştır. Ayrıca, zeminden yapıya aktarılan deprem etkilerinin geoteknik yöntemler ve malzemeler kullanılarak azaltıldığı Geoteknik Sismik İzolasyon (GSI) Sistemleri gibi farklı zemin iyileştirme yöntemleri kullanılarak hasarlar azaltılabilir. Çakıl ve Çakıl-Kauçuk Karışımları (GRM), daha fazla taşıma kapasitesi, daha az deprem kaynaklı oturmalar ve yüksek geçirgenlik sağladıkları için GSI sistemi için alternatif malzemeler olabilir. Bu tezde, önerilen Çakıl ve Çakıl Kauçuk Karışım (GRM) malzemelerinin az ve orta yükseklikteki binaların sismik performansı üzerindeki etkinliğini 1/10 ölçekli 3 ve 5 katlı bina modellerinin davranışını sarsma tablası testleri ile değerlendirilmesi amaçlanmaktadır. Farklı sismik hareketler altında farklı kauçuk içeriği, GSI kalınlığı ve kat sayısı dikkate alınarak sarsma masası deneyleri yapılmıştır. Bu tez kapsamında tüm iyileştirilmiş vakalar, sadece Silivri Kumu içeren iyileşmemiş vakalarla karşılaştırılmıştır. Bu çalışma, Çakıl veya Çakıl Karışımları ile çevreleyen bina temellerinin, deprem enerjisini zemin içinde yayarak deprem tehlikelerinin azaltılmasında önemli ve olumlu bir rol oynadığını göstermiştir.

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# LIST OF SYMBOLS

| | |
|---|---|
| *a* | Acceleration |
| *A* | Accelerometer |
| *f* | Frequency |
| *G* | Shear modulus |
| $G_{max}$ | Maximum shear modulus |
| *Hz* | Hertz |
| *m* | Mass |
| *Sa* | Spectral acceleration |
| *t* | Thickness |
| *T* | Period |
| *W* | Weight |
| *Cc* | The Coefficient of Uniformity |
| *Cu* | The Coefficient of Curvature |
| *Dr* | Relative Density |
| *g* | Gravitational Acceleration |
| *G* | Gravitational Constant |
| *Gs* | Specific Gravity |
| *SP* | Poorly Graded Sand |
| Φ | The Internal Friction Angle |

# LIST OF ACRONYMS/ABBREVIATIONS

| | |
|---|---|
| *A* | Accelerometer |
| *ASTM* | American Society for Testing and Materials |
| *D* | Displacement Sensor |
| *FAS* | Fourier Amplitude Spectrum |
| *GRM* | Gravel Rubber Mixture |
| *GSI* | Geotechnical Seismic Isolation |
| *ODS* | Optical Distance Sensor |
| *PGA* | Peak Ground Acceleration |
| *PGD* | Peak Ground Displacement |
| *PGV* | Peak Ground Velocity |
| *SI* | Seismic Isolation |

# 1. INTRODUCTION

## 1.1. General

Earthquakes can be hazardous to occupants and its assets especially in some regions such as Turkey, Japan, Chile, and United States of America. etc. There are various components effecting hazards like the magnitude of earthquake, distance of the epicenter, the structure of soil and the methods of building construction and the merging of these components.

Nowadays, some regulations were published to mitigate the hazards occurring on the buildings during earthquake, and structural engineers design structures by considering these regulations. However, they recommend that adding more structural elements to the building to enhance resistance capacity of structures. Also, some earthquakes cause excessive accelerations or large inter story drifts in the structures. Furthermore, the structures can be damaged as much as not repair.

However, the earthquake hazards can be mitigated by making use of different soil improvement methods. In recent years, a novel method which is the changing of existing foundation soils to provide better performance under different loading condition is one of the most preferred seismic protection techniques against severe seismic conditions in structures. Also, the one of soil improvement methods is improving the soil under the building foundation with mixtures like sand-rubber and gravel-rubber.

Several research have been done to determine the behavior of Gravel Rubber Mixtures (GRM) in the use of civil engineering applications. All these works showed that the inclusion of GRM can particularly enhance the resistance of soil foundations, but the results should need more evidence to be clear. In this thesis, the experimental studies were conducted to mitigation of earthquake hazards of medium-rise buildings by using soil improvement methods including GRM.

## 1.2. Objectives and Problem Statement

The last research showed that seismic isolation methods are beneficial to decrease earthquake hazards, but they are not affordable especially for the developing countries. Because of that, more cost-effective and more practicable solutions should be applied for these countries. Tsang (2008)[1] presented a new approach named Geotechnical Seismic Isolation (GSI) on addressed to these situations and problems. Most of the GSI systems can be considered as distributed covering and isolating all foundation surfaces so this property is different from common systems based on isolation at discrete supporting points.

There are several researches related seismic isolation with rubber-soil mixtures. This research has shown that rubbers have beneficial physical and mechanical properties for designing and building of the civil structures. In the parallel to these results, rubber-sand mixtures are largely being used and investigated in literature for seismic isolation.

But these mixtures have low-elastic modulus and high-compressibility, and these properties cause differential settlement and insufficient bearing capacity for the foundation. As a solution to solve this important problem, a novel geomaterial as Gravel-Rubber Mixtures (GRM) introduced by Hazarika et al. (2016) [2]. Nevertheless, studies on GRM are still very limited compared to sand rubber mixtures. Therefore, this thesis is the pioneering and unique study in the experiments on the evaluation of the efficiency of gravel-rubber mixtures as GSI material.

This thesis focusses on the investigating the efficiency of the GRM as GSI material on the mitigation of earthquake hazards of low and medium-rise buildings by performing shaking table tests. In this research, a new GSI material was investigated to assess how the seismic performance of the low-to-midsize building model would be affected.

Rubber content, the thickness of GSI, different earthquake motions and the number of storeys were selected as key parameters and were examined the effects of these parameters on the seismic performance of building models. At the end of this study, the cases have the best seismic performance was determined for 5-storey and 3-storey building models.

# 2. LITERATURE REVIEW

## 2.1. Seismic Isolation Systems

Seismic isolation which is an efficient technique has been used around the world to protect structural and non-structural components from the damaging effects ofground shaking for years. (Warn and Ryan,2012) [3]. One of the Seismic Isolation systems is base isolation concepts and it includes many component as Figure 2.1

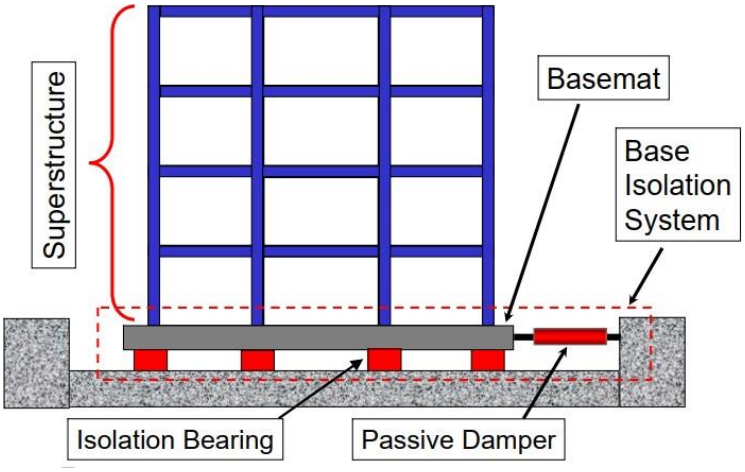



Figure 2.1. Building Structure with Base Isolation Systems (Symans, 2009)[4].

Many different ideas were proposed to allow a structure to slide like the use of rollers, similar materials, and sand layers up to now. Furthermore, some buildings have been built on rollers in Sevastopol, and a 5 stories school in Mexico City. Even, a structure that is located in China and has a sand layer between the foundation and the structure was designed to allow for sliding during an earthquake. (Kelly, 2004)[5] ‘*’tomb of cyrus’’* that was built in Pasargadac, Iran in 6$^{th}$ century is the first structure that has the basis of the base isolation concepts for protecting structures from earthquakes. It has great deep smoothed stone and mortar foundation. These stones were connected for forming a plate at the time of earthquake.

Also, other ancients have tried various isolation systems such as forming layers sand or gravel under the foundation and constructing above a stack cut- out stones. Furthermore, timber was used to dissipate the earthquake induced energy under bearing

walls by rolling on each other. (Hussain, 2014)[6]. Jules Touaillon was published a US patent for a novel and efficient method of constructing buildings to be resistant against earthquakes. The impressive renders showed the elevation of a building that improved by an isolation system that making up of an order of opposite facing concave spherical surfaces separating with by balls (Figure 2.2). (Makris,2019)[7]

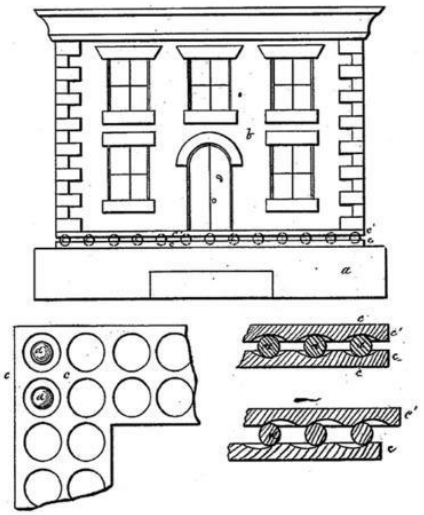


Figure 2.2. Plans for Isolating a Structure in 1870 (Makris,2019).

The first application of seismic isolation was applied in the design of the Imperial Hotel in Tokyo, Japan. This structure was completed in 1921. There was an 8-feet layer of fairly good soil and below 70-feet layer of soft mud with minimum shear strength at the hotel site. (Makris,2019)[7]

In 1970's, base isolation was used on bridges in the early 1970's then buildings came later. The first patent for the recent innovation of mechanical isolators was released in 1980. (Hussain, 2014)[6]. Base isolation was firstly used in bridges in 1970's (Kelly, 2001)[8]. In 1985, the seismic isolation was applied firstly in America by means of elastomeric bearings as base isolation (Kelly, 2004)[4].

Qualitatively, ordinary structures experience increasing acceleration at upper floors and deformations for stories of the structure (i.e.,interstory drifts). However, isolated structures have deformation at the first story of the structure primarily (i.e., within the isolation system) then the accelerations are relatively uniform through the height.

Behavior of conventional and base isolated structures is given in Figure 2.3. There are many objectives of Seismic Isolation systems, and these can explained as below (Symans, 2009)[4]:

- Increase of the likelihood of using structures at earthquake event.
- Structural and non-structural elements become less deformed.
- Decreasing acceleration response to protect the structures
- Increase of the flexibility for extending period of vibration.
- Dissipating the energy for controlling the isolation system displacement.
- Rigidity when exposed low loads like wind and earthquakes forces.

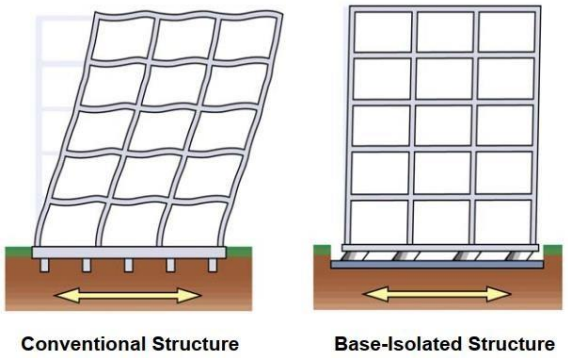



Figure 2.3. Conventional and Base Isolated Structures Behaviour (Symans, 2009)[4].

Seismic isolation provides the longer fundamental natural period of structures by adding flexible isolation mechanisms at the bottom of the structures to separate the structure with the ground. In this way, the amount of the energy dissipating to the structure is reduced. (Figure 2.4) When it is compared isolated structures with non-isolated structures, former one needs less floor accelerationand interstudy drift demands for earthquake excitation. When the demand reduces, the superstructure start to be elastic or nearly elastic after the design process. (Warn and Ryan,2012)[5]

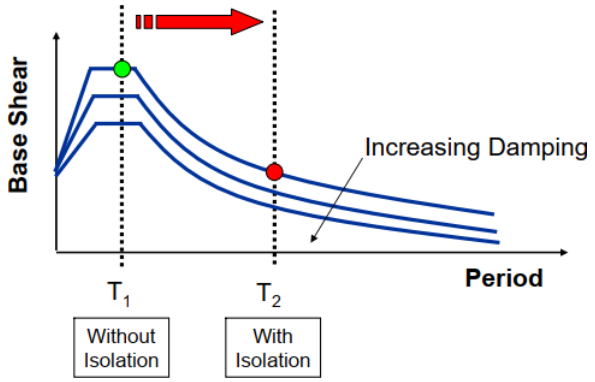



Figure 2.4. Effect of Seismic Isolation (Acceleration Response Spectrum Perspective)

The main effect of Seismic Isolation (SI) is to extend the natural period which increases the displacement demand. But the displacement demand is transferred from the superstructure to the isolators (Figure 2.5).

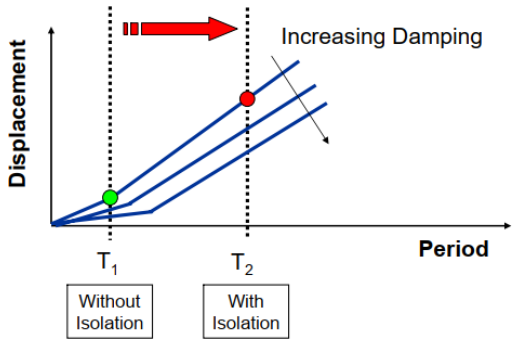



Figure 2.5. Effect of Seismic Isolation (Displacement Response Spectrum Perspective) (Symans, 2009)[4].

## 2.2. GSI-Geotechnical Seismic Isolation Concept

Since 1970's structural earthquake engineering studies have focused on the improvements of capacity design basis and inelastic-structural response. Theseconcepts affected the design of the structure as earthquake resistant. Although the concepts are successful to ensure the life safety, some earthquakes (e.g. 1994 Northridge, 1995 Kobe) which occurred in 90's and 2000's caused huge amount of economic losses due to the structural damages. Thus, it must be limited loss of life and property in the future earthquakes and this limitation can be provided with becoming the use of seismic

isolation and energy dissipation systems as a more attractive approach. (Tsang and Pitilakis, 2019)[9].

Seismic isolation with laminated elastomeric bearings or sliding bearings for structures has been common since 1960's. However, this design approach has been transitioned from the prescriptive to versatile performance those days and the use of new technology including the concept of Geotechnical Seismic Isolation (GSI) start to be more prominent.

Tsang (2008)[1] firstly brought the GSI concept that dissipates the seismic energy inside the soil before it transmits into the structure and reduce the effect of earthquake forces to superstructure. Thus, it is different from conventional structural isolation systems with this feature (Forcellini, 2020)[10]. Geotechnical Seismic Isolation has been applied in recent constructions in Greece, Portugal (Pecker, 2003)[11].

Common base isolation systems have some limitations such as the installation and maintenance costs and discovering modern cost-efficient methodologies is essential for developing countries. (Tsiavos et al. 2019)[12] Because of that, there are two recently proposed distinctive and promising methods by GSI Concepts for developing countries. (Figure 2.6) One of them is smooth synthetic liners dissipating seismic energy through sliding under the structure foundation and between soil layers. (Yegian and Kadakal, 2004; Yegian and Catan, 2004)[13,14]. The other one is rubber-soil mixtures (RSM) which have been proposed around the foundation of structures for absorbing seismic energy and exerting a function like that of a cushion (Tsang, 2008)[1].

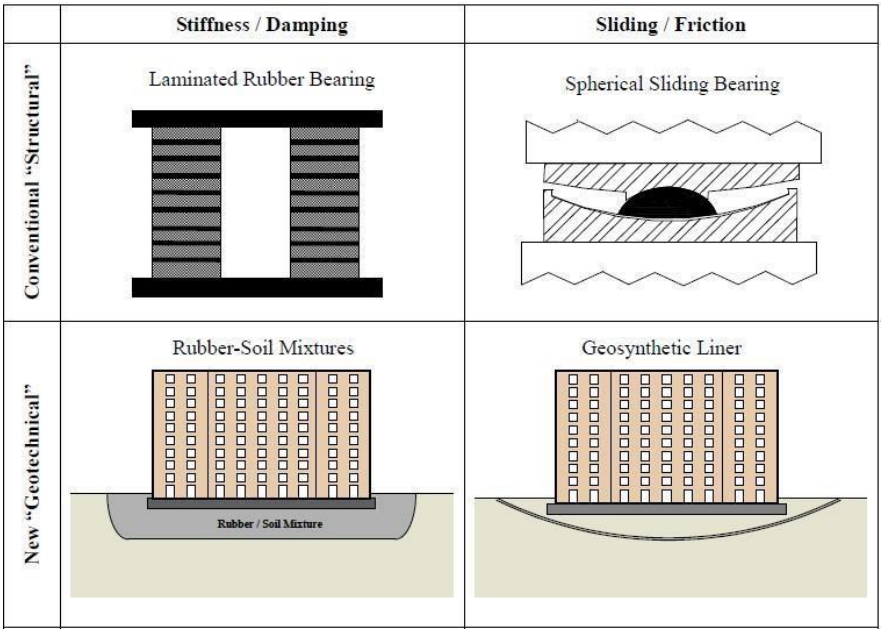



Figure 2.6. SI System Classification (Tsang, 2009).

Comprehensive information about Rubber-Soil Mixtures and Geosynthetics for Geotechnical Seismic Isolation (GSI) was given in the next parts.

### 2.2.1. GSI - Geotechnical Seismic Isolation with Geosynthetics

The use of the geosynthetics is a GSI methods. Geosynthetics is fabricated material that produced from polymer fibres used for civil engineering applications as well. Geosynthetics materials have five main functions: to discrete different geomaterials; to strength soil masses; to behave as a filter in controlling the transfer of solid particles through the soil; to supply drainage lines within the soil; or to block fluid flow by behaving as a flow obstacle. (Gohil et al.,2009)[15] But some research have shown that geosynthetics materials are used as a seismic isolation material. (Sekman, 2016)[16].

Yegian & Lahlaf (1992)[17], Kavazanjian et al. (1991)[18], Zimmie et al. (1994)[19] have noted that slip deformations appear along geosynthetic interfaces during dynamicshear excitations, and it causes reducing accelerations transmitted to the soil or structures. In light of these results, they proposed that geosynthetics can be consideredas isolation material.

Yegian et al. (1999)[20] presented the foundation isolation concept to the literature in the first time, and the concept relies on the absorption of seismic. (Figure 2.7) By this way, structures would less effect from earthquake waves. Furthermore, experiments were conducted with both rigid block and simple story structure model to investigate this concept and preliminary tests that made on geosynthetics showed that this concept of soil isolation with geosynthetics is a good option for isolating structures from seismic energy coming from the soil.

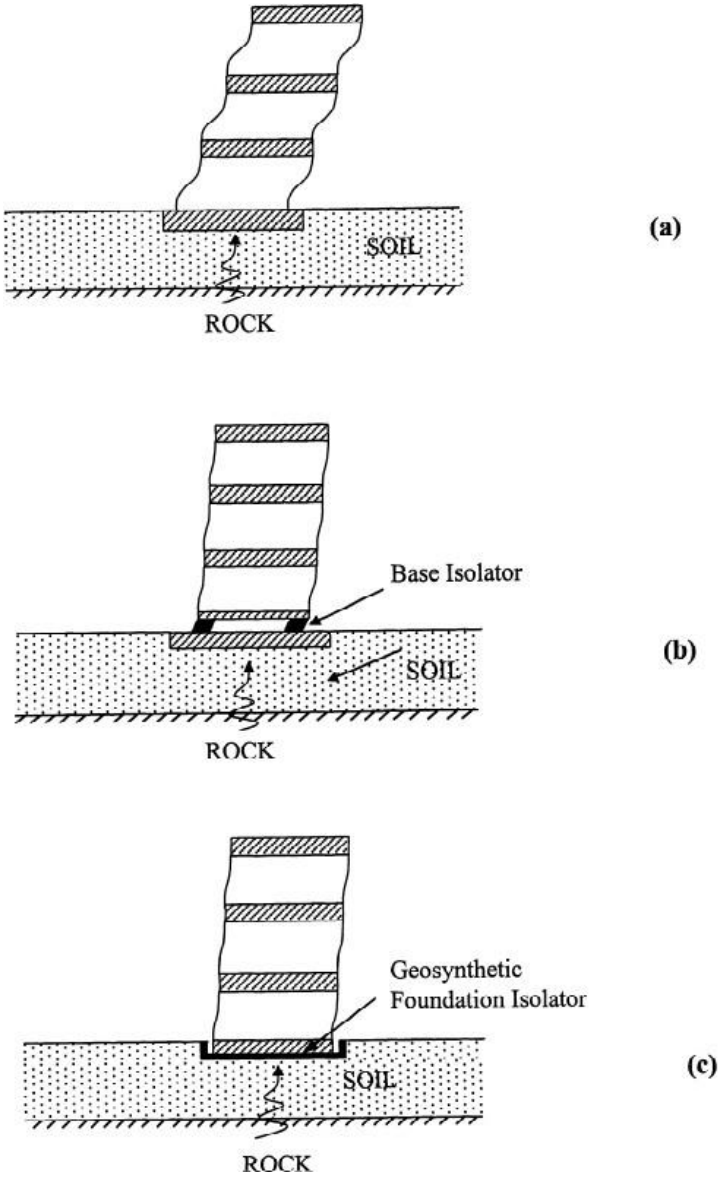



Figure 2.7. (a) Imposed to Earthquake, (b) Conventional Base Isolation (c) Geosynthetic Base Isolation Imposed Earthquake Motion. Forces (Yegian et al.,1999)[18]

Kavazanjian et al. (1991)[16]; and Yegian & Lahlaf (1992)[17] proposed the concept of using a smooth geosynthetic liner underneath building foundations to dissipate earthquake energy through sliding along the geosynthetic interface and research program identified a synthetic liner that is well suited for seismic isolation. Moreover, Yegian and Kadakal, (2004) [13], has proposed different alternative schemes for the use of the liner. The first was the placement of the liner immediately underneath the structure's foundation. In Figure 2.8, Itis foundation isolation can be seen schematically. Also, Yegian & Catan, (2004)[14] made contribution to this concept.

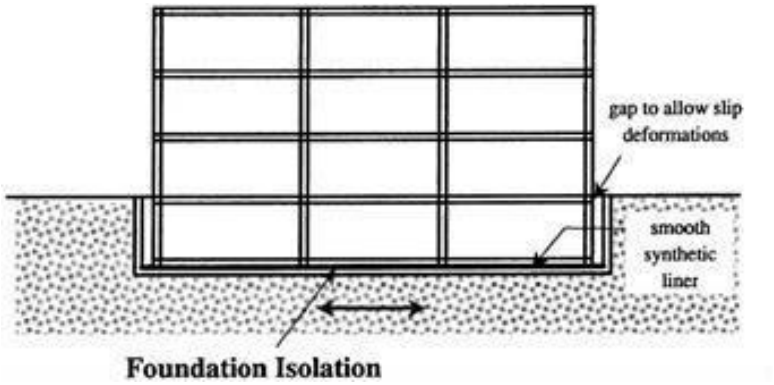



Figure 2.8. Isolation in Foundation (Kadakal, and Yegian (2004)[14]).

In another approach, the smooth synthetic liner is within the soil below the structure's foundation. Soil isolation is shown schematically at Figure. 2.9

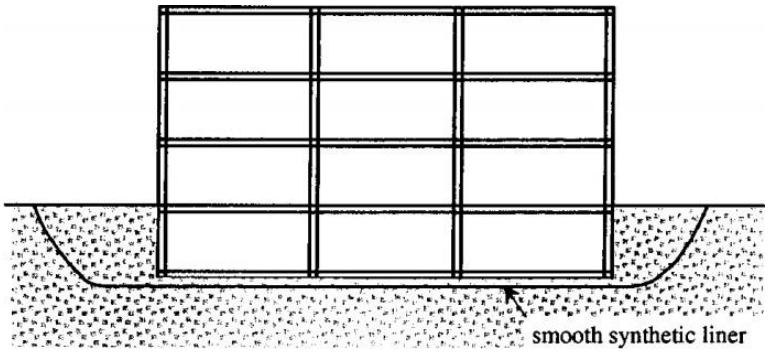



Figure 2.9. Isolation in Soil (Catan and Yegian (20004).

Earthquakes that happened in New Zealand (Christchurch, 09/2010, 02/2011 and 06/2011) showed that various geogrids can be efficient for mitigating liquefaction and associated structural damage. When investigations were conducted after the second and third seismic events, the benefit of the usage of the geogrids against seismic force was confirmed in houses that were reconstructed after the first earthquake. Because of that, authorities have made a decision of adopting a more stringent design approach, and New Zealand Ministry of Business, Innovation, Employment (MBIE) issued the Guidance document "Repairing and rebuilding houses affected by the Canterbury earthquakes", December 2012. The document for guidance is relevant to building sites that are classified to meet the technical categories TC2 and TC3. TC2 means that liquefaction is possible in earthquakes that has high magnitude. Common improvement foundation repair and rebuild options in accordance with MBIE guidance are appropriate for decreasing this chance. (Figure 2.10) Also, TC3 means that liquefaction is possible in future in earthquakes that has high magnitude. Individual engineering evaluation is necessary to select the suitable foundation repair or rebuild option. (Figure 2.11)

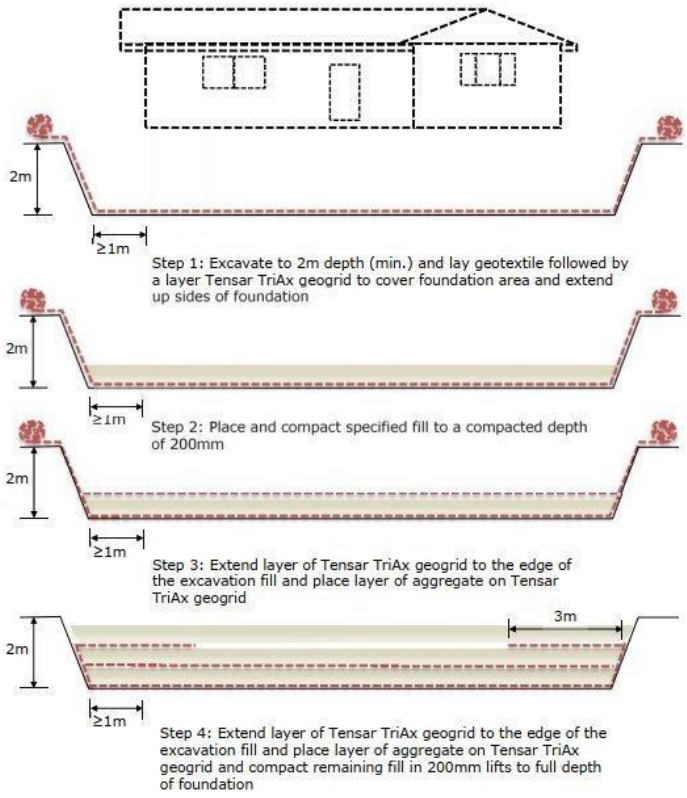



Figure 2.10. Shallow Foundation Treatment in TC2

These define different foundation classes based on damage potential. Construction Options mentioned in the New Zealand MBIE Guide are as follows for the TC2 and TC3 Foundations.

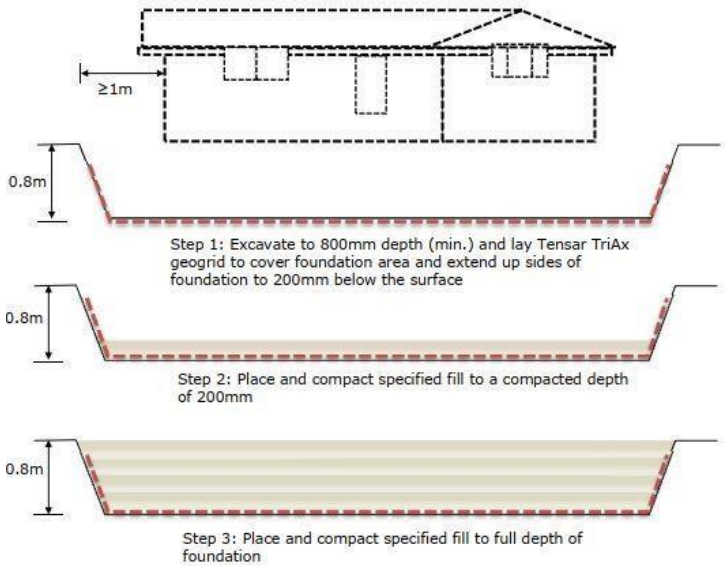



Figure 2.11. Enhanced Foundation in TC3

### 2.2.2. Geotechnical Seismic Isolation (GSI) and Rubber Soil Mixtures (RMS)

Rubber is great capable of absorbing energy, so it is used for vibration control and dampening broadly. Also, the use of scrap tires makes a huge contribution to sustainability by consuming the great stockpile of scrap tires globally. Seismic Isolation with Rubber Soil Mixture (RSM) is provided with replacing the soil surrounding the foundation by this mixture. Thanks to that, the seismic energy dissipates in the layer that is below the foundation, so the structure exposed less earthquake force. Also, this concept was firstly applied in Macedonia in 1969 for earthquake protection of building structure. (Nanda et al. 2018)[21]

Attom (2006)[22] made direct shear tests to examine the shredded tires on the shear strength properties of various sands. In this study, shredded tires were mixed with sand types with varying gradations. Also, each type was mixed with different percentages of shredded tires: 10%, 20%, 30% and 40% by dry weight. It was founded that the mixture increased the shear strength parameters. Also, it improved several engineering properties of sand.

Tsang (2008)[1] has firstly researched the usage of RSM replacing sand covering the foundation of building by an array of parametric studies and numerical simulation. The proposed method was shown in Figure 2.12 by a drawing. The national building structure considering in the study has a typical architectural plan of a residential, hospital or office building. At the end of this study, it reached that the use of the rubber-soil mixture reduces the ground accelerations by 90%.

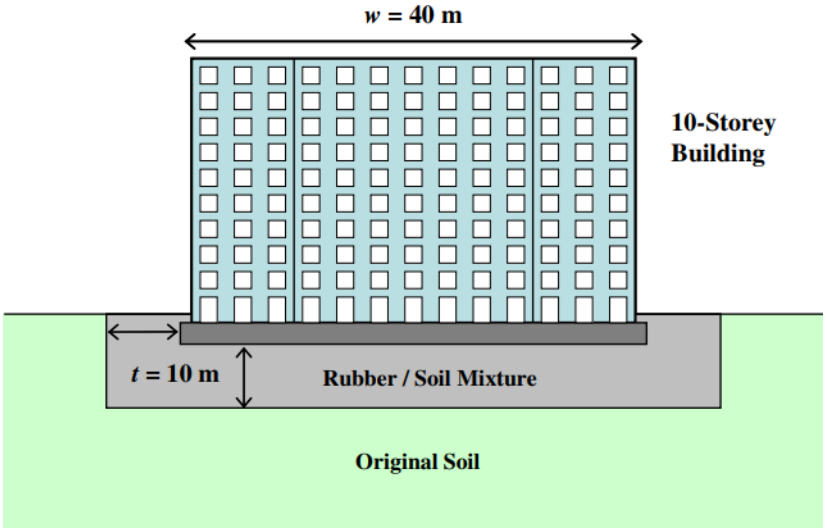



Figure 2.12. Proposed Method with Rubber-Soil Mixtures (RSM) (Tsang, 2008).

Xiong and Li, (2013)[23] conducted a series of shaking-table tests on the GSI system to investigate its dynamic behaviour during motion. (Figure 2.13) These comprehensive tests were completed by considering various parameters like RSM thickness, acceleration magnitude, rubber content by volume, and weight of the superstructure. Also, as key indicator of the GSI system protection performance, they chose the reduction of the peak absolute acceleration.

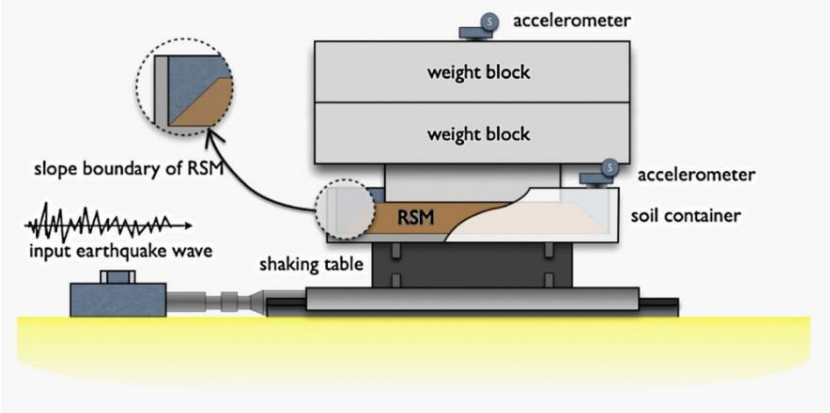



Figure 2.13.Experimental Setup and RSM, (Xiong and Li, 2013).

Obtained results that from this study showed the dynamic response of GSI which is a novel seismic isolation technique during earthquake, and these are as following: The results can be shown as follows:

There was a small difference in the isolation effect among RSM layers with 35% and 50% rubber by volume. Thus, an RSM layer with 35% rubber should be able to provide sound seismic protection and satisfy the bearing capacity demands of the superstructure. The thickness of the RSM layer significantly influences the response reduction with the GSI system.

A GSI system generally can attenuate the response of the structure, in terms of the maximal output acceleration, by 30–50%. The seismic isolation performance of the GSI technique increases with an increase in the intensity of the input acceleration. Experiments showed that the isolation index could be reduced to 0.48 with an input acceleration of 0.5 g. It proves the remarkable seismic isolation performance of the GSI technique during earthquake motions.

## 2.3. GSI - Geotechnical Seismic Isolation with Gravel-Rubber Mixtures (GRM)

GRM show to be a rising alternative for sand-rubber mixtures in many civil engineering applications and understanding their physical and mechanical properties are vital to correctly evaluate their performance. However, there are insufficient research on the geotechnical characterization of gravel-rubber mixtures up to now. Available research has focused to determine their physical & mechanical behaviors of these mixtures.

Hazarika and Abdullah (2016)[2] referred that the availability and cost efficiency should be considered the selection of the soil and recycled rubber to create soil-rubber mixtures in the civil engineering applications. Essentially, the recycled rubber should be cut into smaller while mixing with sandy soils to avert segregation, but this situation causes the raise the implementation cost. In order to solve this problem, they proposed to change the sandy soils with gravel soils.

A following study by Hazarika et al. (2020)[24] showed that practicing gravel-rubber layers under the foundation of residential buildings may provide the increase bearing capacity and reduce earthquake-induced settlements. Besides that, gravel-rubber mixtures confine the development of pore water pressure during cyclic loading because of the high permeability. Thus, it increases the stability of superstructures and infrastructures.

Pasha et al. (2018)[25] have focused on the effect of different rubber sizes on the mechanical behavior of gravel-rubber mixtures. In their studies, it was considered two types of gravel (i.e., sub-angular and sub-rounded) and three tire chip mixtures (D50R/D50S = 0.35, 1.2, 3.35). The results of this study demonstrated that the more Volumetric Rubber Content (VRC) increases the more decreasing shear strength as independent of rubber and gravel type. However, mixtures with D50R/D50S = 3.35 exhibited greater shear strength at failure compared to the other aspect ratios. The reason of this, more gravel-gravel contact was formed, which resulted in higher shear strength.

In another study, Pasha et al. (2019)[26] has made various consolidated-undrained CTTs on sample of Gravel - Tire Chips Mixture (GTCM) to examine effect of gravel and effective confining pressure on their dynamic behavior as well as liquefaction resistance. Tests have shown that initial shear modulus and liquefaction resistance are greatly affected by gravel fraction in GTCM. Moreover, GTCM specimens have a higher liquefaction resistance at low confining pressure. Also, it was found out that GTCM and tire chips like behavior with high deformability as tire chips inclusion increases in mixture.

Chiraro et al. (2019)[27] tested the direct shear strength of gravel and granulated tyre rubber mixtures for examining the possible of using at the seismic and isolation foundation systems for low and rise structures. The study's results have shown that the friction angle at failure is 39º or higher for all mixtures and it indicates that Gravel-Granulated Tyre Rubber Mixtures are appropriate materials for foundation engineering applications. (Figure 2.14)

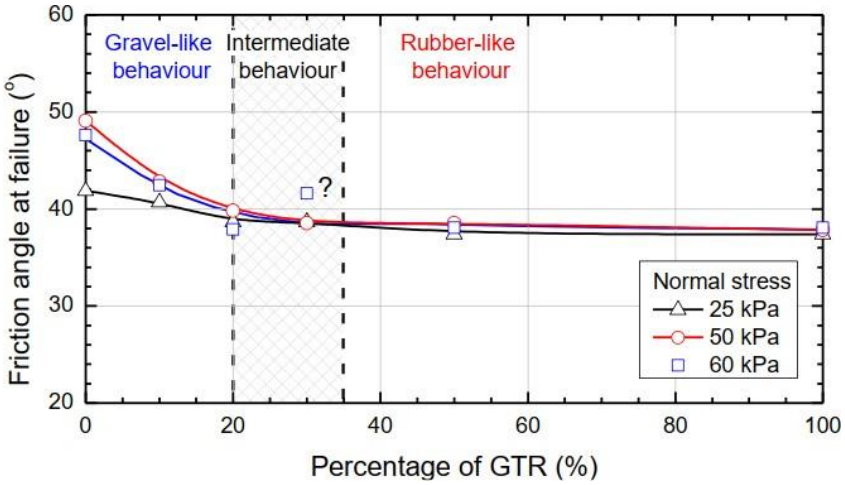



Figure 2.14. Peak Friction Angle for Gravel-GTR mixtures, (Chiraro et al., 2019)

Pasha et al. (2020)[28] made a study to examine the effect of confining pressure, relative density, and gravel fraction ($V_{Gravel}/V_{Tire}$) on the mechanical behavior and deformation characteristic of gravel and Gravel–Tire Chips Mixture (GTCM). It was determined that the behavior of GTCM significantly influenced by the percentage of tire chips in mixture and Peak shear strength and tangent modulus of GTCM decreases as gravel fraction reduce in the mixture. Also, three different behavioral zones have been observed as gravel-like, gravel–tire chips like and tire chips like behaviors.

Tasalloti et al. (2021)[29] carried out direct shear tests to investigate the strength and deformation properties of different gravel-granulated tyre rubber (G-GTR) mixtures under different normal stress. Mixtures were prepared at various volumetric rubber content (VRC) of 0%, 10%, 25%, 40% and 100%, by considering a mixture of small and large rubber grain with a rounded poorly graded gravel. In this research, VRC was defined as the ratio of the volume of rubber (VR) to the total volume of solids (i.e. volume of rubber (VR) and volume of gravel (VG)) in the mixture.

Also, two sizes of granulated tire rubber (GTR), namely large rubber ($R_{LRG}$) and small rubber ($R_{SML}$), were mixed with a rounded poorly graded gravel (GRND) for forming mixtures with different volumetric rubber content (VRC) to examine both rubber content and rubber size effects on the mechanical behavior of gravel-granulated tire rubber mixtures (G-GTR) (Figure 2.15).

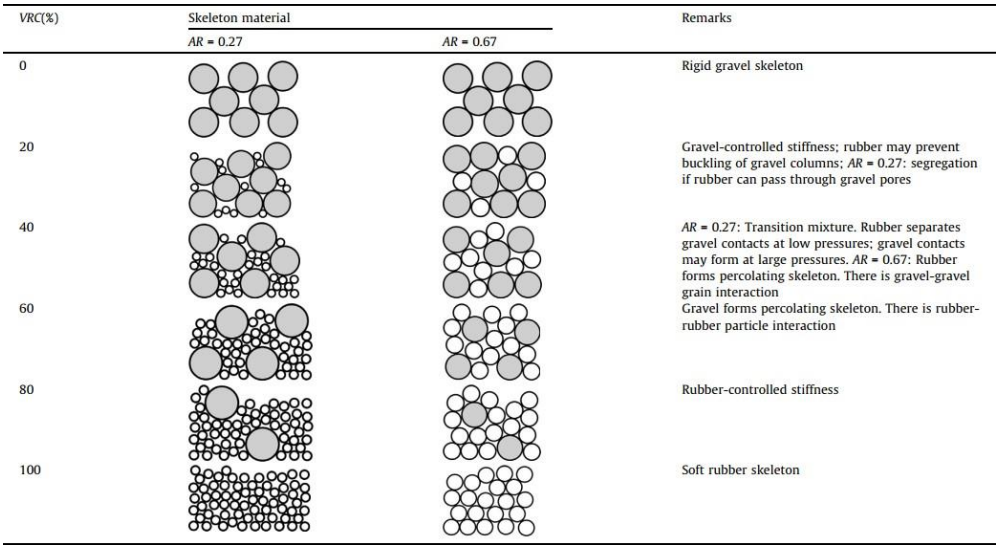



Figure 2.15. Rubber-Gravel Interaction in Mixtures with Different VRC and AR (Tasalloti et al. 2021)[29]

At the end of this studies, they have reached significant results. First of all, the effect of rubber size is more apparent at lower VRC. On the condition that one-dimensional compressive strains are acceptable, this study recommended that mixtures whose Volumetric Rubber Content (VRC) is less than 40 percent are suitable materials for the greater part of geotechnical engineering applications because the friction angle is generally more than 30 percent. (Figure 2.16) Also, this study presents an important

insight about the effect of VRC content, rubber size and behavior of rubber-gravel interaction during the direct shear tests. Some results are as below:

- Mixtures have small rubber tends to compress than other mixtures including large rubber except at VRC=10%.
- Gravel rubber mixtures including VRC ≤ 20 can be used with safety as structural fills for geotechnical applications.
- Mixtures with 20% < VRC ≤ 40% should be used as general fills only for vertical stress level exceeding 30 kPa.

**PERFORMANCE-BASED CRITERIA FOR G-GTR MIXTURES**

| | Compressibility $\varepsilon_i \leq 3\%$ | | | Shear strength $\phi \geq 30^o$ | | |
|---|---|---|---|---|---|---|
| ***VRC*** **(%)** | $\sigma_n \leq 30$ kPa | | | | | |
| ***AR*** | ***VRC***≤20 | 20<***VRC***<40 | ***VRC*** ≥40 | 0<***VRC***≤20 | 20<***VRC***<40 | ***VRC*** ≥40 |
| 0.67 | Very good | Very good | Poor | Very good | Very good | Very good |
| 0.27 | Very good | Good | Poor | Very good | Very good | Very good |
| | 30 kPa < $\sigma_n \leq$ 60 kPa | | | | | |
| ***AR*** | ***VRC***≤20 | 20<***VRC***<40 | ***VRC*** ≥40 | 0<***VRC***≤20 | 20<***VRC***<40 | ***VRC*** ≥40 |
| 0.67 | Very good | Good | Poor | Very good | Very good | Good |
| 0.27 | Very good | Poor | Poor | Very good | Very good | Good |
| | 60 kPa < $\sigma_n \leq$ 100 kPa | | | | | |
| ***AR*** | ***VRC***≤20 | 20<***VRC***<40 | ***VRC*** ≥40 | 0<***VRC***≤20 | 20<***VRC***<40 | ***VRC*** ≥40 |
| 0.67 | Very good | Poor | Poor | Very good | Very good | Good |
| 0.27 | Very good | Poor | Poor | Very good | Very good | Poor |

**Very good**: The material meets performance criterion for structural fills
**Good:** The material just meets performance criterion for structural fills
**Poor:** The material does not meet performance criterion for structural fills, and should be used as a general fill only

Figure 2.16. Selection of G-GTR Mixtures as Fill Materials for Geotechnical Applications, (Tasalloti et al. 2021)[29].

Pitilakis et al. (2021)[30] has performed a large-scale experiment included ambient noise, free- and forced vibration tests for evaluating the effect of GRM layers under foundations as a GSI. Within scope of this study, three holes were excavated and backfilled with GRM includes various rubber content per weight for the rubber percentage as 0, 10, 30%, respectively to provide as foundation soil (Figure 2.17).

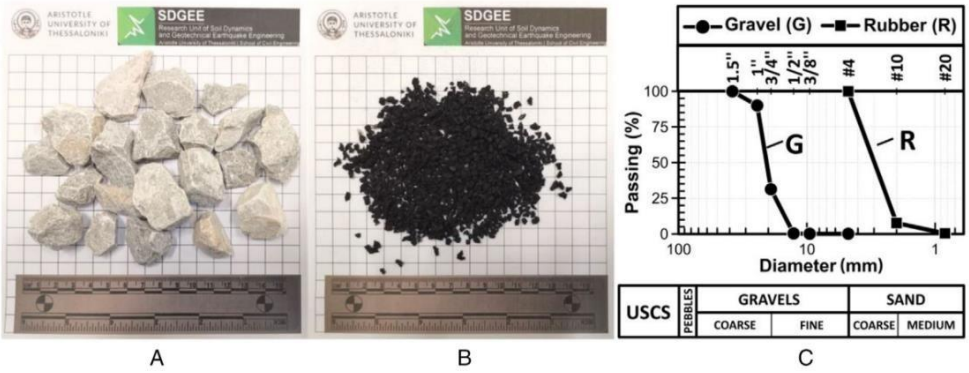



Figure 2.17. a) Gravel b) Rubber Materials c) Grain Size Distribution (Pitilakis et al.,2021)

The results of this studied indicated that the alteration in the structure's dynamic characteristics (fundamental frequency, increase in the damping, and reduction in the structure's response) are almost negligible (less than 5%) for a GRM layer with low rubber content (10%). But they noted an important modification in the dynamic properties of the GSI-structure system for 30% rubber content, as its stiffness decreases and its damping increases. In the all experiments, they also monitored a significant decrease in fundamental frequency of the system and structure's responsein 4.5 - 7 Hz frequency gap. Besides that, this study indicates that an upper bound of 30% rubber per mixture weight should be considered otherwise the mixture cannot be effectively compacted at the beyond of this threshold. Moreover, it brings out that a majority of the energy dissipates in the GRM layer before its radiation to the surrounding soil and the useful effects of the GRM as a GSI system of the structure.

As a summary, this study presents GSI layers consist of a GRM with 30% rubber content isolates the structure in a good way. The increase of system damping and substantial energy dissipation within the GRM layers emphasize its effectiveness as a GSI system.

## 2.4. SI-Seismic Isolation from Low to Rise Structures

Mavronica et al., (2010)[31] have studied on the RSM beneath foundation of a 5-story building on building's seismic behavior. (Figure 2.18) Within the scope of this study, it was compared the seismic response of the building has un-improved soil with those has improved soil with mixture of soil- rubber. To investigate various soil parameters and earthquake characteristics, parametric and numerical analyses were conduct by using software programs such as SAP2000. In these analyses, the peak absolute top-floor accelerations of the buildings were considered as a parameter measuring the efficiencyof soil-rubber mixture on building's dynamic response.

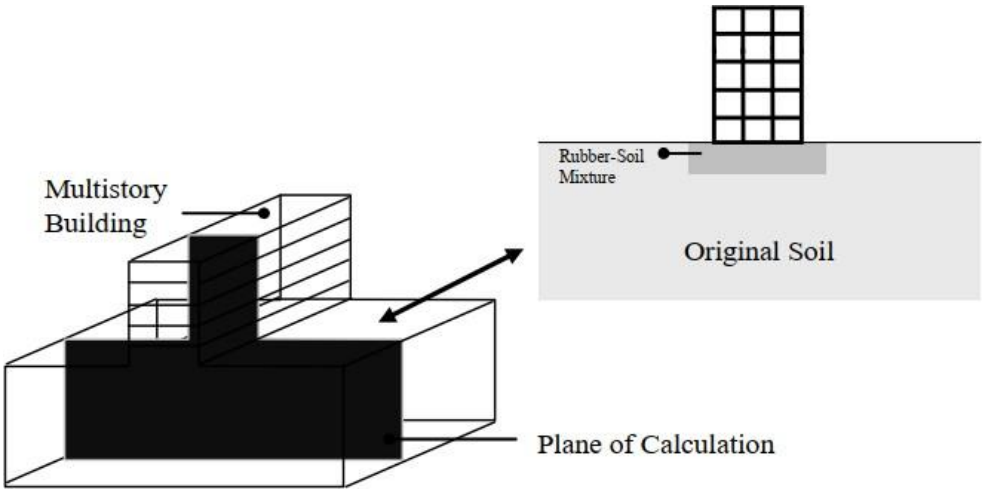



Figure 2.18. Schematic of the Distributed Seismic Isolated Method; a Coupled Soil-Structure System, (Mavronica et al., 2010)[31]

Analysis results reveal that the peak absolute top-floor accelerations reach the maximum reduction for lower content of the rubber as the intervention layer thickness increases. Moreover, the reduction of peak absolute accelerations, for varying damping ratio increase with the increase of the additional material damping ratio, while it is influenced by the excitation characteristics (Mavronica et al, 2010)[31].

Tsang et al. (2012)[32] has presented research on a potential SI method by making use of scrap rubber tires for the earthquake protection. (Figure 2.19) The method includes shredded rubber tire and soil. Then it was placed around building foundations. In the study, realistic building models have been adopted and inter-story drift demand & acceleration response are selected as key performance indicator (KPI). Currently, displacement (and interstorey drift) demand has already been recognized as more important in assessing seismic performance of structures. The research showed that low-cost feature of this proposed method could give beneficial undeveloped regions in terms of resources and technology.

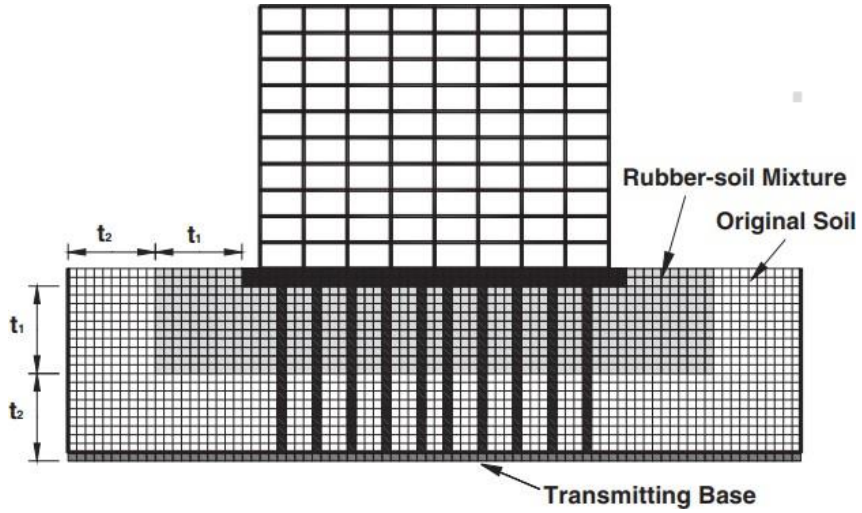



Figure 2.19. FEM of the GSI System with RSM (Tsang et al., 20122)

Paniamani et. al., (2015)[33] conducted a study to improve cost-efficient damping scheme using soil rubber mixtures for low- and mid-rise buildings. It makes up of two important pillars. First one is focusing on the characterization of RSM and discovering the optimal size of rubbers by carrying out many direct shear tests and Unconsolidated - Undrained triaxial test with seven different rubber sizes (Figure 2.20).

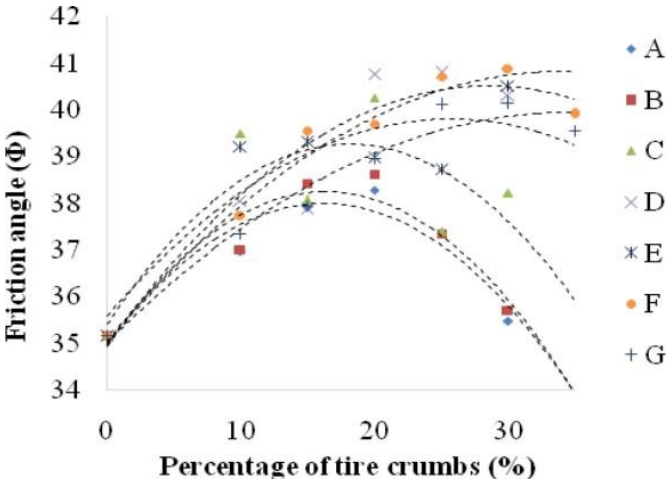



Figure 2.20. Friction Angles for Different Size and Rubber Content
(Panjamani et al.., 2015)[33]

The other part cares about designing of isolation systems under buildings and detection of dimension of the system by making comprehensive numerical simulations with different thickness of RSM, rubber content in RSM and input motion to analyse the damping effect of RSM. As a result, this study revealed that the RSM provide more shear strength, the capacity of energy absorption, and stiffness, and reduce acceleration and inter storey drift for 75% rubber by volume at the different floors by 50%. (Figure 2.21)

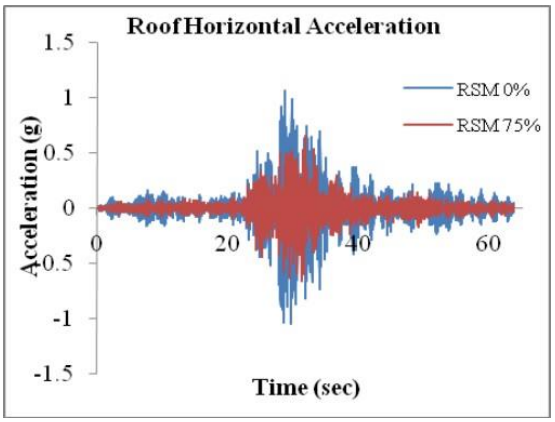



Figure 2. 21.Normalized Horizontal Acceleration for Roof with RSM 75
(Panjamani et al.., 2015)[33]

Nanda et al., (2018)[34] have numerically studied the efficiency of a layer of Sand -Shredded rubber mixture as isolation. During this study, ABAQUS CAE software was used for modelling the response of soil structure. The model made up of two key elements. The first one is bottom soil strata, the other one is three-dimensional buildings that are above of these strata. These buildings are 2 & 4 storied moment resisting RC frames. To evaluate of the performance of Rubber Soil Mixtures (RSM), seismic responses at the buildings' roof with and without providing RSM were compared. The study showed that the more the depth of RSM layer the more the isolation systems absorb the earthquake energy, and the system is more effective for low height buildings and high depth of RSM. Furthermore, the proposed method decreases the horizontal ground acceleration by 50% on average (Table 2.1).

Table 2.1. The Value of Peak Horizontal Accelerations (Nanda et al., 2018)[34]

| Earthquake | Story | Peak Horizontal Acceleration Without RSM (g) | Depth of RSM | Peak Horizontal Acceleration With RSM (g) | Reduction (%) |
|---|---|---|---|---|---|
| ISZ5 | 4 | 6.68 | 2 | 3.84 | 42.51 |
| | | | 4 | 3.03 | 54.64 |
| | | | 6 | 2.84 | 57.49 |
| | 2 | 3.53 | 2 | 2.02 | 42.78 |
| | | | 4 | 1.28 | 63.74 |
| | | | 6 | 1.08 | 69.41 |
| LOMA PRIETA | 4 | 11.94 | 2 | 8.17 | 31.57 |
| | | | 4 | 6.77 | 43.30 |
| | | | 6 | 6.30 | 47.24 |
| | 2 | 8.26 | 2 | 4.10 | 50.36 |
| | | | 4 | 3.36 | 59.32 |
| | | | 6 | 2.83 | 65.74 |

Xu and Fatahi (2019)[35] have proposed a geosynthetic reinforced composite soil (GRCS) foundation system to protect medium rise buildings having a shallow foundation facing with structural drift or foundation settlements. (Figure 2.22) A common concrete building that improved to be moment resist was placed in the soil and 1995 Kobe, 1994 Northridge, 1978 Tabas earthquakes were applied numerically for investigating the proposed GRCS. The results showed that it could provide engineers with an efficient solution for medium rise buildings facing earthquake-induced residual drifts and settlements.

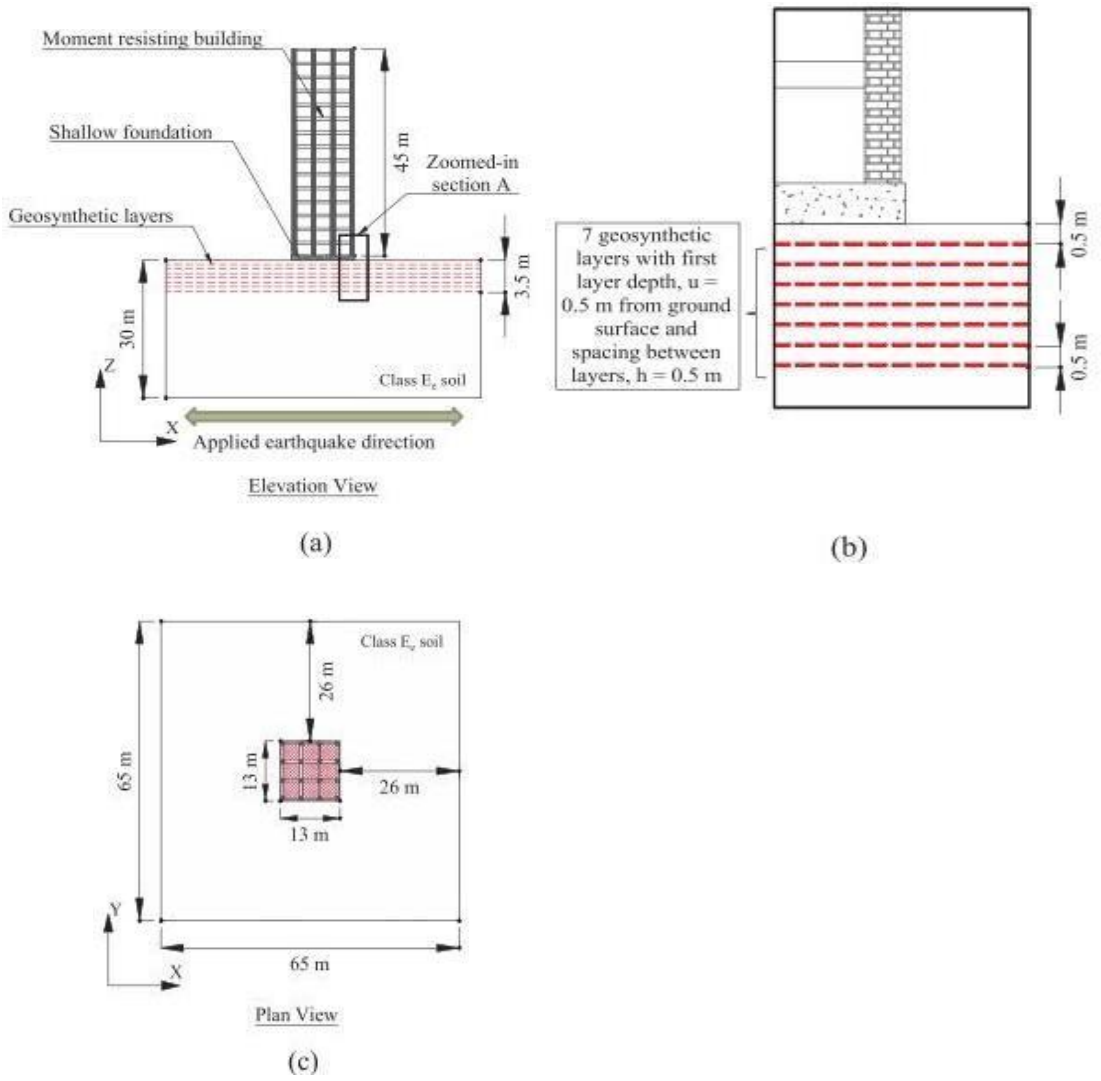



Figure 2.22. Set-up of GRCS: a) Elevation View, b) Section A, and C) plan view. (Ruoshi and Fatahi, 2019)

# 3. MATERIALS AND METHODS

## 3.1. Properties of Model for Experiment

Shaking table, the laminar box, measuring devices and the scaled building models are used to carry out the experimental stage of this thesis study. In this chapter, the details about the properties of test equipment will be presented.

### 3.1.1. Shake Table

The test system that is in the Bogazici University Kandilli Observatory Earthquake Research Institute Shaking Table Laboratory was used. The shaking table is a uniaxial hydraulic table whose size is 3 (three) meters x 3(three) meters and can shake a maximum 10-ton payload with 2G and apply horizontal vibration. Also, it is appropriate for seismic applications because the hydraulic actuator can produce a 24 cm (+/- 12 cm) total stroke. Furthermore, the system is supported by a digital outer loop control system and the up-to-date modified computer-based software system. The general view of the shaking table is in Figure.3.1



Figure 3.1. Shaking Table and Laminar Box

### 3.1.2. Measuring Devices

To measure displacements Optical Distance Sensors (ODS) were selected as devices. These sensors are capable to measure ranges between 150 mm and 1200 mm with 2% absolute accuracy. Furthermore, various accelerometers whose capacities are between (+/-)3g and (+/-)20g were used for measuring the acceleration in the experiments. The sample rate for cyclic sinusoidal motions was 1000 samples / second (sec) in earthquake motions, the sample rate was taken as 500 sample/sec. In Figure 3.2, accelerometers and displacement sensor are shown.

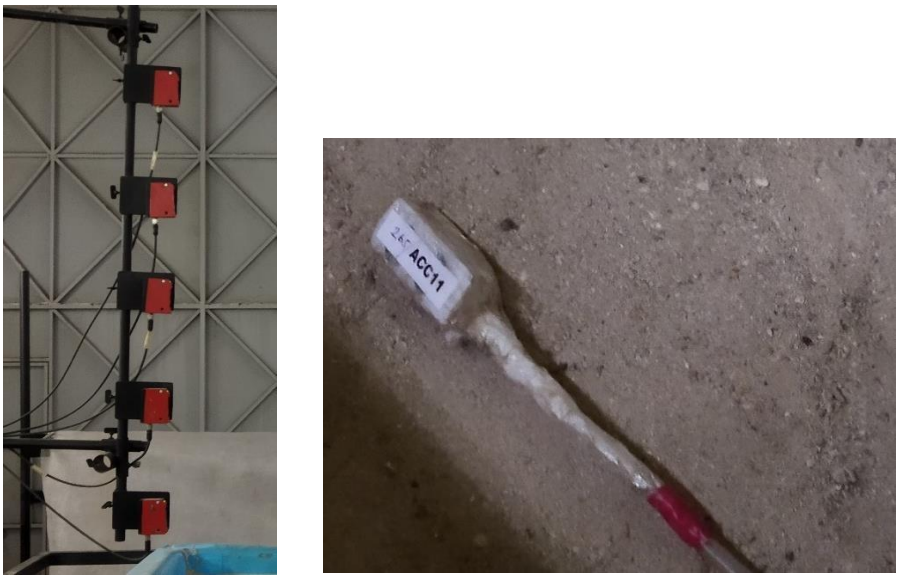



Figure 3.2. Displacement Sensors and Accelerometer.

### 3.1.3. Laminar Box

Because of the necessary of confinement in the soil, a container that placed on shaking table was used to carry out experimental stage. As a container, a laminar box was selected in this experimental study. Laminar boxes are manufactured by an array of steel laminates supported by ball bearings and guards fixed to the external frame. Rectangular laminar boxes are the most preferred ones in the literature. The basic design principle of these boxes is to destroy container's the lateral stiffness for providing that soil leads the response of the soil box system.

The laminar box which used in this study was built and tested firstly by Sekman (2016)[16]. Previously, it was made use at various experimental studies about building model and soil-rubber mixture seismic isolation. The laminar box that was used in this study was constructed as 1.5 meters x 1 meter x 1.3. meters

The laminar box includes 18 steel I-beam layers and various elements. While designing the laminar box, the most important point is to slide and to stop the laminates in the movement of box and it was provided with roller bearings and rubber stoppers in this example. Friction forces between laminates were diminished by adding six sets roller bearings for every laminate. Each set includes three roller bearings placed side by side. It means that the system includes 324 roller bearings provide the sliding to the laminates as seen in Figure 3.3.

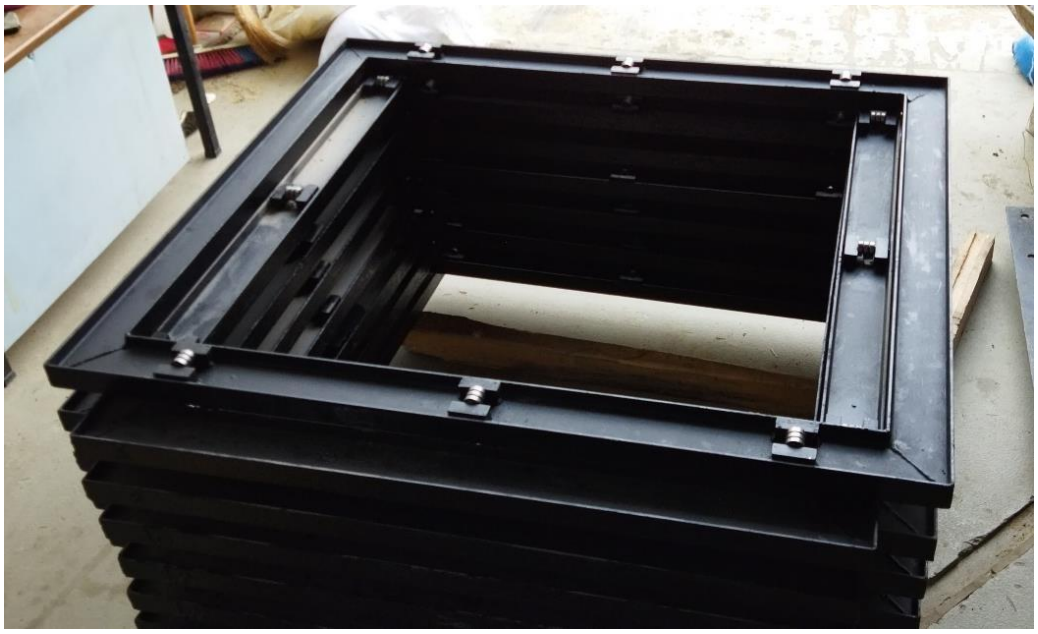


Figure 3.3. Roller Bearings and Rubber Strip Stopper.

Additional inertial effects that could be caused by stroking the roller bearings to rubber strips at the end of the bearing houses were restricted by using shock absorption feature of rubber. (Sekman 2016)[16] Before experimental study, the layers of laminar box were dismantled and were detailed cleaned, oiled. Then, all performance tests were carried out. Also,friction and membrane effects were investigated and controlled.

- **Friction Effect**

Static Pull-Out tests were carried out by means of force meter which has 25 kg load measurement capacity are required for the first motion. Thanks to these tests, the friction effect on box performance was researched. These tests began from the bottom layer to above layers for every layer. The measured friction forces each layer are exhibited in Figure 3.4.

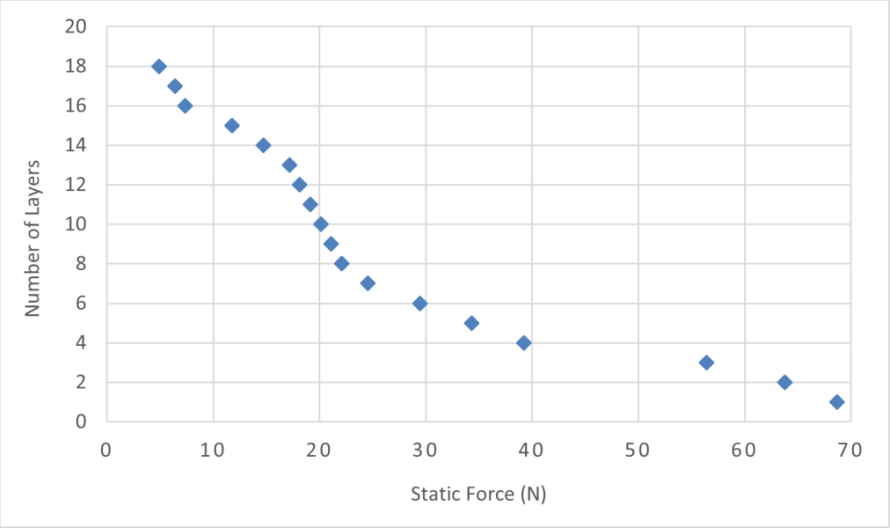



Figure 3.4. The Forces of Laminar Box.

The maximum force to begin movement for bottom layer was 68,67 Newton and the average friction force was 28 N. The average friction coefficient was determined as 0.06. It means that static friction force can be ignored.

- **Membrane Effect**

In experiments, rubber membrane that has 1.0 mm thickness was utilized. The stiffness of the membrane was rather little in comparison with the soil which is within the laminar box. Thus, performance tests that was conducted with and without membrane showed that the membrane does not impact the performance of box. Due to that, the membrane effect was ignored in this research.

### 3.1.4. Scaled Building Models

In this study, the suitability of GRM for low-rise and medium-rise buildings was investigated so the model prototypes were preferred 5 stories and 3 stories building models within the scope of these tests. Due to the measures of the current laminar box, the scaling factor of the models was limited as 1:10

One of the vital points is the behavior of soil-building model in the course of the process of scaling and design of the model. Since this study focuses on the efficiency of gravel-rubber mixtures during earthquake, the building model was scaled according to the behavior of the soil-building model and base pressure. Table 3.1 showed all necessary scale factor parameters.

Tablo 3.1. The Scaled Building Model Parameters. (Harris & Sabnis (1999)[36])

| Parameter | 1:10 Scale Model/ Prototype | |
|---|---|---|
| Length | L | 1/10 |
| Time | $\sqrt{L}$ | $1/\sqrt{10}$ |
| Mass | $L^2$ | 1/ 100 |
| Displacement | L | 1/10 |
| Acceleration | 1 | 1/1 |
| Stress | 1 | 1/1 |
| Strain | 1 | 1/1 |
| Force | $L^2$ | 1/100 |

The properties of the buildings are like that the floors of the building models were manufactured as 30.00 centimeters (cm) x 30.00 cm x 1.00 cm St 42 steel. Every floor carries six weight blocks. The measure of these blocks is 30 centimeters (cm) x 30.00cm x 2.00 cm, it was made by using St 42 Steel. Between the floors there is high carbon steel columns which are 26.50 centimeters (cm) x 5.00cm x 0.50cm. The columns connect floors each other with 8.8 metric eight bolts to floors. Every weight block was created separately. Thanks to that, the building model can be carried and dismantled readily. The height of the 5-story is 135 cm. the final height 3-story building was 81 cm without foundation. Figure 3.5 showed that 5-story scaled building model.

Also, it must be specified that this building model was manufactured and used by Sekman (2016) for the study about geotechnical seismic isolation.



Figure 3.5. A View of 5 Storey Scaled Building Model

## 3.2. Materials

In this study, Gravel, and Gravel-Rubber Mixture (GRM) samples have different rubber contents for investigating the effects of the gravel and gravel-rubber content as GSI-Geotechnical Seismic Isolation material. GRMs were formed at four rubber ratios of 0% , 10%, 20%, and 30% by weight. Mixtures' names are shortened as TC0, TC10, TC20 and TC30, respectively.

### 3.2.1. Silivri Sand

The grain-size distribution of Silivri Sand used in experiments was found by looking at Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis (ASTM D6913/D6913M-17) in Figure 3.6. The Uniformity Coefficient (Cu) is 2.48. The Curvature coefficient (Cc) of the sand is 1.12.

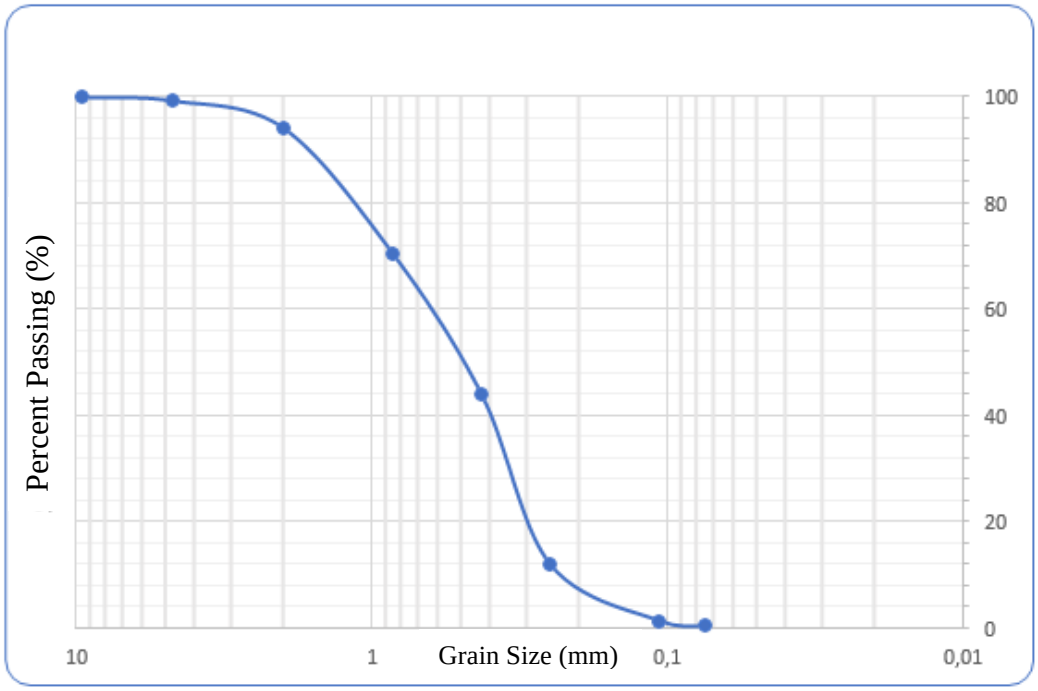



Figure 3.6. Grain Size Distribution of Silivri Sand

### 3.2.2. Gravel

‘’Class-1 Gravel" was used in the experiments. This class include between 5 mm and 12mm gravels according to TS EN 933-1:2012-Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method.

The Uniformity Coefficient (Cu) is 2 and The Curvature coefficient (Cc) of the gravel is 1.125. It also classified as poorly graded (GP).

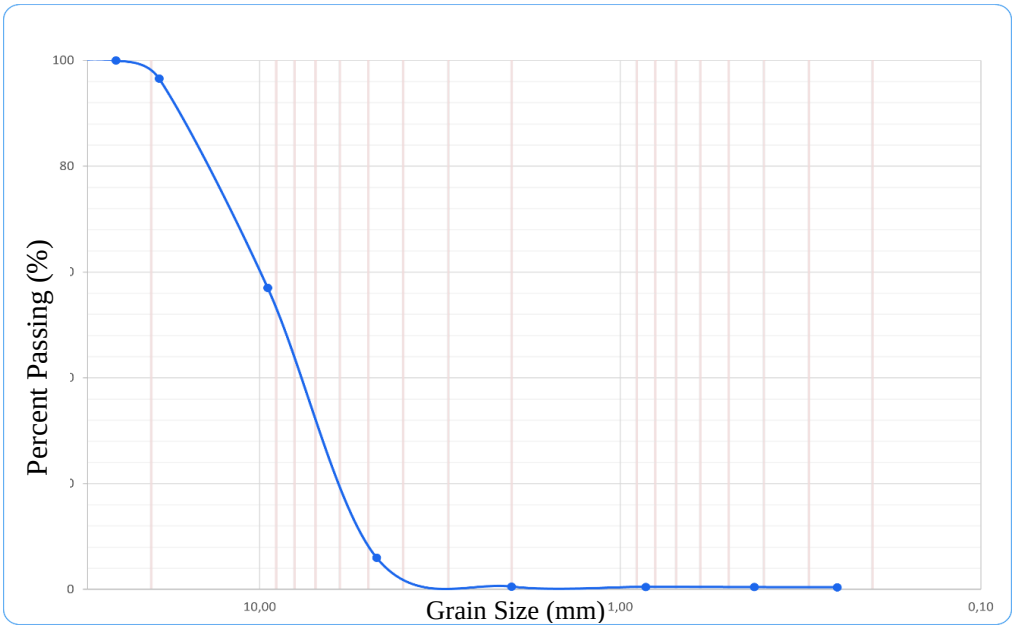



Figure 3.7. Grain Size Distribution of the Class-1 Gravel

### 3.2.3. Rubber

Tire crumbs were selected to compare with former research results of Yildiz, (2011)[37]. Size of tire crumbs (TC) is between 1- and 5-mm. Unit weight of rubber is 6.1 kN/m$^3$.

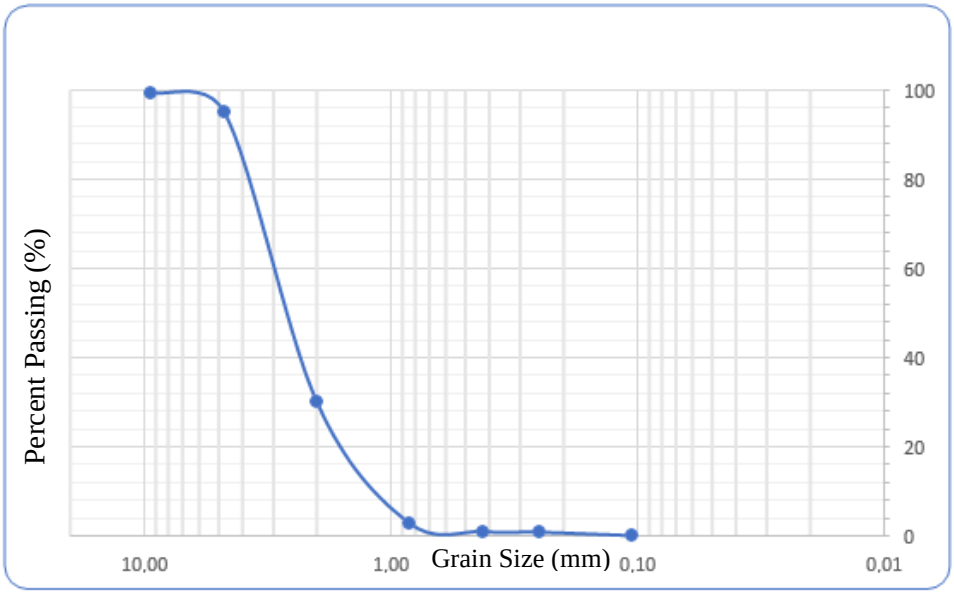



Figure 3.8. Grain Size Distribution of Tire Crumb

## 3.3. Ground Motions

Five severe earthquake motions such as 1940 El Centro, 1995 Kobe and 1999 Kocaeli-İzmitStation were chosen for the shaking table testsas input seismic motions. The essential criteria of choosing of the evaluation are frequency content and the simulation capacity of equipment's.

Also, the horizontal components were considered because the shaking table which was used in the research is the uniaxial.

The data that is relevant to the earthquakes was shown in Table 3.2. Also, time-acceleration graphs of earthquake motions can be seen in Figure 3.9, 3.10, and 3.11

Tablo 3.2. Information on El Centro, Kobe, Kocaeli and Izmir Earthquake Motions

| Name | Date | Station | Magnitude | Comp. | HPF (Hz) | LPF (Hz) | PGA (g) | PGV (cm/s) | PGD (cm) |
|---|---|---|---|---|---|---|---|---|---|
| Kocaeli, Turkey | 17.08.1999 | Izmit | 7.5 | E-W | 0.1 | 30 | 0.21 | 27 | 14.6 |
| El Centro Array #9 | 19/08/40 4:37 | Imperial Valley -02 | 6.9 | N-S | 0.1 | 15 | 0.32 | 31.7 | 18 |
| Kobe, Japan | 16/01/95 20:46 | KJMA | 6.9 | N-S | 0.05 | * | 0.82 | 77.8 | 18.8 |

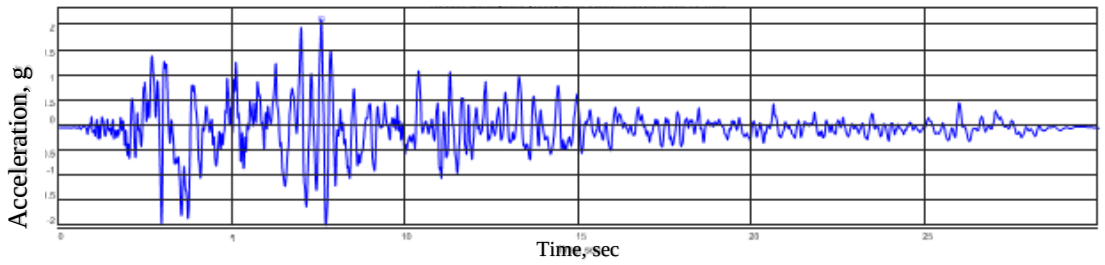



Figure 3.9. Acceleration - Time History of Kocaeli Earthquake Motion (1999) Izmit Station

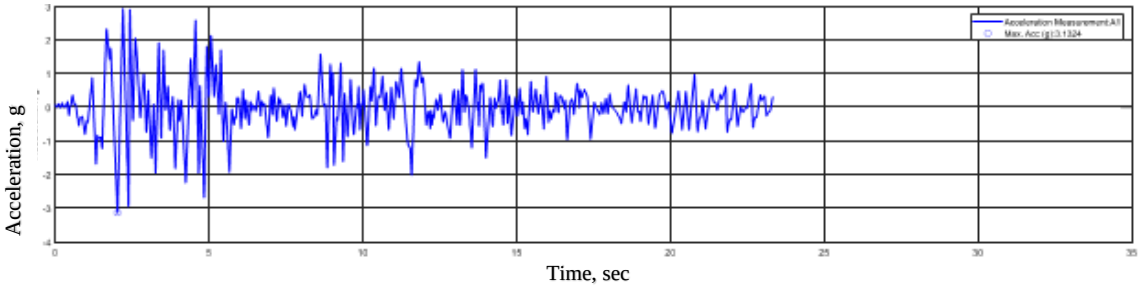



Figure 3.10. Acceleration - Time History of El Centro Earthquake Motion (Imperial Valley Station-02).

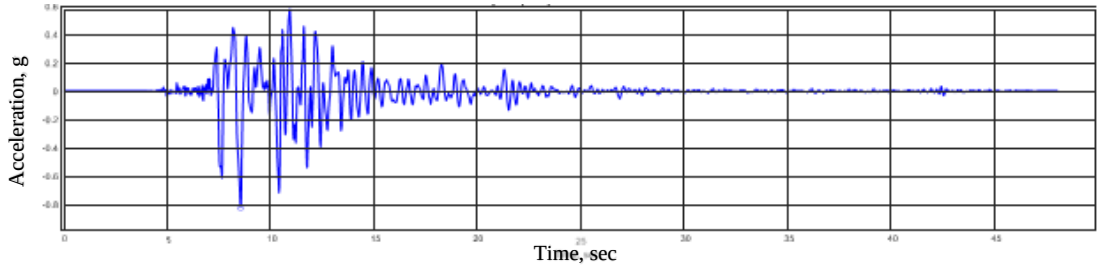



Figure 3.11. Acceleration - Time History of Kobe Earthquake Motion (1995) KJMA.

### 3.3.1. Location of Sensors on Scaled Building Model and in Soil

In order to examine the effectiveness of Gravel Rubber mixtures in soil and on the building during earthquake motions, totally 19 accelerometers and 9 laser displacement meters were assembled to the shaking table, laminar box and building models.

For the soil, just accelerometers were preferred. After the sensors in the soil were placed, the scaled building model's sensors was located. An accelerometer and a laser displacement meter were located in the middle of each story floor consecutively for observing elaborately the effect of the Gravel - Rubber Mixtures as a GSI on story drifts.

In Figure 3.14, the locations of sensors in the soil are exhibited and Figures 3.15 and 3.16 show general view of scaled building models of with sensors. Also, in Figure 3.17. the projection of displacement sensors on 5-storey building model can be seen.

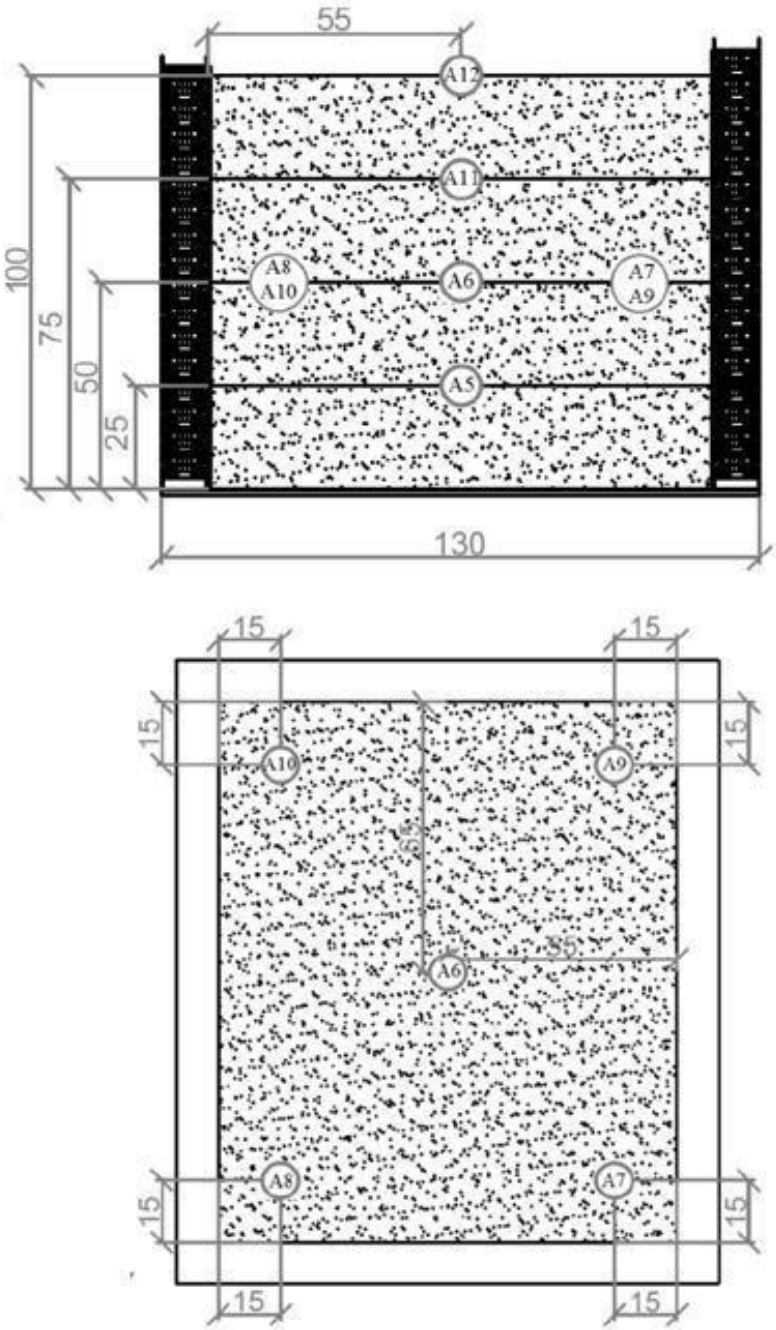



Figure 3.12. General View of Accelerometer's Locations in Soil.

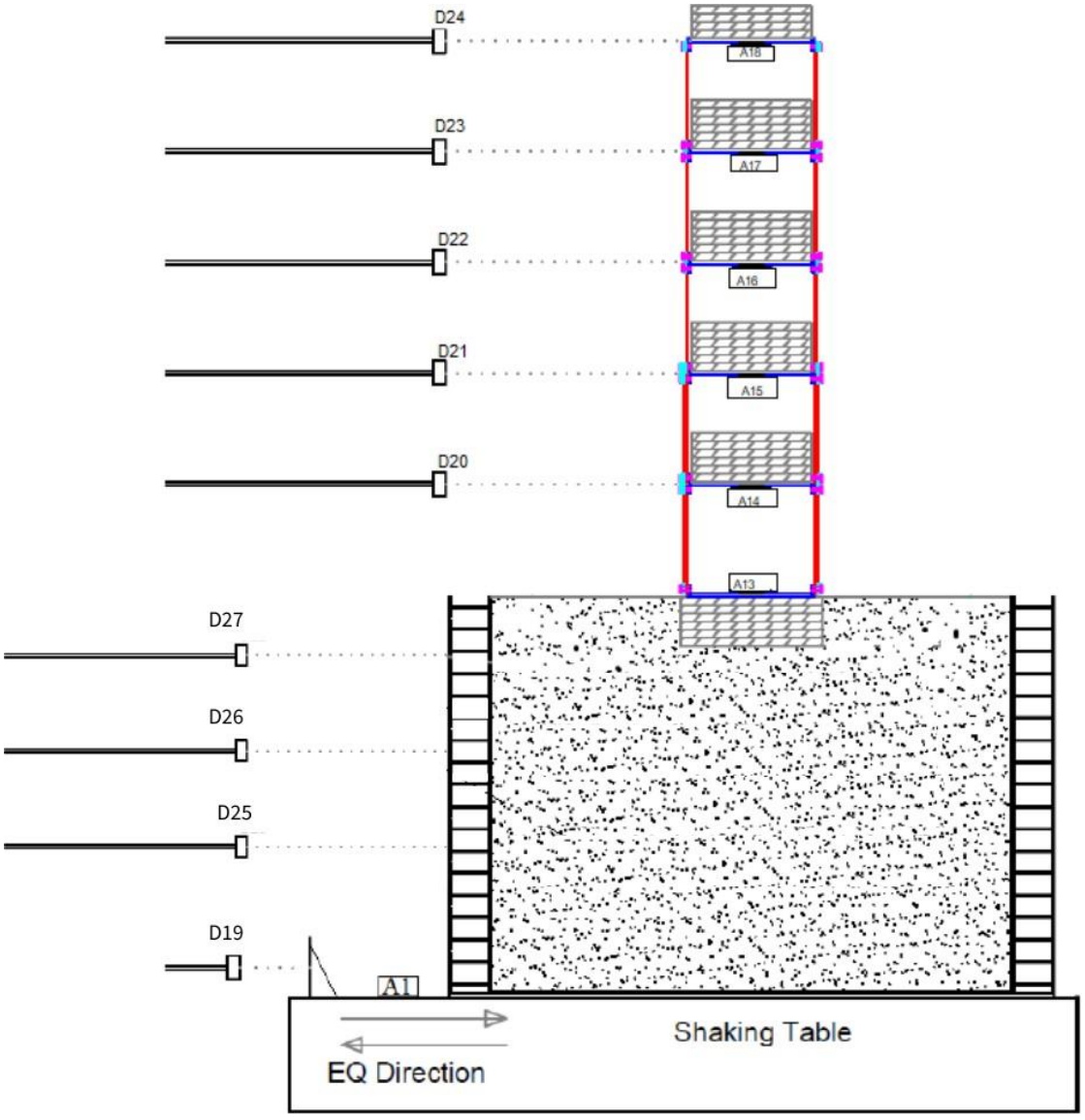



Figure 3.13. The Sketch of Scaled Building Model and Sensors for 5-Storey Building

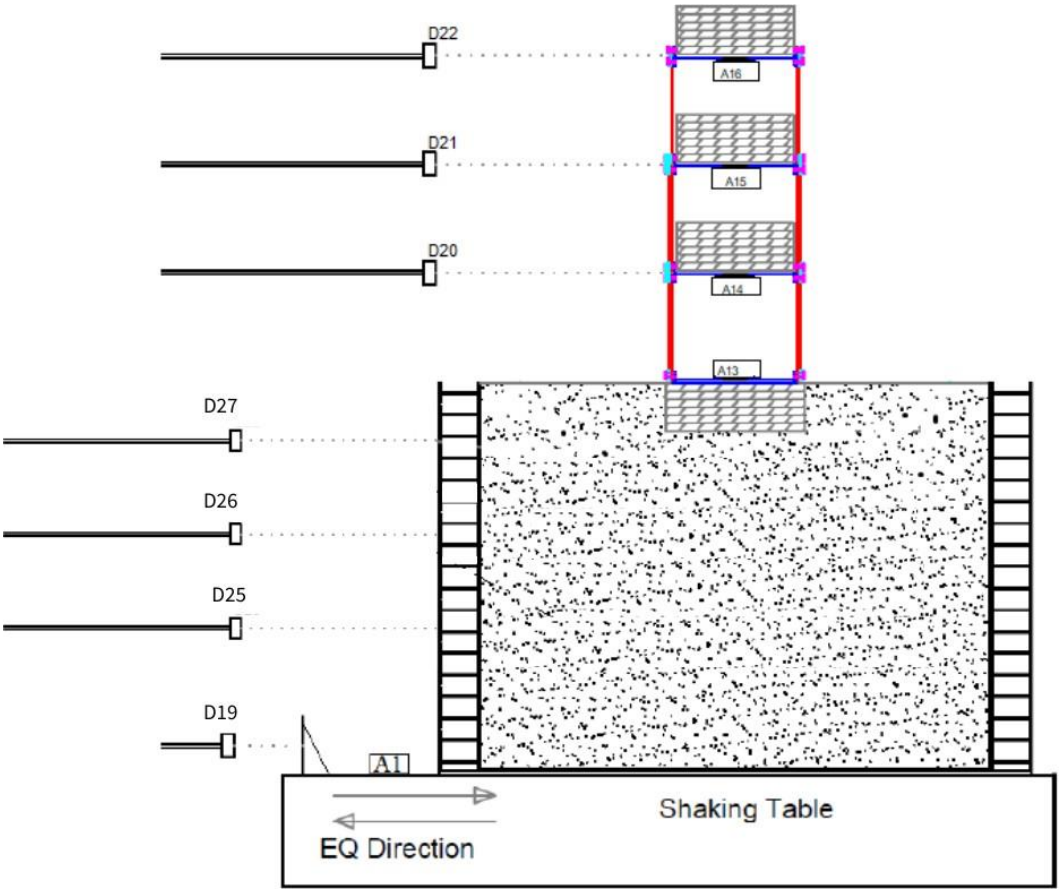



Figure 3.14. The Sketch of Scaled Building Model and Sensors For 3-Storey Building



Figure 3.15. A View of the Scaled Building Model with Projection of Sensors.

### 3.3.2. The Scaled Input Motions

Input motions that mentioned in Chapter 3.3 were applied to unimproved and improved with Gravel Rubber Mixtures the models. Motion input data were scaled 1:10 by multiplying duration with √10 scaling factor for protecting to dynamic assimilation in the shaking. By this way, the earthquake records that were determined in the previous chapter could be implemented to the building models.

Total 14 cases were planned and applied with 2 different thickness, 2 different building model and 4 different rubber contents. Considered cases in this study are shown in Table 3.3.

Table 3.3. Considered Cases for Experimental Study

| Cases | | | | | | Ground Motions | | |
|---|---|---|---|---|---|---|---|---|
| Case Number | Storeys | Type of GRM | Rubber (%) | Thickness of GRM (cm) | Code | Kocaeli-İzmit (Near)(g) | El-Centro (Near)(g) | Kobe (Near)(g) |
| 1 | 5 | Sand | 0 | 0 | 5-Sand | 0,21g | 0,32g | 0,81g |
| 2 | 5 | Gravel | 0 | 10 | 5-TC0/10 | | | |
| 3 | 5 | Gravel | 0 | 15 | 5-TC0/15 | | | |
| 4 | 5 | Crumb | 30 | 10 | 5-TC30/10 | | | |
| 5 | 5 | Crumb | 30 | 15 | 5-TC30/15 | | | |
| 6 | 5 | Crumb | 20 | 15 | 5-TC20/15 | | | |
| 7 | 5 | Crumb | 10 | 15 | 5-TC10/15 | | | |
| 8 | 5 | Crumb | 20 | 10 | 5-TC20/10 | | | |
| 9 | 5 | Crumb | 10 | 10 | 5-TC10/10 | | | |
| 10 | 3 | Sand | 0 | 0 | 3-Sand | | | |
| 11 | 3 | Gravel | 0 | 10 | 3-TC0/10 | | | |
| 12 | 3 | Gravel | 0 | 15 | 3-TC0/15 | | | |
| 13 | 3 | Crumb | 30 | 10 | 3-TC30/10 | | | |
| 14 | 3 | Crumb | 30 | 15 | 3-TC30/15 | | | |

### 3.3.3. Sample Preparation

Firstly, the laminar box was put on the shaking table and assembled to the table. After the greasing of inner wall, membrane was placed. The unit weight of Silivri Sand is 18.4 kN/m$^3$ with relative density of 0.85 for the sand.

675 kg sand was placed in the box by means of big bags and compacted as a first step. After compaction, an accelerometer (A5) was placed into the sand. Then more 675 kg sand was added to the box and compacted. Many accelerometers (A6, A7,A8,A9 and A10) was placed with compaction. These accelerometers were located the middle of the box and 10 cm far from the corners. Laminar box includes 1350 kg sand accelerometer can be seen in Figure 3.16. Then, more 675 kg sand were located and compacted, and an accelerometer (A11) was added. Ultimately, the last quarter of the laminar box was filled, the sand was compacted and accelerometer- (A12) was put.

When completed these stages, a steel casing was driven. Sand was removed to change GRM without disturbing compacted sand. Half of the prepared GRM sample and an accelerometer (A11) was added on the middle of this layer. The model was located at box center. Also, gaps were filled with GRM. The section of the position of GRM is shown in Figure 3.17. Thicknesses of GRM (t) were selected as 10 and 15 cm in tests.

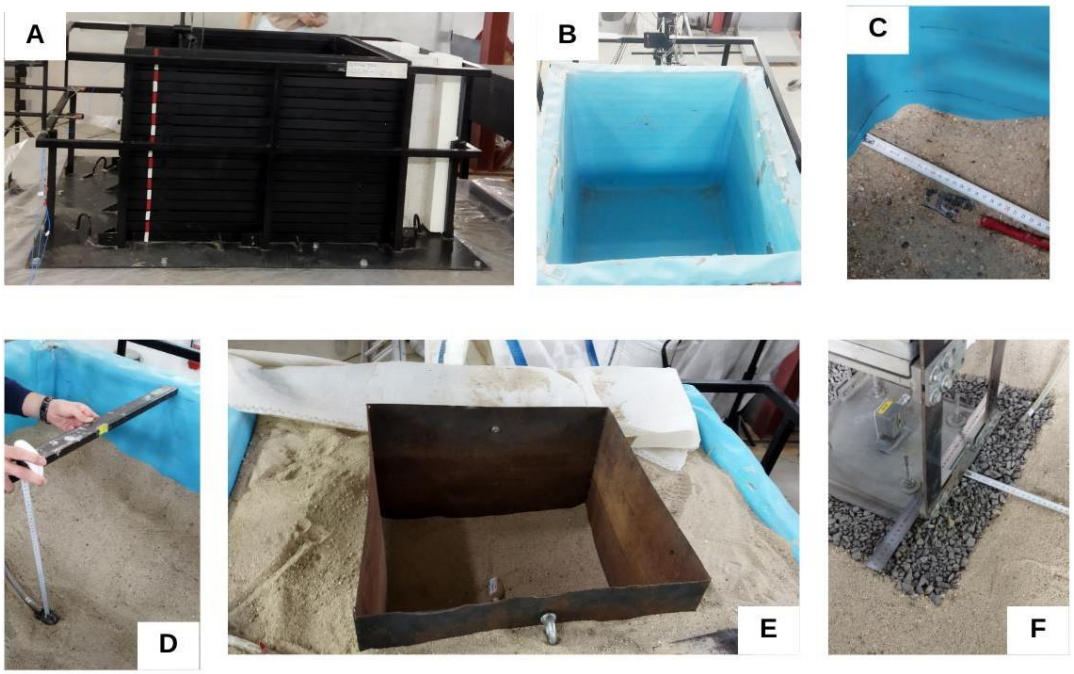



Figure 3.16. (a) Laminar Box, (b) Laminar box with Membrane, (c) The Placement of Accelerometer at the Corners, (d) Placement of Accelerometer in the Middle of the Box, (e) The Square Thin Steel Casing, (f) 10 cm Isolated Area

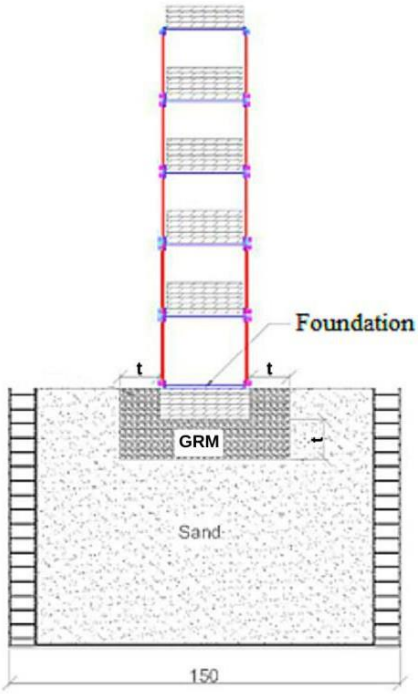



Figure 3.17. Building Model Placed on Geotechnical Seismic Isolation System with GRM.

# 4. EXPERIMENTAL RESULTS

In this thesis, different cases were investigated to make efficient comparison in terms of story number, GRM content, GRM thickness and ground motions. The unisolated models which were conducted without isolation material is vital to compare with the isolated cases and to make parametric study. All cases were performed with building model and all shaking table experiments clarified the effects of GRM, rubber ratio of GRM, the thickness of GRM on seismic performance of building models.

Two main performance criteria which were the acceleration, and the top floor displacement were selected. In addition to these performance parameters, spectral accelerations and period lengthening ratio were calculated and added to tables.

## 4.1. Experimental Results without GSI for 5 Story Model

5-story building model were used for the first case that doesn't include any improvement material. By this model, the behavior of buildings without improvement is observed. This first results were considered to compare with improved cases results.

### 4.1.1. Case 1: Unisolated Case (5-Sand) under Kocaeli Earthquake Motion

Figure 4.1, It was showed Horizontal Foundation Response (FHR), the Top Floor Horizontal Response (TFHR), and First Floor Drift (FFD) graphs.

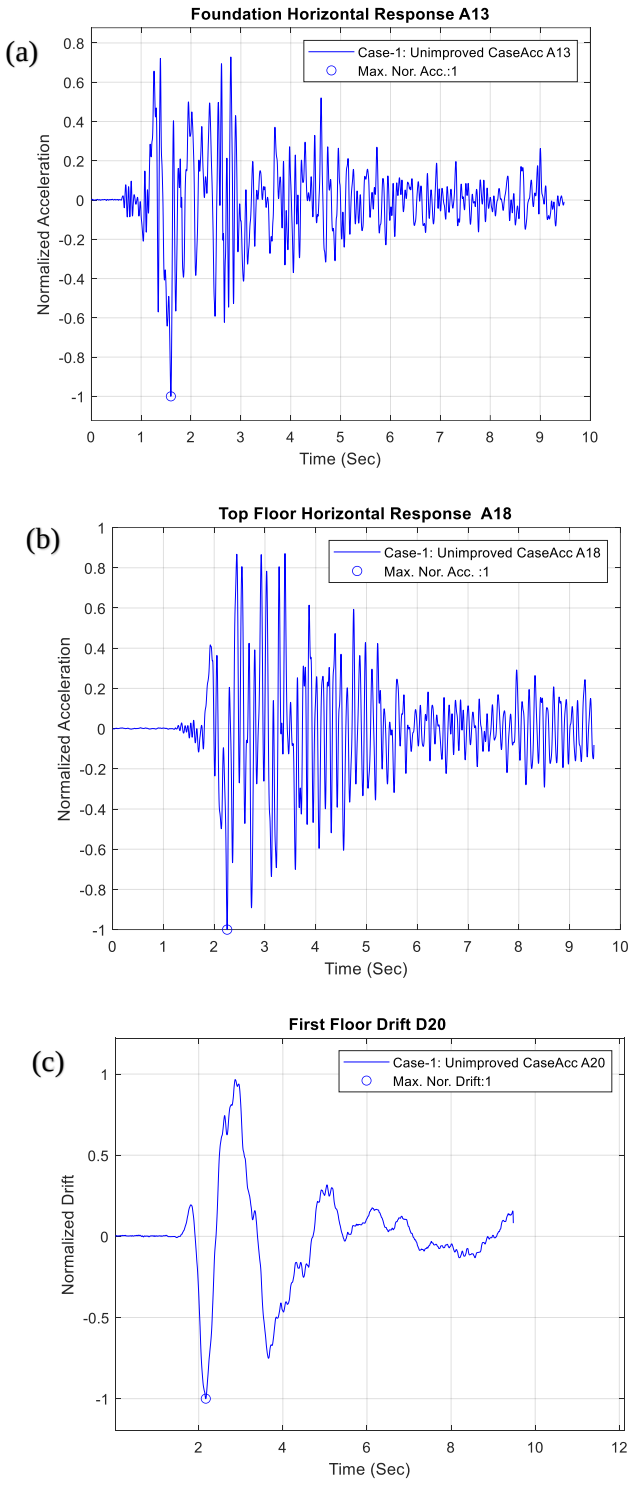



Figure. 4.1. (a) FHR, (b) TFHR, (c) FFD of 5-Sand Case

### 4.1.2. Case 1: Unisolated Case (5-Sand) under El Centro Earthquake Motion

Figure 4.2, Horizontal Foundation Response (FHR), the Top Floor Horizontal Response (TFHR), and First Floor Drift (FFD) graphs.

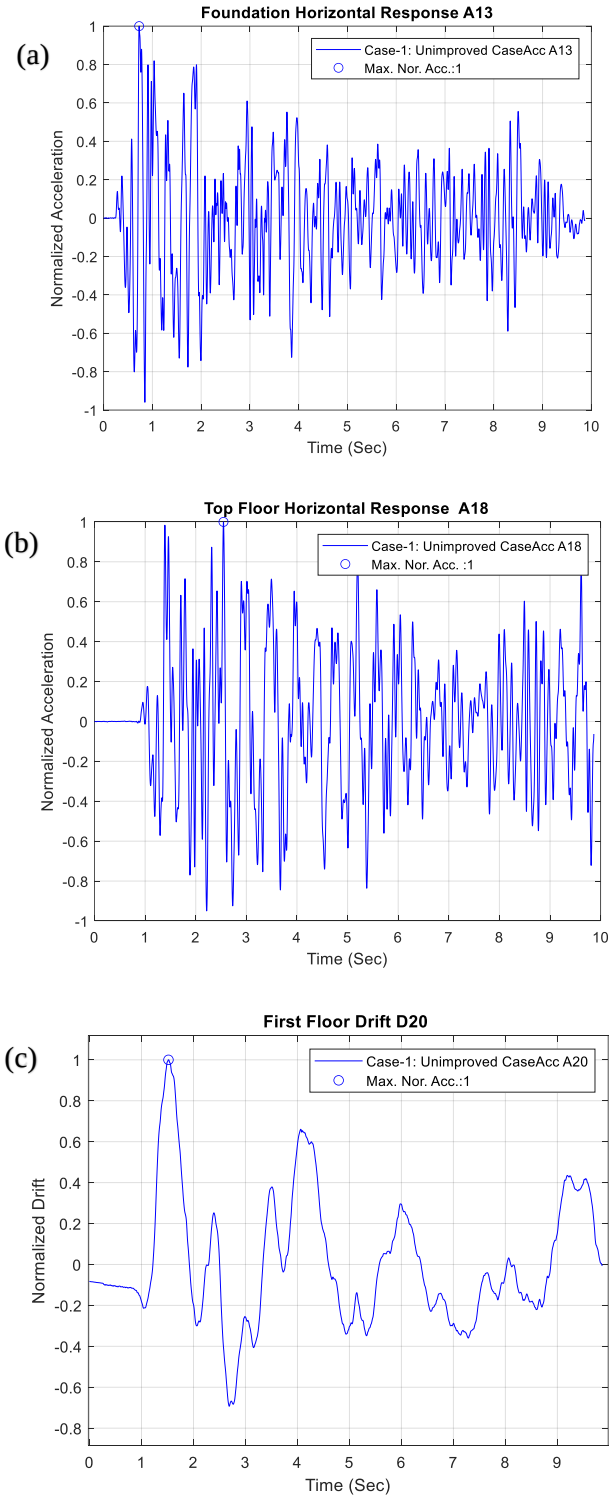



Figure. 4.2. (a) FHR, (b) TFHR, (c) FFD of 5-Sand Case

### 4.1.3. Case 1: Unisolated Case (5-Sand) under Kobe Earthquake Motion

Figure 4.3, It was showed Horizontal Foundation Response (FHR), the Top Floor Horizontal Response (TFHR), and First Floor Drift (FFD) graphs.

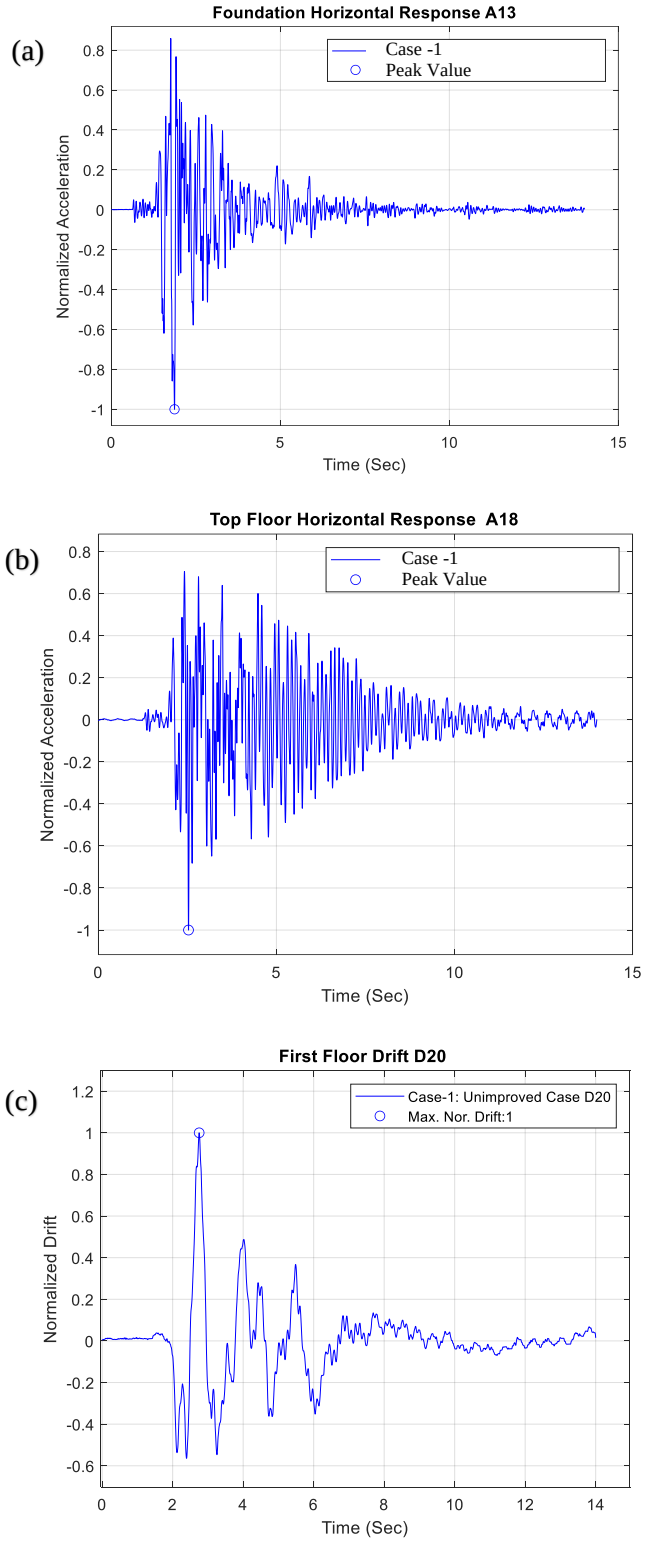



Figure. 4.3. (a) FHR, (b) TFHR, (c) FFD of 5-Sand Case

## 4.2. Experimental Results of Isolated Cases for 5 Story Building Model

The results of tests are shown by comparing unimproved cases results with control model results.

### 4.2.1. Case 2: Only Gravel with 10 cm Thickness (5-TC0/10) as GSI Material

For second case, 5-story building foundation surrounded with 10 cm thickness gravel. The results of Kocaeli, El Centro and Kobe earthquake motions are represented in this part.

- **5-TC0/10 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.4 and Table 4.1.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of some stories were decreased by 18-21 %. Moreover, the inter-story drift ratio showed a critical reduction of 36-72%. Besides, peak spectral acceleration increased generally and except for the third story any period lengthening couldn’t be observed.

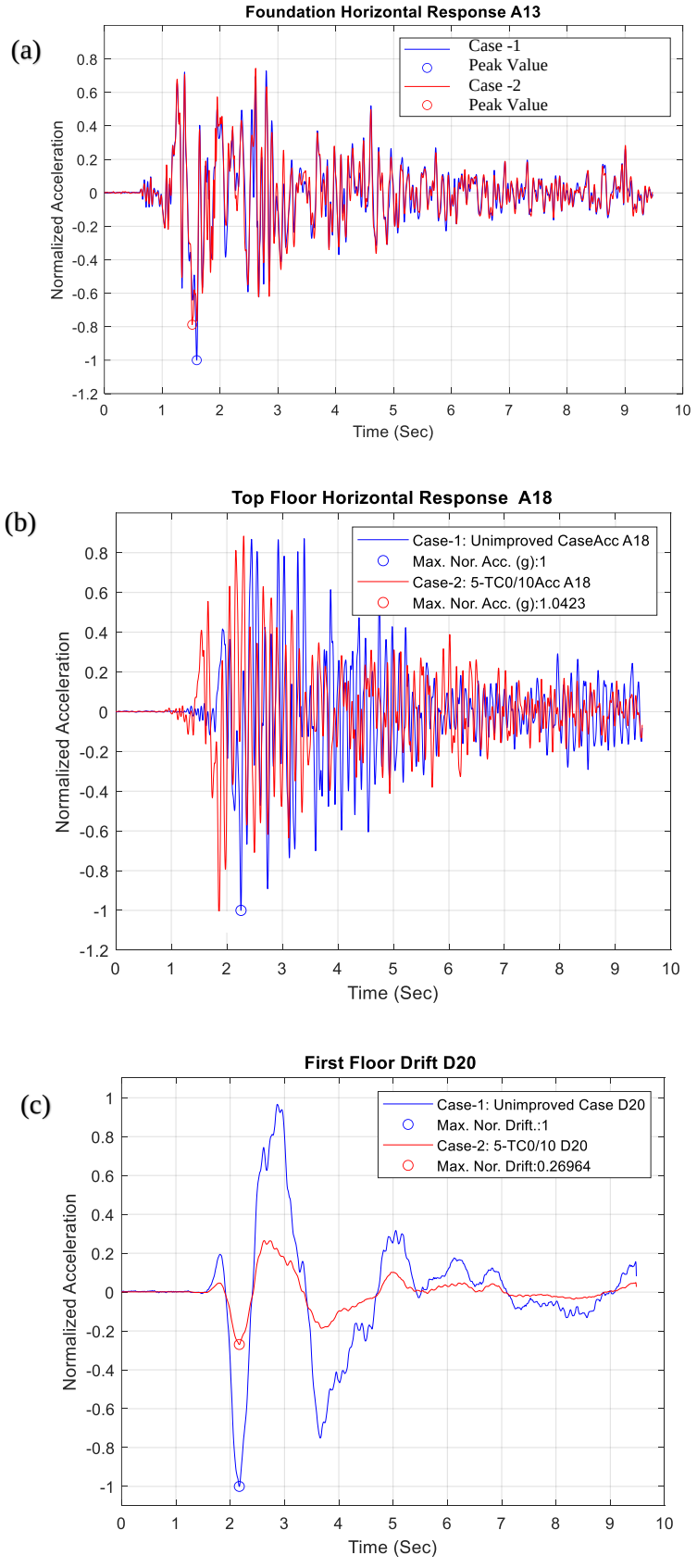



Figure 4.4. (a) FHR, (b) TFHR, (c) FFD of 5-TC0/10 under Kocaeli Earthquake Motion

Table 4.1. Results of 5-TC0/10 under Kocaeli Earthquake Motion

| 5-TC0/10 - Kocaeli EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,02 | 0,20 | 0,07 | 0,47 | 0,06 | 0,40 | 0,05 | 0,38 | 0,05 | 0,45 | 0,08 | 0,56 |
| 5-TC0/10 | 0,02 | 0,15 | 0,05 | 0,38 | 0,06 | 0,50 | 0,04 | 0,41 | 0,04 | 0,36 | 0,07 | 0,58 |
| % Reduction | 0 | 21 | 30 | 19 | -8 | -24 | 11 | -8 | 19 | 18 | 15 | -4 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,01483 | 0,08634 | 0,00063 | 0,01151 | 0,00180 | 0,01882 | 0,00069 | 0,00931 | 0,00010 | 0,00395 |
| 5-TC0/10 | * | * | 0,00412 | 0,02331 | 0,00027 | 0,00381 | 0,00046 | 0,00458 | 0,00045 | 0,00548 | 0,00013 | 0,00254 |
| % Reduction | * | * | 72 | 73 | 57 | 67 | 74 | 76 | 34 | 41 | 39 | 36 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,6 | | 2,9 | | 2,2 | | 1,4 | | 1,5 | | 2,7 | |
| 5-TC0/10 | 0,7 | | 2,4 | | 3,1 | | 1,5 | | 1,5 | | 2,8 | |
| % Reduction | -3,9 | | 18,1 | | -43,3 | | -13,6 | | 5,1 | | -3,9 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,0 | | 1,0 | | 1,0 | | 1,6 | | 1,0 | | 1,0 | |

- **5-TC0/10 against El-Centro Earthquake Motion**

Case results are shown Figure 4.5 and Table 4.2.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of some stories were decreased by 9 %. Moreover, the inter-story drift ratio showed a critical reduction of 58-76%. Besides, peak spectral acceleration decreased generally and except for the foundation and $5^{th}$ floor, period lengthening could be observed.

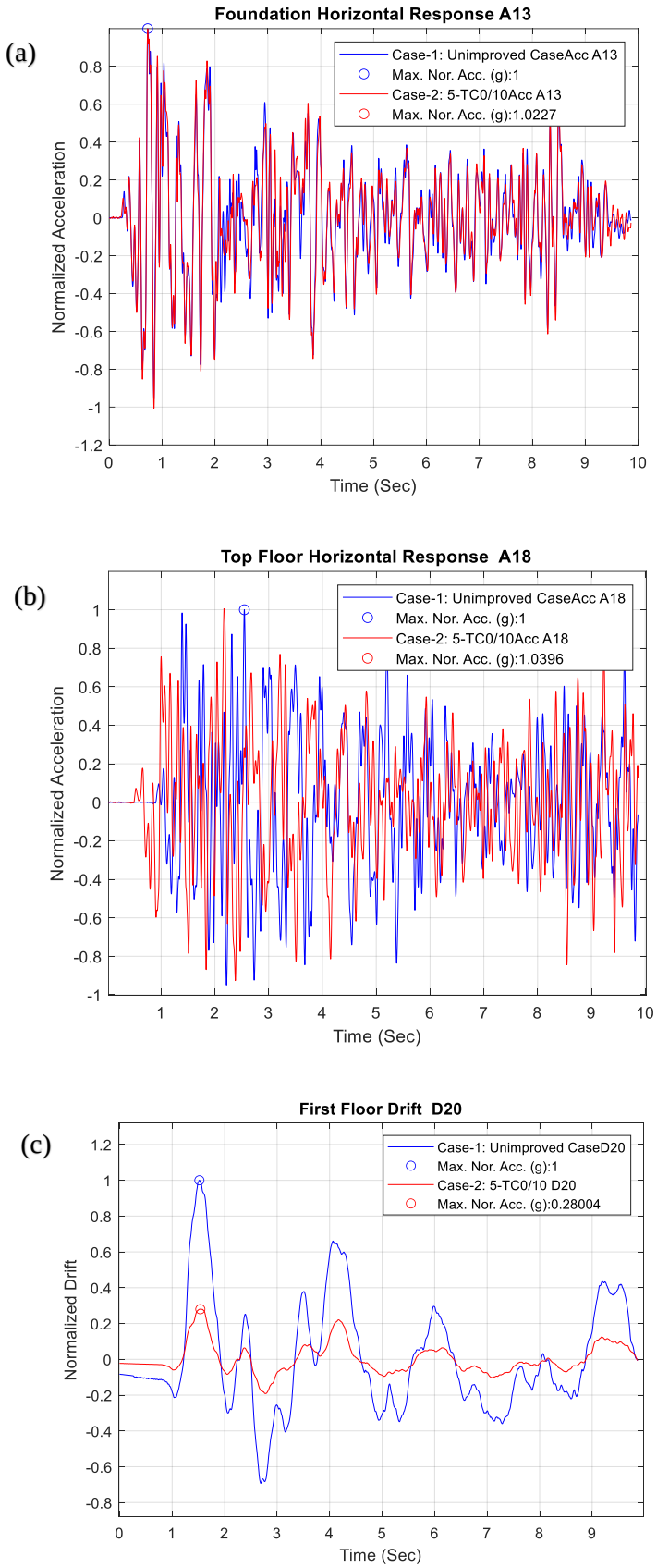



Figure 4.5. (a) FHR, (b) TFHR, (c) FFD of 5-TC0/10 under El Centro Earthquake Motion

Table 4.2. Results of 5-TC0/10 under El Centro Earthquake Motion

| 5-TC0/10 - El Centro EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,03 | 0,20 | 0,06 | 0,33 | 0,05 | 0,32 | 0,07 | 0,34 | 0,07 | 0,32 | 0,09 | 0,43 |
| 5-TC0/10 | 0,03 | 0,21 | 0,06 | 0,33 | 0,06 | 0,35 | 0,06 | 0,31 | 0,06 | 0,36 | 0,08 | 0,44 |
| % Reduction | 1 | -2 | 4 | -1 | -18 | -10 | 12 | 9 | 21 | -12 | 12 | -4 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0177 | 0,0926 | 0,0010 | 0,0062 | 0,0023 | 0,0108 | 0,0013 | 0,0090 | 0,0008 | 0,0021 |
| 5-TC0/10 | * | * | 0,0048 | 0,0259 | 0,0004 | 0,0024 | 0,0006 | 0,0045 | 0,0005 | 0,0019 | 0,0002 | 0,0004 |
| % Reduction | * | * | 73 | 72 | 58 | 61 | 72 | 58 | 61 | 79 | 75 | 81 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,81 | | 1,73 | | 1,46 | | 1,48 | | 1,50 | | 1,80 | |
| 5-TC0/10 | 0,84 | | 1,53 | | 2,08 | | 1,22 | | 1,20 | | 1,94 | |
| % Reduction | -3 | | 11 | | -42 | | 18 | | 20 | | -8 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,00 | | 1,04 | | 1,04 | | 1,07 | | 1,07 | | 1,00 | |

- **5-TC0/10 under Kobe Earthquake Motion**

Case results are shown in Figure 4.6 and Table 4.3.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of some stories were decreased by 12-34 %. Moreover, the inter-story drift ratio showed an important reduction of 67-75%. Besides, peak spectral acceleration decreased generally and except for the first, third and 5$^{th}$ floor, period lengthening could be observed.

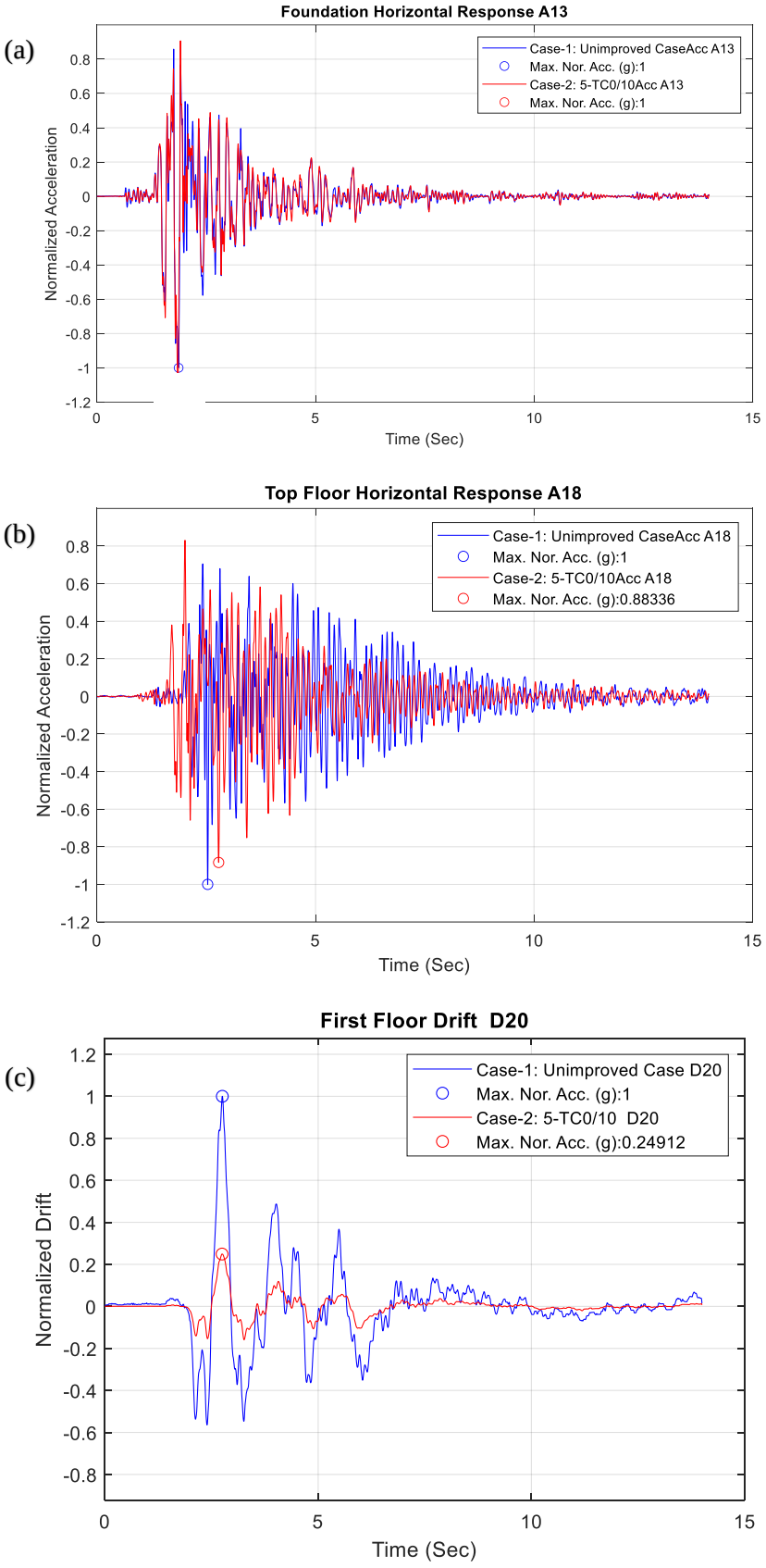



Figure 4.6. (a) FHR, (b) TFHR, (c) FFD of 5-TC0/10 under Kobe Earthquake Motion.

Table 4. 3. Results of 5-TC0/10 under Kobe Earthquake Motion

| 5-TC0/10 - Kobe EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,05 | 0,56 | 0,11 | 0,70 | 0,10 | 0,91 | 0,09 | 0,91 | 0,09 | 0,62 | 0,13 | 1,07 |
| 5-TC0/10 | 0,05 | 0,66 | 0,09 | 0,86 | 0,11 | 0,79 | 0,07 | 0,60 | 0,07 | 0,50 | 0,12 | 0,95 |
| % Reduction | 0 | -17 | 16 | -23 | -8 | 12 | 21 | 34 | 19 | 20 | 8 | 12 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0107 | 0,0856 | 0,0025 | 0,0135 | 0,0037 | 0,0247 | 0,0029 | 0,0209 | 0,0018 | 0,0155 |
| 5-TC0/10 | * | * | 0,0028 | 0,0213 | 0,0005 | 0,0040 | 0,0008 | 0,0066 | 0,0009 | 0,0070 | 0,0005 | 0,0043 |
| % Reduction | * | * | 74 | 75 | 79 | 70 | 78 | 73 | 69 | 67 | 71 | 72 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 1,67 | | 4,10 | | 3,81 | | 5,12 | | 2,52 | | 3,84 | |
| 5-TC0/10 | 1,71 | | 3,57 | | 5,05 | | 3,23 | | 2,43 | | 4,67 | |
| % Reduction | -2 | | 13 | | -33 | | 37 | | 4 | | -22 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 2,1 | | 1,0 | | 1,6 | | 1,0 | | 2,3 | | 1,0 | |

### 4.2.2. Case 3: Only Gravel with 15 cm Thickness (5-TC0/15) as GSI Material

For Case-3, the foundation of the 5-story building model was surrounded by 15 cm thickness gravel. The results of Kobe, El Centro and Kocaeli earthquake motions are presented here.

- **5-TC0/15 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.7 and Table 4.4.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of some stories were decreased by 12-34 %. Moreover, the inter-story drift ratio showed a critical reduction of 67-75%. Besides, peak spectral acceleration decreased generally and except for the first, third and $5^{th}$ floor, period lengthening was observed.

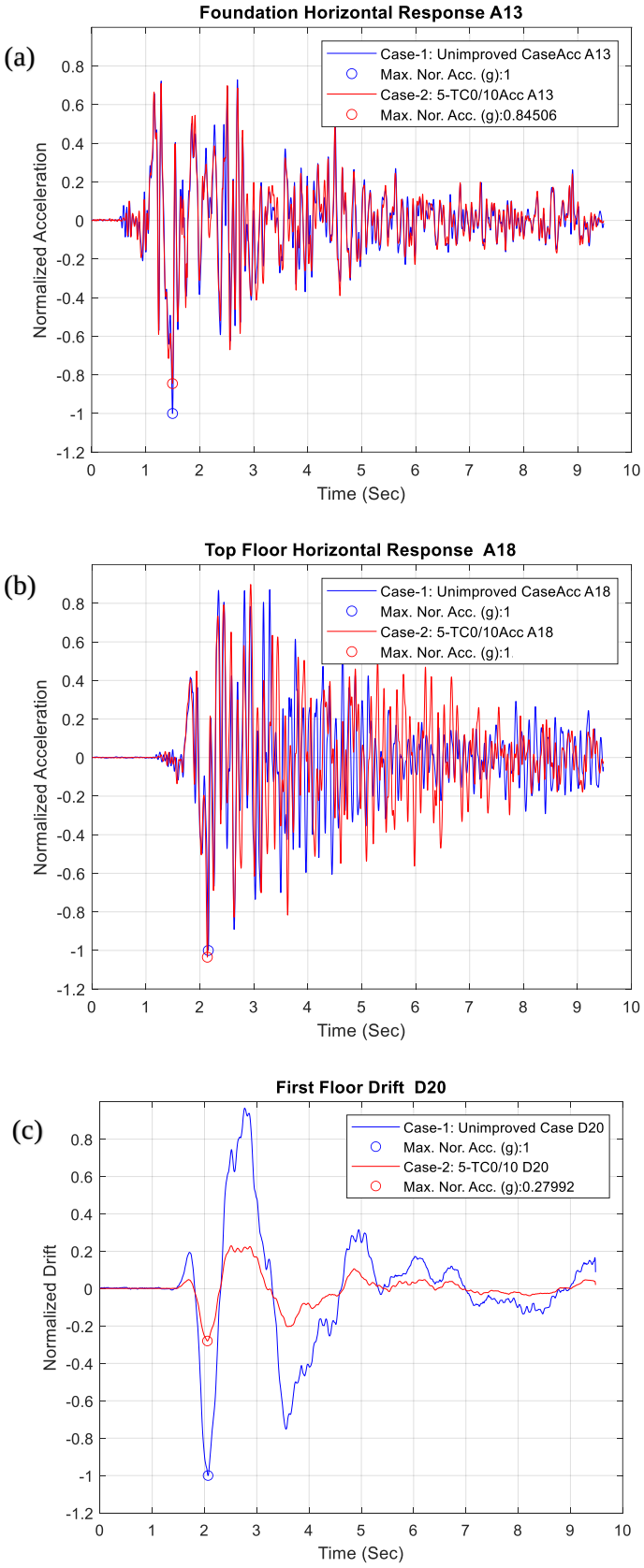



Figure 4.7. (a) FHR, (b) TFHR, (c) FFD of 5-TC0/15 under Kocaeli Earthquake Motion

Table 4. 4. Results of 5-TC0/15 under Kocaeli Earthquake Motion

| 5-TC0/15 - Kocaeli EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,02 | 0,20 | 0,07 | 0,47 | 0,06 | 0,40 | 0,05 | 0,38 | 0,05 | 0,45 | 0,08 | 0,56 |
| 5-TC0/15 | 0,02 | 0,17 | 0,06 | 0,38 | 0,07 | 0,45 | 0,05 | 0,36 | 0,05 | 0,40 | 0,08 | 0,58 |
| % Reduction | 0 | 15 | 23 | 20 | -16 | -12 | -4 | 6 | 0 | 10 | 2 | -3 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0148 | 0,0863 | 0,0006 | 0,0115 | 0,0018 | 0,0188 | 0,0007 | 0,0093 | 0,0001 | 0,0039 |
| 5-TC0/15 | * | * | 0,0050 | 0,0270 | 0,0003 | 0,0019 | 0,0009 | 0,0042 | 0,0005 | 0,0024 | 0,0001 | 0,0025 |
| % Reduction | * | * | 66 | 69 | 49 | 84 | 51 | 78 | 24 | 74 | 32 | 38 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,64 | | 2,87 | | 2,16 | | 1,36 | | 1,53 | | 2,71 | |
| 5-TC0/15 | 0,67 | | 2,31 | | 3,09 | | 1,52 | | 1,53 | | 2,86 | |
| % Reduction | -5 | | 20 | | -43 | | -12 | | 0 | | -6 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,1 | | 1,0 | | 1,0 | | 1,6 | | 1,0 | | 1,0 | |

- **5-TC0/15 against El-Centro**

Case results are shown in Figure 4.8 and Table .4.5.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were increased by 4-26 %. Moreover, the inter-story drift ratio showed a critical reduction of 58-140%. Besides, peak spectral acceleration increased generally and except for foundation and $5^{th}$ floor, period lengthening could be observed.

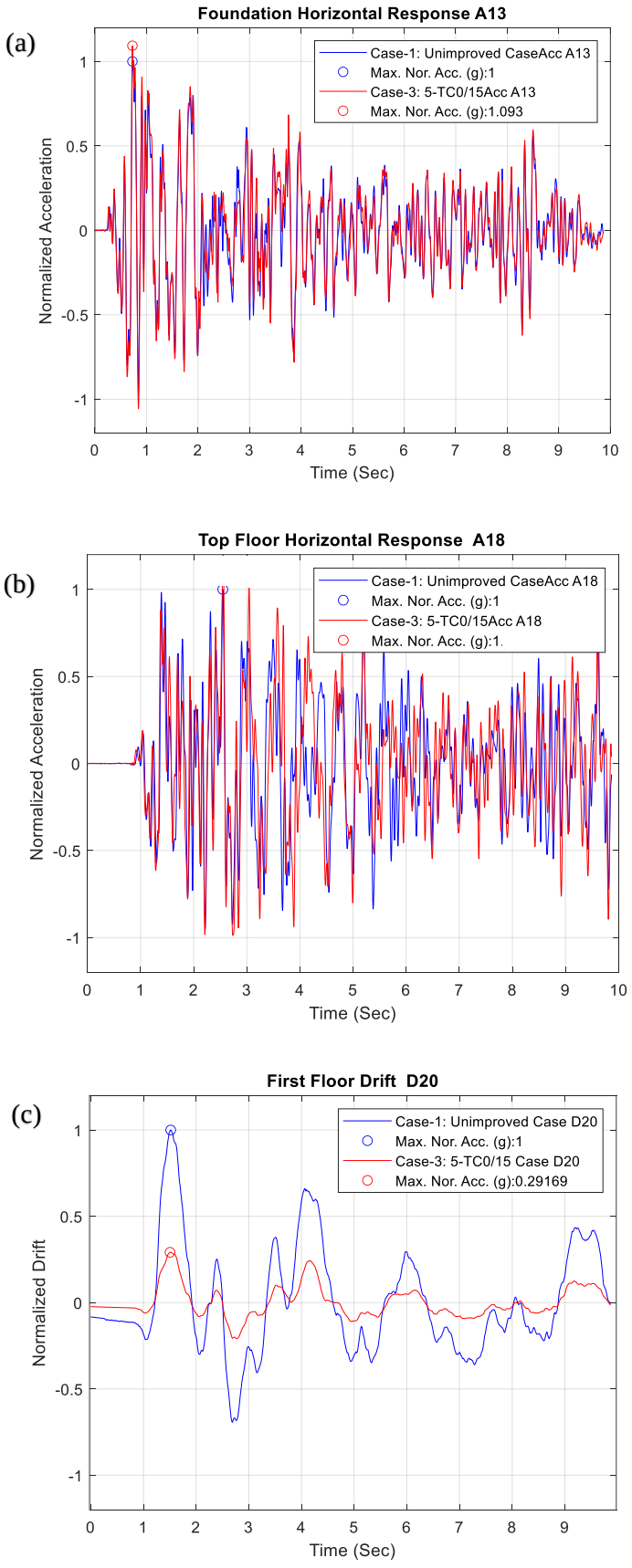



Figure 4.8. (a) FHR, (b) TFHR, (c) FFD of 5-TC0/15 under El Centro Earthquake Motion

Table 4. 5. Results of TC0/15 under El Centro Earthquake Motion

| 5-TC0/15 - El Centro EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,03 | 0,20 | 0,06 | 0,33 | 0,05 | 0,32 | 0,07 | 0,34 | 0,07 | 0,32 | 0,09 | 0,43 |
| 5-TC0/15 | 0,03 | 0,22 | 0,06 | 0,41 | 0,07 | 0,36 | 0,06 | 0,36 | 0,07 | 0,40 | 0,09 | 0,52 |
| % Reduction | -5 | -9 | -1 | -26 | -27 | -16 | 4 | -4 | 6 | -24 | 2 | 22 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,018 | 0,093 | 0,001 | 0,006 | 0,002 | 0,011 | 0,001 | 0,009 | 0,001 | 0,002 |
| 5-TC0/15 | * | * | 0,005 | 0,026 | 0,000 | 0,002 | 0,001 | 0,005 | 0,000 | 0,002 | 0,000 | 0,000 |
| % Reduction | * | * | 73 | 72 | 58 | 61 | 72 | 58 | 61 | 79 | 75 | 81 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,81 | | 1,73 | | 1,46 | | 1,48 | | 1,50 | | 1,80 | |
| 5-TC0/15 | 0,88 | | 1,71 | | 2,25 | | 1,44 | | 1,56 | | 2,15 | |
| % Reduction | -8 | | 1 | | -53 | | 3 | | -4 | | -20 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,00 | | 1,04 | | 1,04 | | 1,07 | | 1,07 | | 1,00 | |

- **5-TC0/15 under Kobe**

Case results are shown in Figure 4.9 and Table 4.6.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 4-27% especially on upper floors. Moreover, the inter-story drift ratio showed a critical reduction of 74-80%. Besides, peak spectral acceleration increased generally and except for first, third and $5^{th}$ floor, period lengthening could be observed.

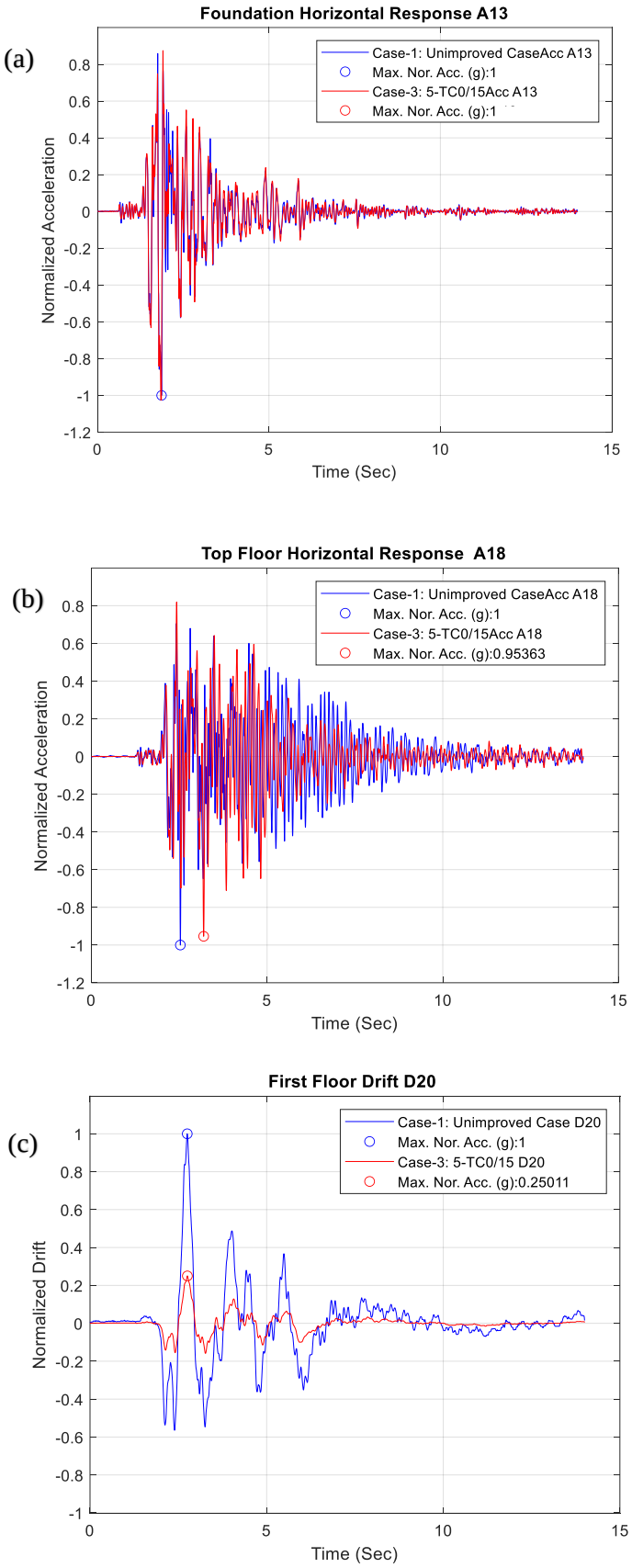



Figure 4. 9. (a) FHR, (b) TFHR, (c) FFD of 5-TC0/15 under Kobe Earthquake Motion

Table 4. 6. Results of TC0/15 under Kobe Earthquake Motion

| 5-TC0/15 - Kobe EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,05 | 0,56 | 0,11 | 0,70 | 0,10 | 0,91 | 0,09 | 0,91 | 0,09 | 0,62 | 0,13 | 1,07 |
| 5-TC0/15 | 0,05 | 0,64 | 0,09 | 0,84 | 0,11 | 0,87 | 0,08 | 0,66 | 0,08 | 0,58 | 0,12 | 1,02 |
| % Reduction | 0 | -13 | 14 | -20 | -9 | 4 | 13 | 27 | 14 | 6 | 4 | 5 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,011 | 0,086 | 0,003 | 0,013 | 0,004 | 0,025 | 0,003 | 0,021 | 0,0018 | 0,016 |
| 5-TC0/15 | * | * | 0,003 | 0,021 | 0,001 | 0,003 | 0,001 | 0,006 | 0,001 | 0,005 | 0,0005 | 0,007 |
| % Reduction | * | * | 74 | 75 | 76 | 76 | 74 | 74 | 71 | 76 | 74 | 52 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 1,67 | | 4,10 | | 3,81 | | 5,12 | | 2,52 | | 3,84 | |
| 5-TC0/15 | 1,71 | | 3,81 | | 5,27 | | 3,99 | | 2,59 | | 4,96 | |
| % Reduction | -2 | | 7 | | -38 | | 22 | | -3 | | -29 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 2,1 | | 1,0 | | 1,6 | | 1,0 | | 2,3 | | 1,0 | |

### 4.2.3. Case 4: TC30 with 10 cm Thickness (5-TC 30/10) as GSI Material

In Case-4, 5-story model foundation was surrounded with 10 cm thickness GRM includes 30% Tire Crumb. In this test, all selected earthquake motions were applied. However, the results of Kobe El Centro, Kocaeli earthquakes are presented here.

- **5-TC30/10 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.10 and Table 4.7.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 12-40 % especially on upper floors. Moreover, the inter-story drift ratio showed a critical reduction of 17-65%. Besides, peak spectral acceleration decreased generally and except for first and third floors and, period lengthening couldn't be observed.

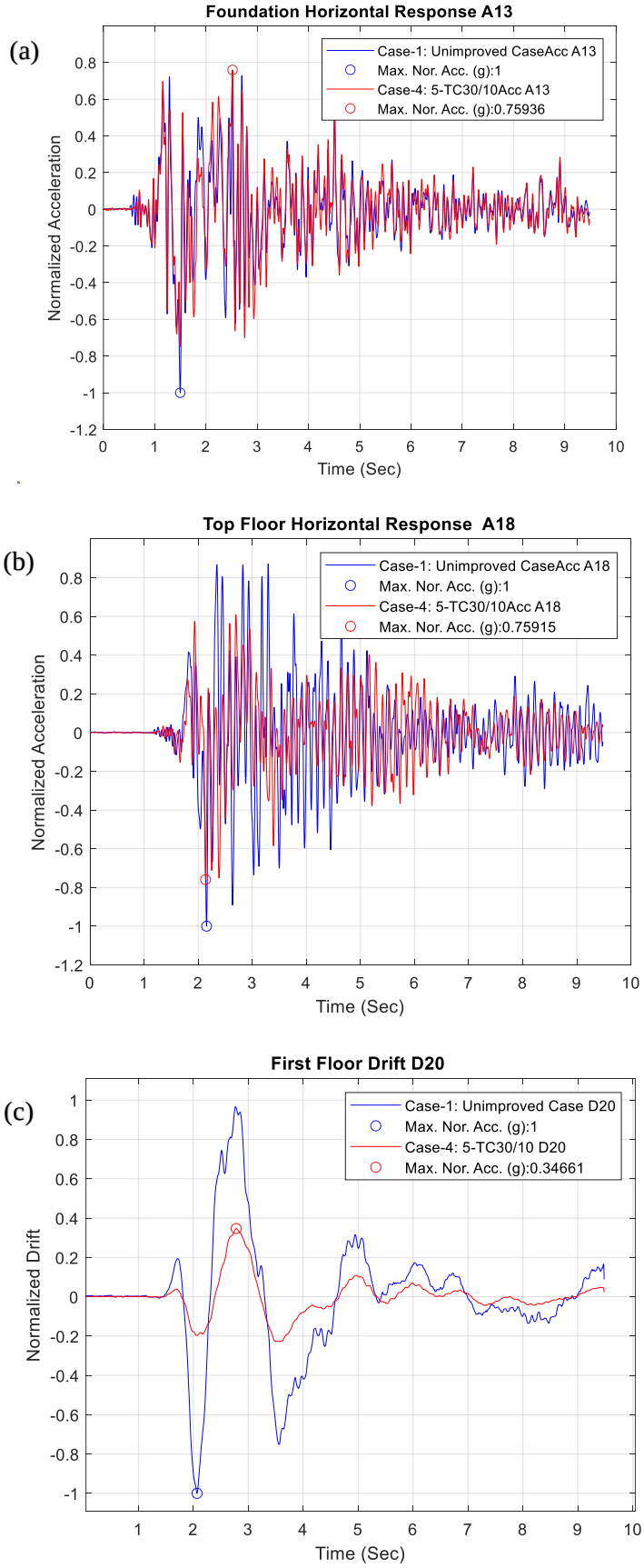



Figure 4.10. (a) FHR, (b) TFHR, (c) FFD of 5-TC30/10 under Kocaeli Earthquake Motion

Table 4. 7. Results of 5-TC30/10 under Kocaeli Earthquake Motion

| 5-TC30/10 - Kocaeli EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,02 | 0,20 | 0,07 | 0,47 | 0,06 | 0,40 | 0,05 | 0,38 | 0,05 | 0,45 | 0,08 | 0,56 |
| 5-TC30/10 | 0,02 | 0,15 | 0,04 | 0,28 | 0,05 | 0,41 | 0,03 | 0,33 | 0,04 | 0,27 | 0,05 | 0,42 |
| % Reduction | 8 | 24 | 48 | 40 | 24 | -3 | 34 | 12 | 34 | 40 | 32 | 24 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0148 | 0,0863 | 0,0006 | 0,0115 | 0,0018 | 0,0188 | 0,0007 | 0,0093 | 0,00010 | 0,0039 |
| 5-TC30/10 | * | * | 0,0047 | 0,0298 | 0,0007 | 0,0064 | 0,0012 | 0,0077 | 0,0010 | 0,0079 | 0,0006 | 0,0033 |
| % Reduction | * | * | 69 | 65 | -14 | 45 | 36 | 59 | 19 | 15 | 18 | 17 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,64 | | 2,87 | | 2,16 | | 1,36 | | 1,53 | | 2,71 | |
| 5-TC30/10 | 0,74 | | 1,68 | | 2,20 | | 1,21 | | 1,13 | | 2,09 | |
| % Reduction | -16 | | 41 | | -2 | | 11 | | 26 | | 23 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,0 | | 1,1 | | 1,0 | | 1,1 | | 1,0 | | 1,0 | |

- **5-TC30/10 against El-Centro Earthquake Motion**

Case results are shown in Figure. 4.11 and Table. 4.8.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 2-13 % especially on upper floors. Moreover, the inter-story drift ratio showed a critical reduction of 35-81%. Besides, peak spectral acceleration decreased generally and except for foundation and 5$^{th}$ floor, period lengthening could be observed.

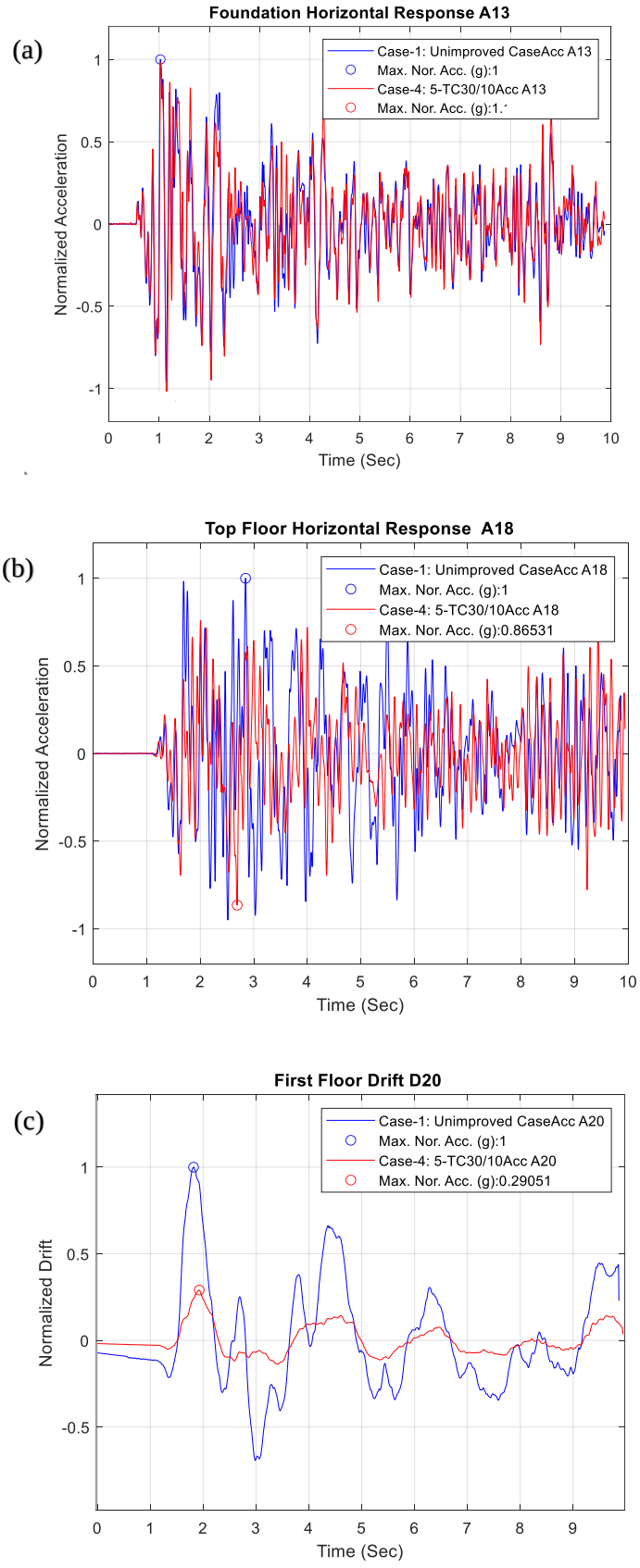



Figure 4.11. (a) FHR, (b) TFHR, (c) FFD of 5-TC30/10 under El Centro Earthquake Motion

Table 4. 8. Results of 5-TC30/10 under El Centro Earthquake Motion

| 5-TC30/10 - El Centro EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,03 | 0,20 | 0,06 | 0,33 | 0,05 | 0,32 | 0,07 | 0,34 | 0,07 | 0,32 | 0,09 | 0,43 |
| 5-TC30/10 | 0,03 | 0,23 | 0,05 | 0,36 | 0,05 | 0,32 | 0,04 | 0,35 | 0,04 | 0,32 | 0,06 | 0,37 |
| % Reduction | 7 | -10 | 12 | -10 | -5 | -2 | 33 | -1 | 46 | 2 | 33 | 13 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0177 | 0,0926 | 0,0010 | 0,0062 | 0,0023 | 0,0108 | 0,0013 | 0,0090 | 0,0008 | 0,0021 |
| 5-TC30/10 | * | * | 0,0045 | 0,0269 | 0,0006 | 0,0028 | 0,0011 | 0,0048 | 0,0008 | 0,0058 | 0,0006 | 0,0035 |
| % Reduction | * | * | 75 | 71 | 41 | 55 | 53 | 55 | 35 | 35 | 29 | 81 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,81 | | 1,73 | | 1,46 | | 1,48 | | 1,50 | | 1,80 | |
| 5-TC30/10 | 0,79 | | 1,47 | | 1,82 | | 1,48 | | 0,95 | | 1,65 | |
| % Reduction | 3 | | 15 | | -25 | | 0 | | 37 | | 8 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,0 | | 1,1 | | 1,1 | | 1,1 | | 0,3 | | 1,0 | |

- **5-TC30/10 under Kobe Earthquake Motion**

Case results are shown in Figure 4.12 and Table 4.9.

According to test results, foundation horizontal acceleration response was affected negatively by improvement. This improvement has positive effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 3-35 % especially on upper floors. Moreover, the inter-story drift ratio showed a critical reduction of 55-112%. Besides, peak spectral acceleration decreased generally and except for 3$^{rd}$ and 4$^{th}$ floors, period lengthening could be observed.

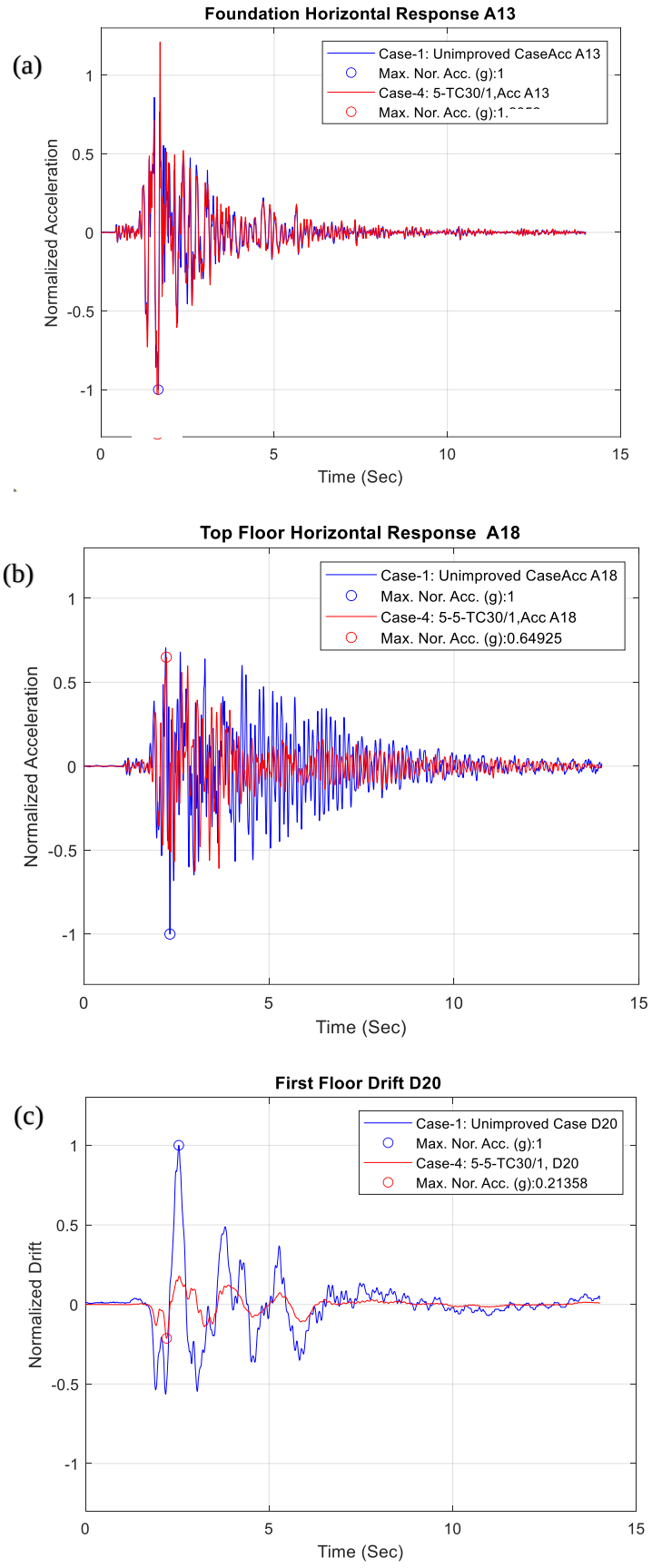



Figure 4. 12. (a) FHR, (b) TFHR, (c) FFD of 5-TC30/10 under Kobe Earthquake Motion

Table 4. 9. Results of 5-TC30/10 under Kobe Earthquake Motion

| 5-TC30/10 - Kobe EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,05 | 0,56 | 0,11 | 0,70 | 0,10 | 0,91 | 0,09 | 0,91 | 0,09 | 0,62 | 0,13 | 1,07 |
| 5-TC30/10 | 0,05 | 0,73 | 0,08 | 0,87 | 0,07 | 0,88 | 0,06 | 0,80 | 0,05 | 0,63 | 0,08 | 0,70 |
| % Reduction | 2 | -29 | 31 | -25 | 24 | 3 | 38 | 11 | 47 | -1 | 38 | 35 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,01 | 0,09 | 0,00 | 0,01 | 0,00 | 0,02 | 0,00 | 0,02 | 0,00 | 0,02 |
| 5-TC30/10 | * | * | 0,00 | 0,02 | 0,00 | 0,00 | 0,00 | 0,01 | 0,00 | 0,01 | 0,00 | 0,01 |
| % Reduction | * | * | 76 | 79 | 82 | 112 | 79 | 70 | 76 | 64 | 71 | 55 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 1,67 | | 4,10 | | 3,81 | | 5,12 | | 2,52 | | 3,84 | |
| 5-TC30/10 | 1,94 | | 3,13 | | 3,57 | | 3,55 | | 1,94 | | 3,32 | |
| % Reduction | -16 | | 24 | | 6 | | 31 | | 23 | | 14 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 2,07 | | 1,17 | | 1,62 | | 1,00 | | 1,00 | | 1,08 | |

### 4.2.4. Case 5: TC30 with 15 cm Thickness (5-TC 30/15) as GSI Material

In Case 5, 5-story model foundation was surrounded with 15 cm thickness GRM includes 30% Tire Crumb. In this test, all selected earthquake motions were applied. However, the results of Kobe El Centro, Kocaeli earthquakes are presented here.

- **5-TC30/15 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.13 and Table 4.10.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 4 - 48 %. Moreover, the inter-story drift ratio showed a critical reduction of 25-69%. Besides, peak spectral acceleration decreased generally, and period lengthening could be observed for all stories.

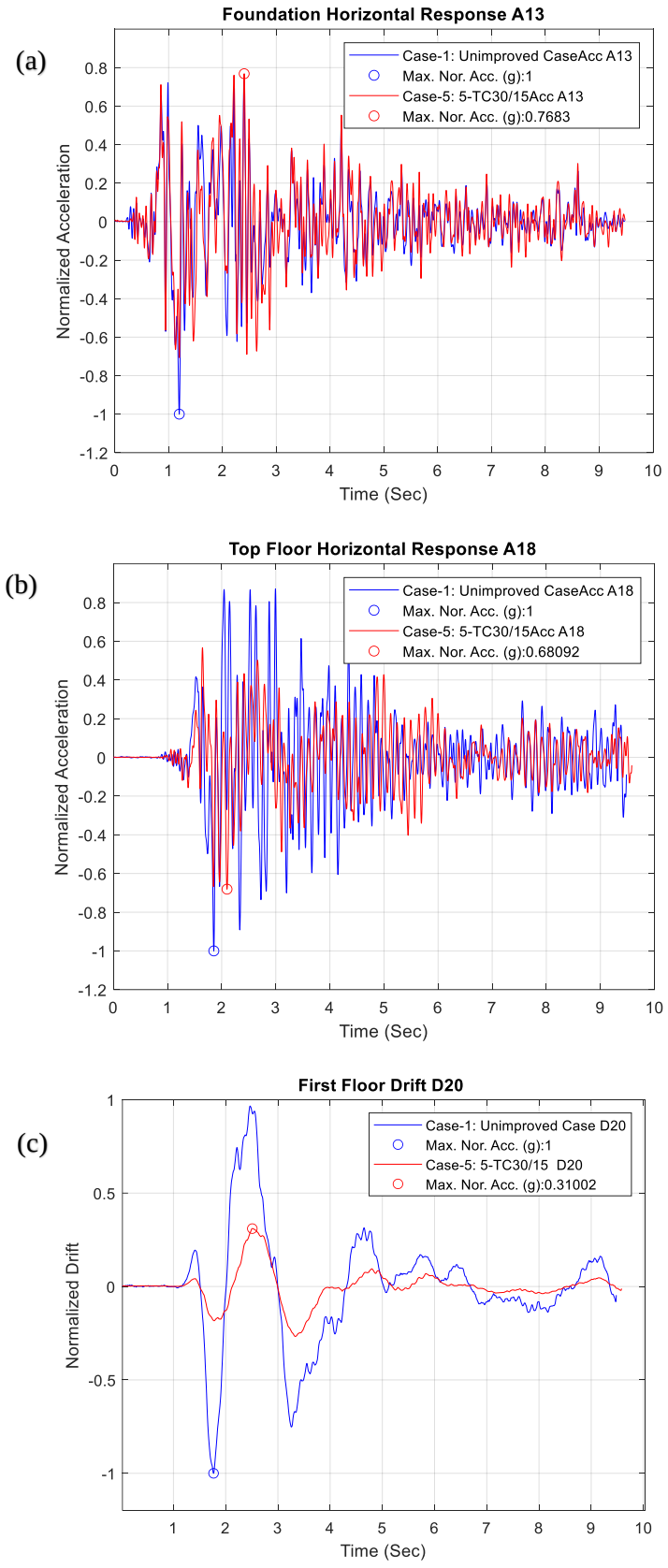



Figure 4. 13. (a) FHR, (b) TFHR, (c) FFD of 5-TC30/15 under Kocaeli Earthquake Motion

Table 4. 10. Results of 5-TC30/15 under Kocaeli Earthquake Motion

| 5-TC30/15 - Kocaeli EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,02 | 0,20 | 0,07 | 0,47 | 0,06 | 0,40 | 0,05 | 0,38 | 0,05 | 0,45 | 0,08 | 0,56 |
| 5-TC30/15 | 0,02 | 0,15 | 0,04 | 0,28 | 0,05 | 0,38 | 0,03 | 0,30 | 0,03 | 0,23 | 0,05 | 0,38 |
| % Reduction | -6 | 23 | 44 | 40 | 20 | 4 | 30 | 21 | 38 | 48 | 36 | 32 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0148 | 0,0863 | 0,0006 | 0,0115 | 0,0018 | 0,0188 | 0,0007 | 0,0093 | 0,0004 | 0,0039 |
| 5-TC30/15 | * | * | 0,0046 | 0,0267 | 0,0008 | 0,0056 | 0,0013 | 0,0090 | 0,0011 | 0,0070 | 0,0008 | 0,0055 |
| % Reduction | * | * | 69 | 69 | 34 | 52 | 29 | 52 | 61 | 25 | 80 | 40 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,64 | | 2,87 | | 2,16 | | 1,36 | | 1,53 | | 2,71 | |
| 5-TC30/15 | 0,82 | | 1,54 | | 2,20 | | 1,18 | | 0,97 | | 1,82 | |
| % Reduction | -29 | | 46 | | -2 | | 13 | | 36 | | 33 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,00 | | 1,08 | | 1,04 | | 1,12 | | 1,04 | | 1,04 | |

- **5- TC30/15 against El-Centro Earthquake Motion**

Case results are shown in Figure 4.14 and Table 4.11.

According to test results, foundation horizontal acceleration response was affected negatively by improvement. This improvement has positive effect on first-floor horizontal response Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were increased by 5 - 14 % except 5$^{th}$ floor. Moreover, the inter-story drift ratio showed a critical reduction of 38-72%. Besides, peak spectral acceleration decreased generally, and period lengthening could be observed for all stories except 4$^{th}$ floor.

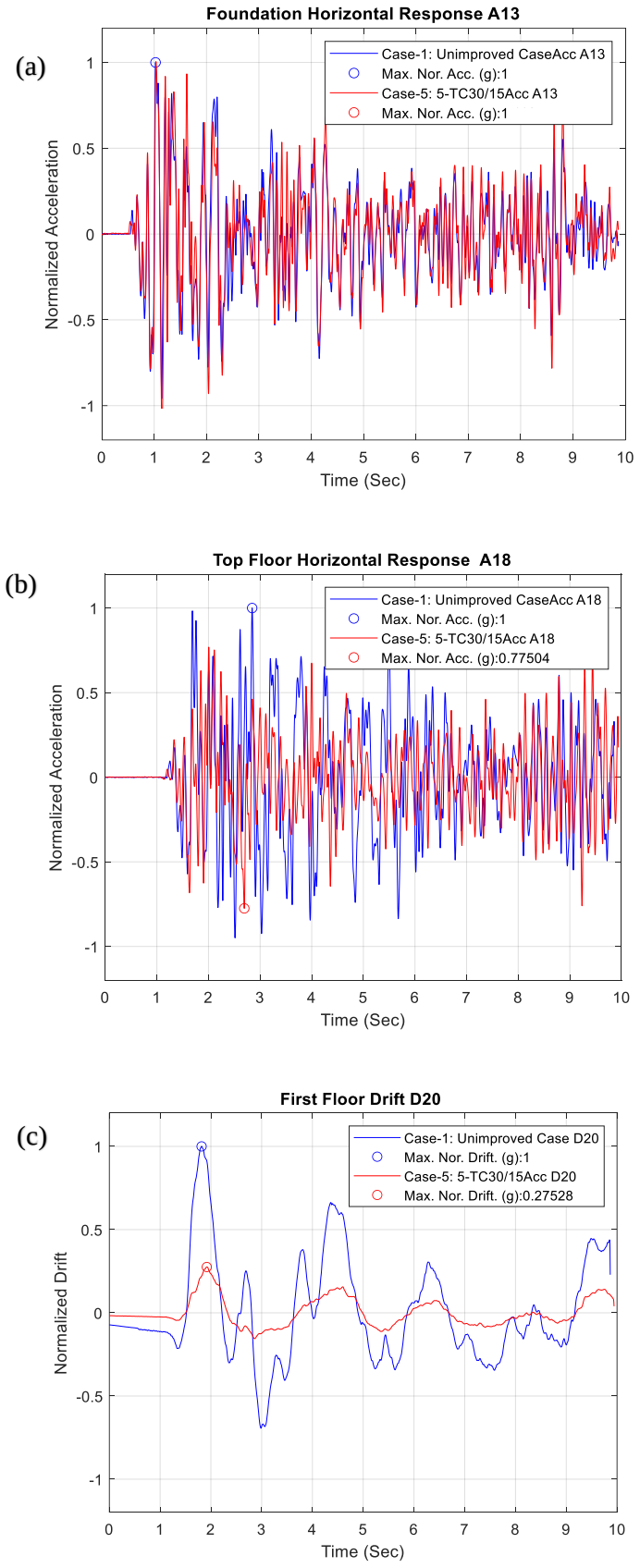



Figure 4.14. (a) FHR, (b) TFHR, (c) FFD of 5-TC30/15 under El Centro Earthquake Motion

Table 4. 11. Results of 5-TC30/15 under El Centro Earthquake Motion

| 5-TC30/15 - El Centro EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,03 | 0,20 | 0,06 | 0,33 | 0,05 | 0,32 | 0,07 | 0,34 | 0,07 | 0,32 | 0,09 | 0,43 |
| 5-TC30/15 | 0,03 | 0,23 | 0,05 | 0,38 | 0,05 | 0,33 | 0,04 | 0,36 | 0,04 | 0,32 | 0,06 | 0,33 |
| % Reduction | 4 | -12 | 12 | -14 | -2 | -5 | 34 | -5 | 51 | 0 | 37 | 22 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0177 | 0,0926 | 0,0010 | 0,0062 | 0,0023 | 0,0108 | 0,0013 | 0,0090 | 0,0008 | 0,0021 |
| 5-TC30/15 | * | * | 0,0045 | 0,0256 | 0,0006 | 0,0024 | 0,0010 | 0,0061 | 0,0007 | 0,0056 | 0,0007 | 0,0057 |
| % Reduction | * | * | 75 | 72 | 41 | 61 | 58 | 43 | 42 | 38 | 16 | 36 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,81 | | 1,73 | | 1,46 | | 1,48 | | 1,50 | | 1,80 | |
| 5-TC30/15 | 0,81 | | 1,44 | | 1,76 | | 1,58 | | 0,94 | | 1,60 | |
| % Reduction | 1 | | 17 | | -20 | | -7 | | 37 | | 11 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,00 | | 1,08 | | 1,08 | | 1,13 | | 0,12 | | 1,04 | |

- **5-TC30/15 under Kobe Earthquake Motion**

Case results are shown in Figure 4.15 and Table 4.12.

According to test results, foundation horizontal acceleration response was affected negatively by improvement. This improvement has positive effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 2 - 38 %. Moreover, the inter-story drift ratio showed a critical reduction of 54-112%. Besides, peak spectral acceleration decreased generally. Except 3$^{rd}$ and 4$^{th}$ floors, period lengthening could be observed.

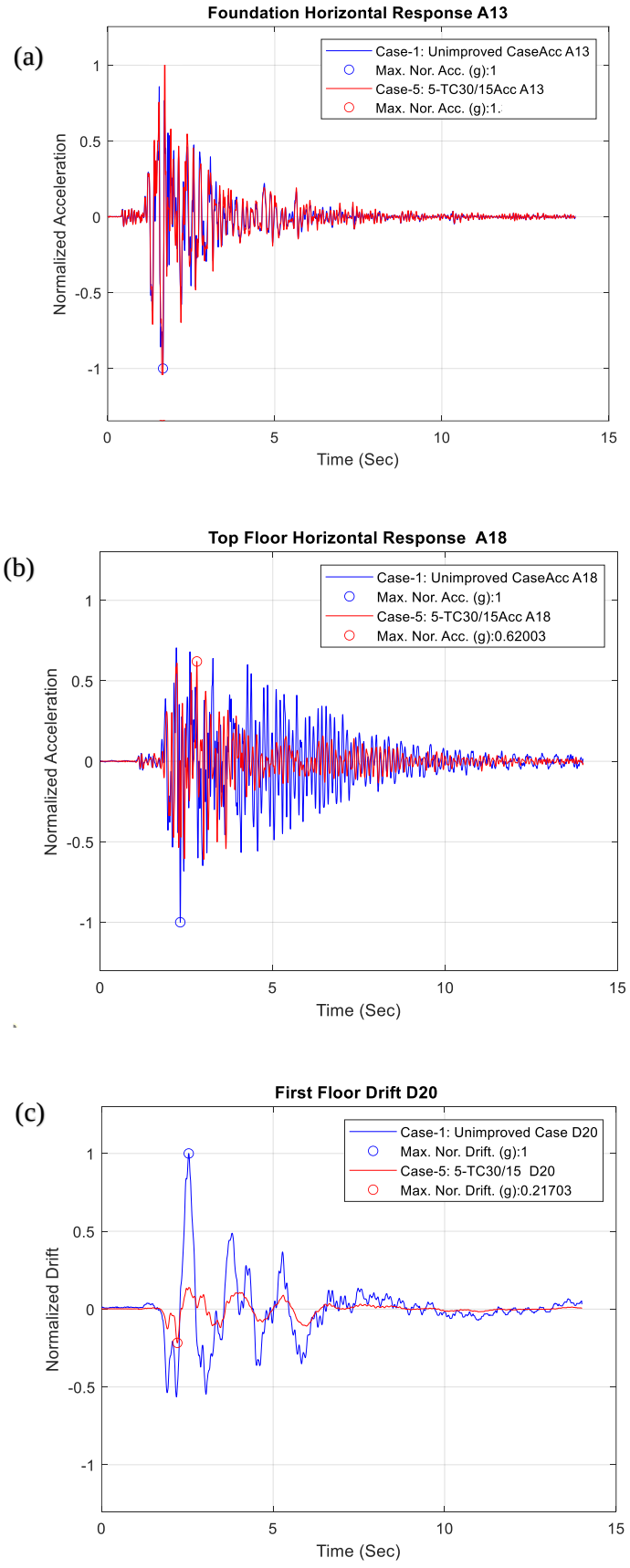



Figure 4. 15. (a) FHR, (b) TFHR, (c) FFD of 5-TC30/15 under Kobe Earthquake Motion

Table 4.12. Results of 5-TC30/15 under Kobe Earthquake Motion

| 5-TC30/15 - Kobe EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,05 | 0,56 | 0,11 | 0,70 | 0,10 | 0,91 | 0,09 | 0,91 | 0,09 | 0,62 | 0,13 | 1,07 |
| 5-TC30/15 | 0,05 | 0,74 | 0,08 | 0,86 | 0,07 | 0,89 | 0,06 | 0,81 | 0,05 | 0,68 | 0,08 | 0,66 |
| % Reduction | 1 | -31 | 31 | -24 | 25 | 2 | 39 | 10 | 48 | -9 | 40 | 38 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0107 | 0,0856 | 0,0025 | 0,0135 | 0,0037 | 0,0247 | 0,0029 | 0,0209 | 0,0018 | 0,0155 |
| 5-TC30/15 | * | * | 0,0024 | 0,0185 | 0,0004 | -0,0016 | 0,0007 | 0,0014 | 0,0007 | 0,0066 | 0,0005 | 0,0071 |
| % Reduction | * | * | 78 | 78 | 84 | 112 | 82 | 95 | 77 | 68 | 70 | 54 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 1,67 | | 4,10 | | 3,81 | | 5,12 | | 2,52 | | 3,84 | |
| 5-TC30/15 | 2,02 | | 3,25 | | 3,55 | | 3,34 | | 2,01 | | 3,26 | |
| % Reduction | -21 | | 21 | | 7 | | 35 | | 20 | | 15 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 2,07 | | 1,17 | | 1,75 | | 1,00 | | 1,00 | | 1,17 | |

### 4.2.5. Case 6: TC 20 with 15 cm Thickness (5-TC 20/ 15) as GSI Material

In Case 6, 5-story model foundation was surrounded with 15 cm thickness GRM includes 20% Tire Crumb. In this test, all selected earthquake motions were applied. However, the results of Kobe El Centro, Kocaeli earthquakes are presented here.

- **5-TC20/15 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.16 and Table 4.13. According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 15 - 41 %. Moreover, the inter-story drift ratio showed a critical reduction of 25-66%. Besides, peak spectral acceleration decreased generally. Except 4$^{th}$ floor, period lengthening could be observed for all model.

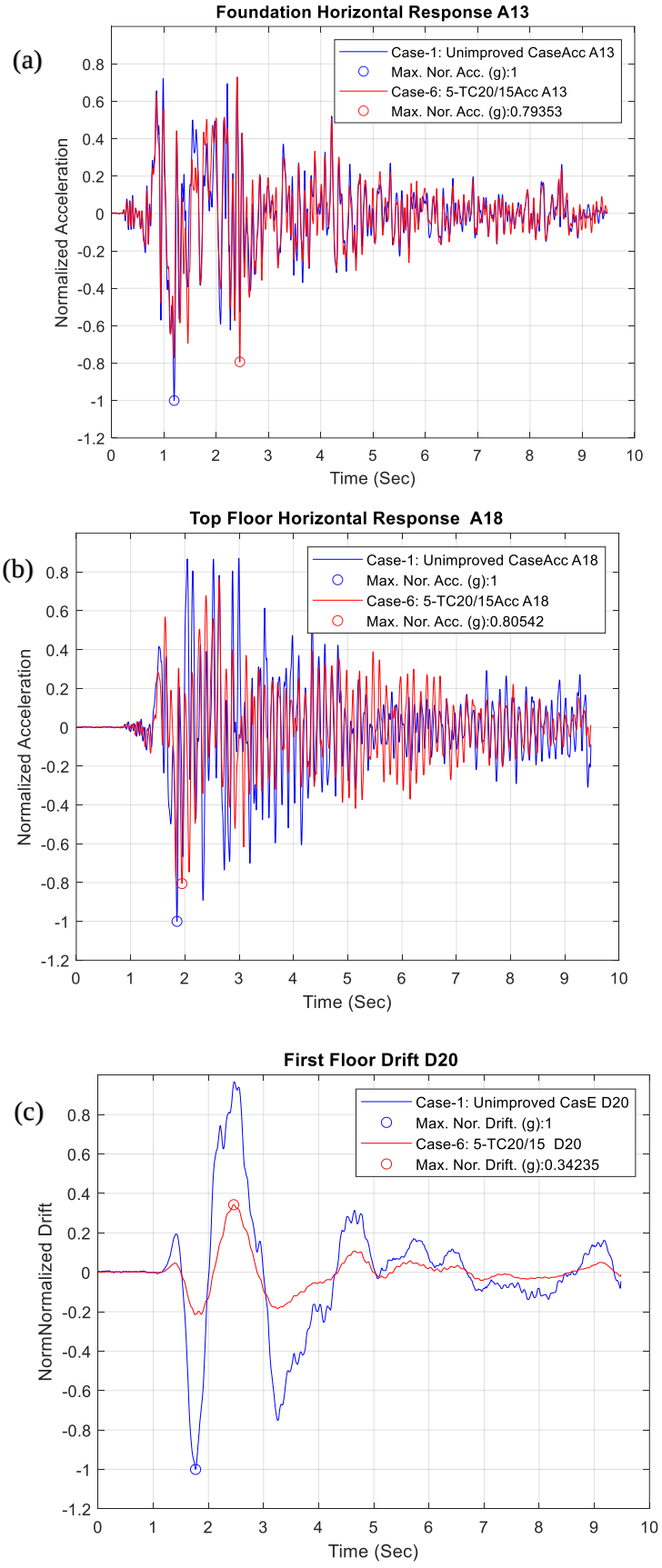



Figure 4.17. (a) FHR, (b) TFHR, (c) FFD of 5-TC20/15 under Kocaeli Earthquake Motion

Table 4.13. Results of 5-TC20/15 under Kocaeli Earthquake Motion

| 5-TC20/15 - Kocaeli EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,02 | 0,20 | 0,07 | 0,47 | 0,06 | 0,40 | 0,05 | 0,38 | 0,05 | 0,45 | 0,08 | 0,56 |
| 5-TC20/15 | 0,02 | 0,15 | 0,06 | 0,35 | 0,07 | 0,43 | 0,04 | 0,32 | 0,04 | 0,26 | 0,07 | 0,45 |
| % Reduction | -12 | 21 | 21 | 27 | -14 | -6 | 17 | 15 | 26 | 41 | 15 | 19 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,01483 | 0,08634 | 0,00063 | 0,01151 | 0,00180 | 0,01882 | 0,00069 | 0,00931 | 0,00047 | 0,00395 |
| 5-TC20/15 | * | * | 0,00498 | 0,02949 | 0,00070 | 0,00562 | 0,00118 | 0,00753 | 0,00077 | 0,00591 | 0,00058 | 0,00298 |
| % Reduction | * | * | 66 | 66 | -12 | 51 | 35 | 60 | -11 | 37 | 24 | 25 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,64 | | 2,87 | | 2,16 | | 1,36 | | 1,53 | | 2,71 | |
| 5-TC20/15 | 0,68 | | 2,04 | | 2,50 | | 1,31 | | 1,14 | | 2,29 | |
| % Reduction | -7 | | 29 | | -16 | | 4 | | 26 | | 15 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,06 | | 1,04 | | 1,04 | | 1,06 | | 1,00 | | 1,04 | |

- **5- TC20/15 against El Centro Earthquake Motion**

Case results are shown in Figure 4.17 and Table 4.14.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 12-19 %. Moreover, the inter-story drift ratio showed a critical reduction of 50-78%. Besides, peak spectral acceleration decreased generally. Except 4$^{th}$ and 5$^{th}$ floors, period lengthening could be observed.

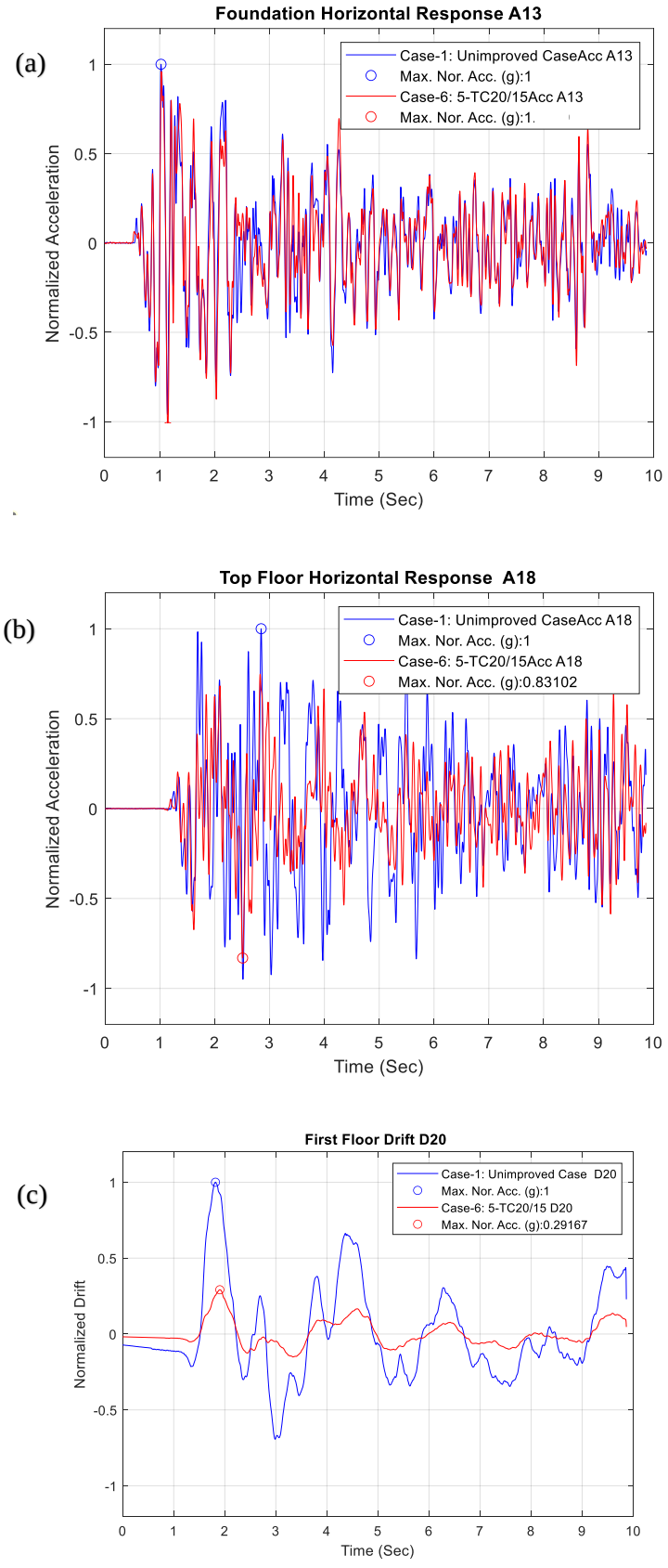



Figure 4.18. (a) FHR, (b) TFHR, (c) FFD of 5-TC20/15 under El Centro Earthquake Motion

Table 4.14. Results of 5-TC20/15 under El Centro Earthquake Motion

| 5-TC20/15 - El Centro EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,03 | 0,20 | 0,06 | 0,33 | 0,05 | 0,32 | 0,07 | 0,34 | 0,07 | 0,32 | 0,09 | 0,43 |
| 5-TC20/15 | 0,03 | 0,21 | 0,05 | 0,33 | 0,05 | 0,27 | 0,04 | 0,30 | 0,04 | 0,26 | 0,05 | 0,36 |
| % Reduction | 10 | -3 | 22 | -1 | 11 | 13 | 40 | 12 | 51 | 19 | 40 | 17 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,018 | 0,093 | 0,001 | 0,006 | 0,002 | 0,011 | 0,001 | 0,009 | 0,001 | 0,002 |
| 5-TC20/15 | * | * | 0,004 | 0,027 | 0,000 | 0,002 | 0,001 | 0,004 | 0,001 | 0,005 | 0,001 | 0,003 |
| % Reduction | * | * | 75 | 71 | 52 | 62 | 52 | 62 | 42 | 50 | 36 | 31 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,81 | | 1,73 | | 1,46 | | 1,48 | | 1,50 | | 1,80 | |
| 5-TC20/15 | 0,77 | | 1,30 | | 1,53 | | 1,30 | | 0,76 | | 1,47 | |
| % Reduction | 5 | | 25 | | -5 | | 12 | | 49 | | 18 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,00 | | 1,04 | | 1,04 | | 1,13 | | 0,25 | | 1,00 | |

- **5-TC20/15 under Kobe Earthquake Motion**

Case results are shown in Figure 4.18 and Table 4.15.

According to test results, foundation horizontal acceleration response was affected negatively by improvement, but this improvement has positive effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 8-38 %. Moreover, the inter-story drift ratio showed a critical reduction of 68-102%. Besides, peak spectral acceleration decreased generally. Except 3$^{rd}$ and 5$^{th}$ floors, period lengthening could be observed.

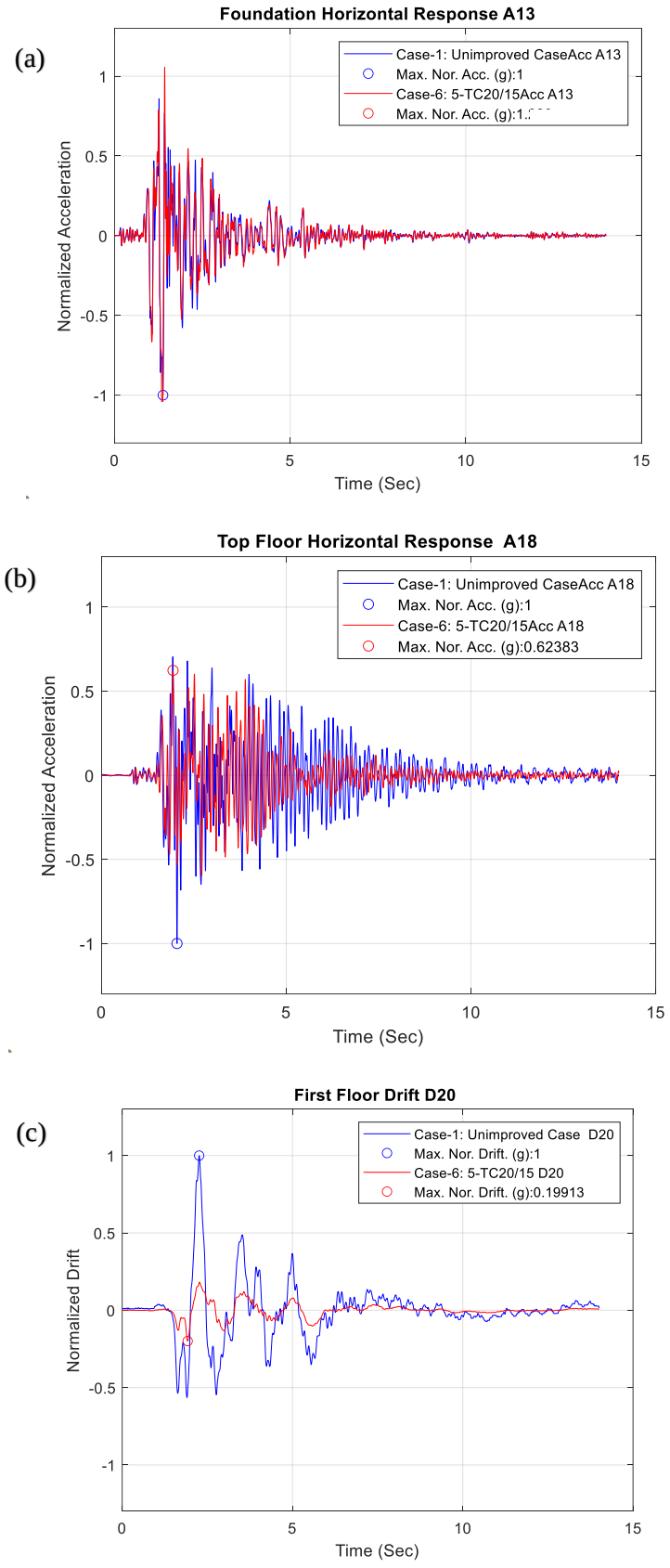



Figure 4.19. (a) FHR, (b) TFHR, (c) FFD of 5-TC20/15 under Kobe Earthquake Motion

Table 4.15. Results of 5-TC20/15 under Kobe Earthquake Motion

| 5-TC20/15 - Kobe EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,05 | 0,56 | 0,11 | 0,70 | 0,10 | 0,91 | 0,09 | 0,91 | 0,09 | 0,62 | 0,13 | 1,07 |
| 5-TC20/15 | 0,05 | 0,69 | 0,08 | 0,83 | 0,08 | 0,83 | 0,06 | 0,61 | 0,05 | 0,42 | 0,09 | 0,67 |
| % Reduction | 7 | -23 | 27 | -20 | 15 | 8 | 38 | 33 | 47 | 32 | 32 | 38 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0107 | 0,0856 | 0,0025 | 0,0135 | 0,0037 | 0,0247 | 0,0029 | 0,0209 | 0,0018 | 0,0155 |
| 5-TC20/15 | * | * | 0,0024 | 0,0170 | 0,0003 | -0,0003 | 0,0007 | 0,0080 | 0,0005 | 0,0054 | 0,0004 | 0,0060 |
| % Reduction | * | * | 78 | 80 | 90 | 102 | 80 | 68 | 82 | 74 | 76 | 62 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 1,67 | | 4,10 | | 3,81 | | 5,12 | | 2,52 | | 3,84 | |
| 5-TC20/15 | 1,85 | | 3,49 | | 4,41 | | 3,06 | | 1,93 | | 3,94 | |
| % Reduction | -10 | | 15 | | -16 | | 40 | | 23 | | -3 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 2,07 | | 1,04 | | 1,50 | | 1,00 | | 2,27 | | 1,00 | |

### 4.2.6. Case 7: TC 20 with 10 cm Thickness (5-TC 20/ 10) as GSI Material

In Case 7, 5-story model foundation was surrounded with 10 cm thickness GRM includes 20% Tire Crumb. In this test, all selected earthquake motions were applied. However, the results of Kobe El Centro, Kocaeli earthquake motions are presented here.

- **5-TC20/10 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.19 and Table 4.16. According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 13-37 %. Moreover, the inter-story drift ratio showed a critical reduction of 10-67%. Besides, peak spectral acceleration decreased generally. Except foundation and 4$^{th}$ floor, period lengthening could be observed.

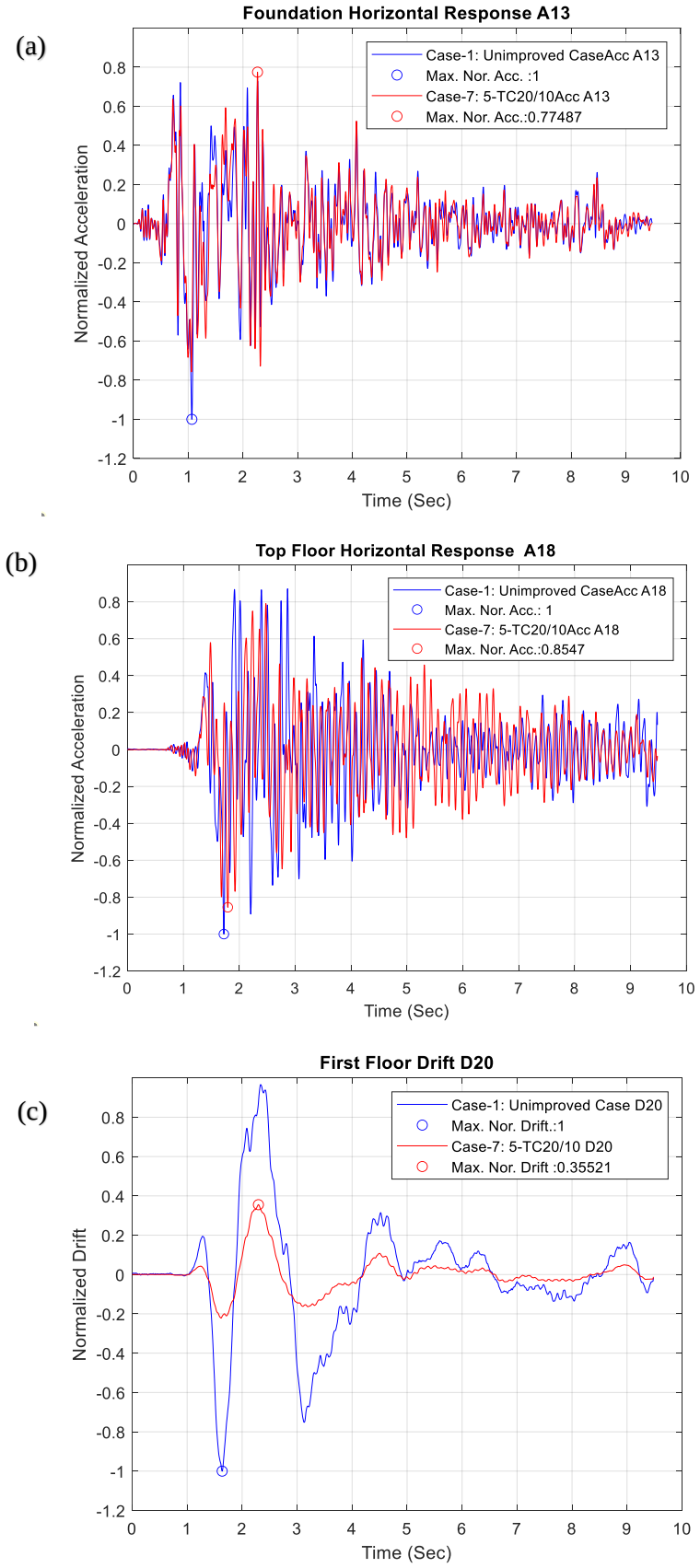



Figure 4.20. (a) FHR, (b) TFHR, (c) FFD of 5-TC20/10 under Kocaeli Earthquake Motion

Table 4.16. Results of 5-TC20/10 under Kocaeli Earthquake Motion

| 5-TC20/10 - Kocaeli EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,02 | 0,20 | 0,07 | 0,47 | 0,06 | 0,40 | 0,05 | 0,38 | 0,05 | 0,45 | 0,08 | 0,56 |
| 5-TC20/10 | 0,02 | 0,15 | 0,05 | 0,36 | 0,06 | 0,44 | 0,04 | 0,33 | 0,04 | 0,28 | 0,06 | 0,48 |
| % Reduction | 7 | 23 | 26 | 25 | -10 | -10 | 24 | 13 | 30 | 37 | 20 | 15 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,01483 | 0,08634 | 0,00063 | 0,01151 | 0,00180 | 0,01882 | 0,00069 | 0,00931 | 0,00010 | 0,00395 |
| 5-TC20/10 | * | * | 0,00409 | 0,03055 | 0,00058 | 0,00593 | 0,00094 | 0,00717 | 0,00074 | 0,00585 | 0,00037 | 0,00354 |
| % Reduction | * | * | 72 | 65 | 7 | 48 | 48 | 62 | -7 | 37 | 18 | 10 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,64 | | 2,87 | | 2,16 | | 1,36 | | 1,53 | | 2,71 | |
| 5-TC20/10 | 0,71 | | 2,15 | | 2,64 | | 1,36 | | 1,16 | | 2,37 | |
| % Reduction | -11 | | 25 | | -22 | | 0 | | 24 | | 13 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,00 | | 1,04 | | 1,04 | | 1,06 | | 1,00 | | 1,04 | |

- **5- TC20/ 10 against El Centro Earthquake Motion**

Case results are shown in Figure 4.20 and, Table. 4.17.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 2-13%. Moreover, the inter-story drift ratio showed a critical reduction of 43-77%. Besides, peak spectral acceleration decreased generally. Period lengthening could be observed except foundation, $4^{th}$ and $5^{th}$ floors.

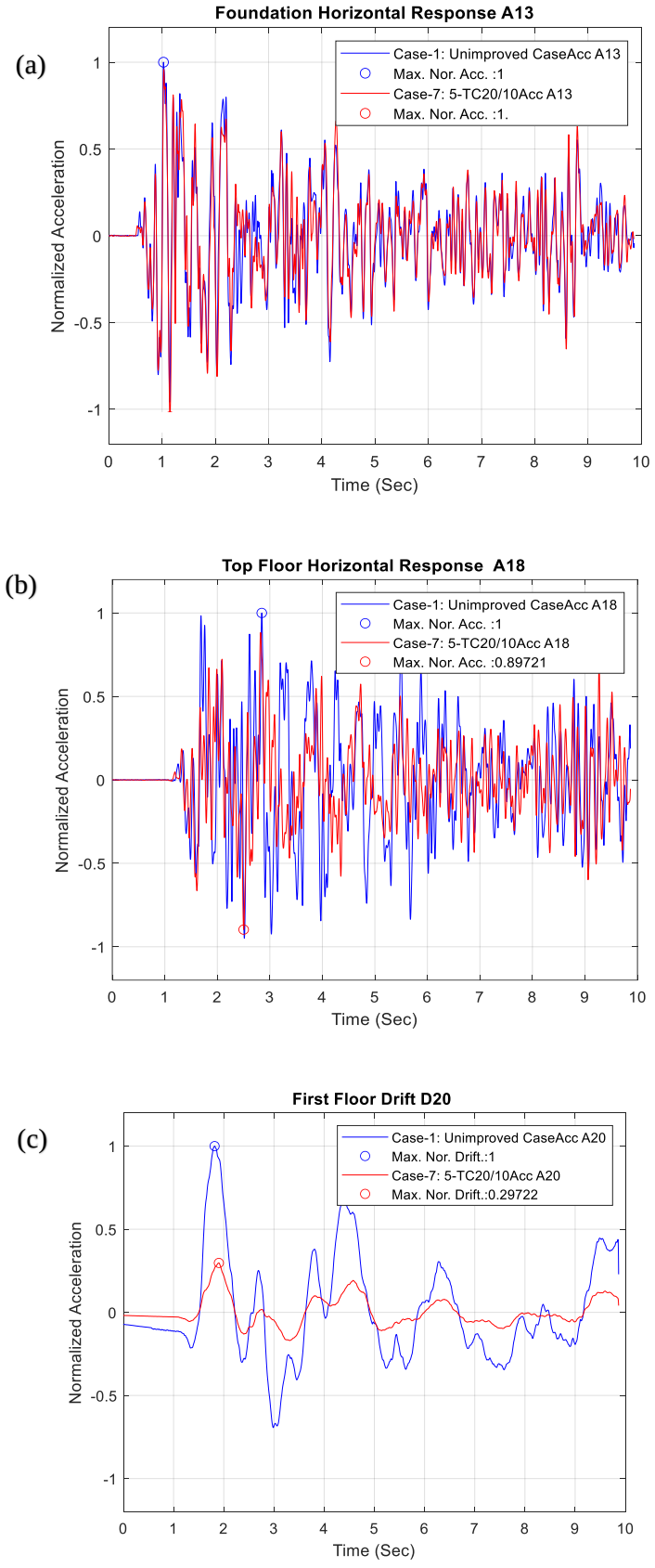



Figure 4. 21. (a) FHR, (b) TFHR, (c) FFD of 5-TC20/10 under El Centro Earthquake Motion

Table 4.17. Results of 5-TC20/10 under El Centro Earthquake Motion

| 5-TC20/10 - El Centro EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,03 | 0,20 | 0,06 | 0,33 | 0,05 | 0,32 | 0,07 | 0,34 | 0,07 | 0,32 | 0,09 | 0,43 |
| 5-TC20/10 | 0,03 | 0,21 | 0,04 | 0,32 | 0,04 | 0,29 | 0,04 | 0,30 | 0,03 | 0,28 | 0,05 | 0,38 |
| % Reduction | 18 | -4 | 29 | 2 | 17 | 8 | 44 | 12 | 53 | 13 | 43 | 10 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0177 | 0,0926 | 0,0010 | 0,0062 | 0,0023 | 0,0108 | 0,0013 | 0,0090 | 0,0008 | 0,0021 |
| 5-TC20/10 | * | * | 0,0041 | 0,0276 | 0,0005 | 0,0026 | 0,0009 | 0,0024 | 0,0008 | 0,0044 | 0,0003 | 0,0014 |
| % Reduction | * | * | 77 | 70 | 51 | 58 | 61 | 77 | 37 | 51 | 57 | 36 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,81 | | 1,73 | | 1,46 | | 1,48 | | 1,50 | | 1,80 | |
| 5-TC20/10 | 0,81 | | 1,39 | | 1,68 | | 1,27 | | 0,81 | | 1,61 | |
| % Reduction | 1 | | 20 | | -15 | | 14 | | 46 | | 10 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,00 | | 1,04 | | 1,04 | | 1,13 | | 0,25 | | 1,00 | |

- **5-TC20/10 under Kobe Earthquake Motion**

Case results are shown in Figure 4.21 and Table 4.18.

According to test results, foundation horizontal acceleration response was affected negatively by improvement, but this improvement has positive effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 10-39 %. Moreover, the inter-story drift ratio showed a critical reduction of 66-89%. Besides, peak spectral acceleration decreased generally. Except 3$^{rd}$ and 5$^{th}$ floors, period lengthening was observed.

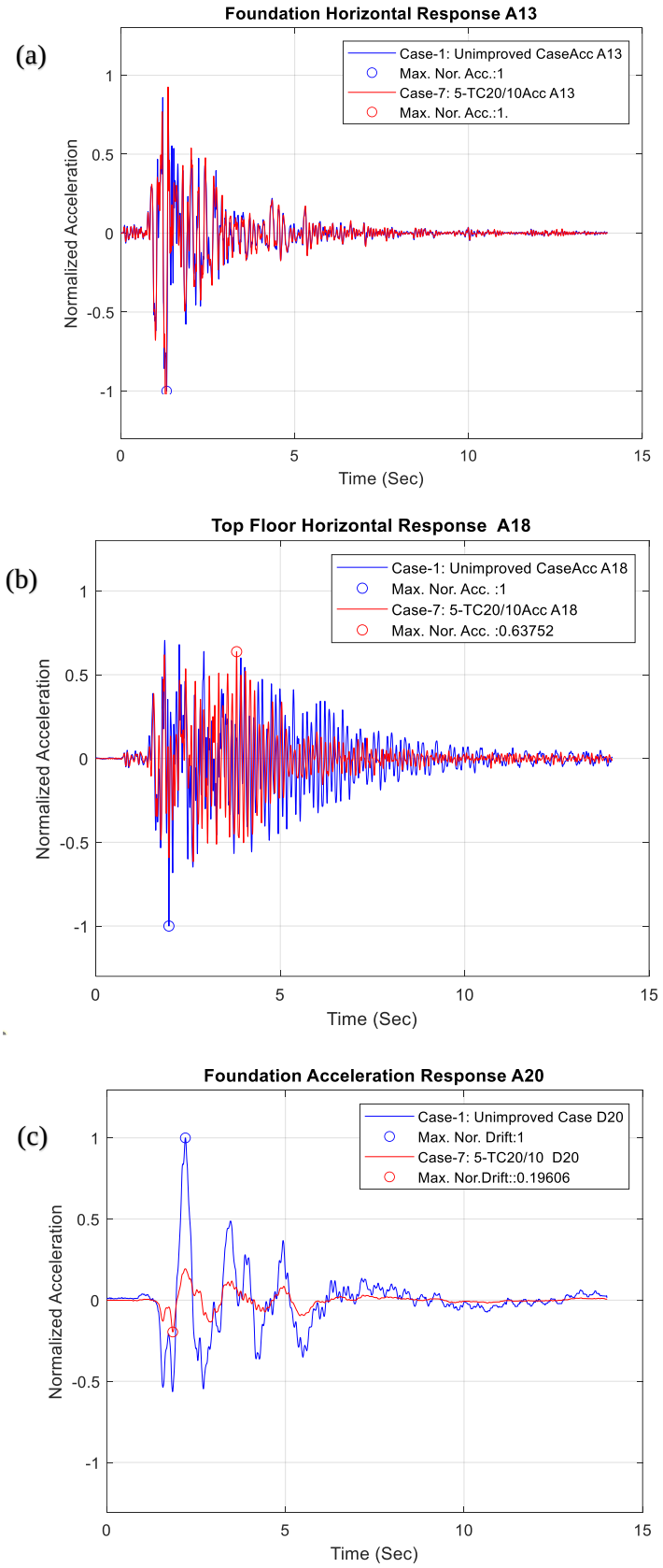



Figure 4. 22. (a) FHR, (b) TFHR, (c) FFD of 5-TC20/10 under Kobe Earthquake Motion

Table 4.18. Results of 5-TC20/10 under Kobe Earthquake Motion

| 5-TC20/10 - Kobe EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,05 | 0,56 | 0,11 | 0,70 | 0,10 | 0,91 | 0,09 | 0,91 | 0,09 | 0,62 | 0,13 | 1,07 |
| 5-TC20/10 | 0,04 | 0,70 | 0,08 | 0,87 | 0,09 | 0,81 | 0,05 | 0,55 | 0,05 | 0,49 | 0,09 | 0,68 |
| % Reduction | 15 | -24 | 28 | -26 | 11 | 10 | 42 | 39 | 46 | 21 | 31 | 36 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0107 | 0,0856 | 0,0025 | 0,0135 | 0,0037 | 0,0247 | 0,0029 | 0,0209 | 0,0018 | 0,0374 |
| 5-TC20/10 | * | * | 0,0022 | 0,0168 | 0,0003 | 0,0016 | 0,0006 | 0,0079 | 0,0006 | 0,0072 | 0,0003 | 0,0043 |
| % Reduction | * | * | 79 | 80 | 88 | 88 | 84 | 68 | 81 | 66 | 81 | 89 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 1,67 | | 4,10 | | 3,81 | | 5,12 | | 2,52 | | 3,84 | |
| 5-TC20/10 | 1,84 | | 3,96 | | 5,15 | | 2,96 | | 2,28 | | 4,58 | |
| % Reduction | -10 | | 3 | | -35 | | 42 | | 10 | | -19 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 2,07 | | 1,04 | | 1,50 | | 1,00 | | 2,18 | | 1,00 | |

### 4.2.7. Case 8: TC 10 with 15 cm Thickness (5-TC 10/ 15) as GSI Material

In Case 8, 5-story model foundation was surrounded with 15 cm thickness GRM includes 10% Tire Crumb. In this test, all selected earthquake motions were applied. However, the results of Kobe El Centro, Kocaeli earthquakes are presented here.

- **5-TC10/15 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.22 and Table 4.19.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 7-24%. Moreover, the inter-story drift ratio showed a critical reduction of 26-67%. Besides, peak spectral acceleration decreased generally. Period lengthening was observed except $4^{th}$ floor.

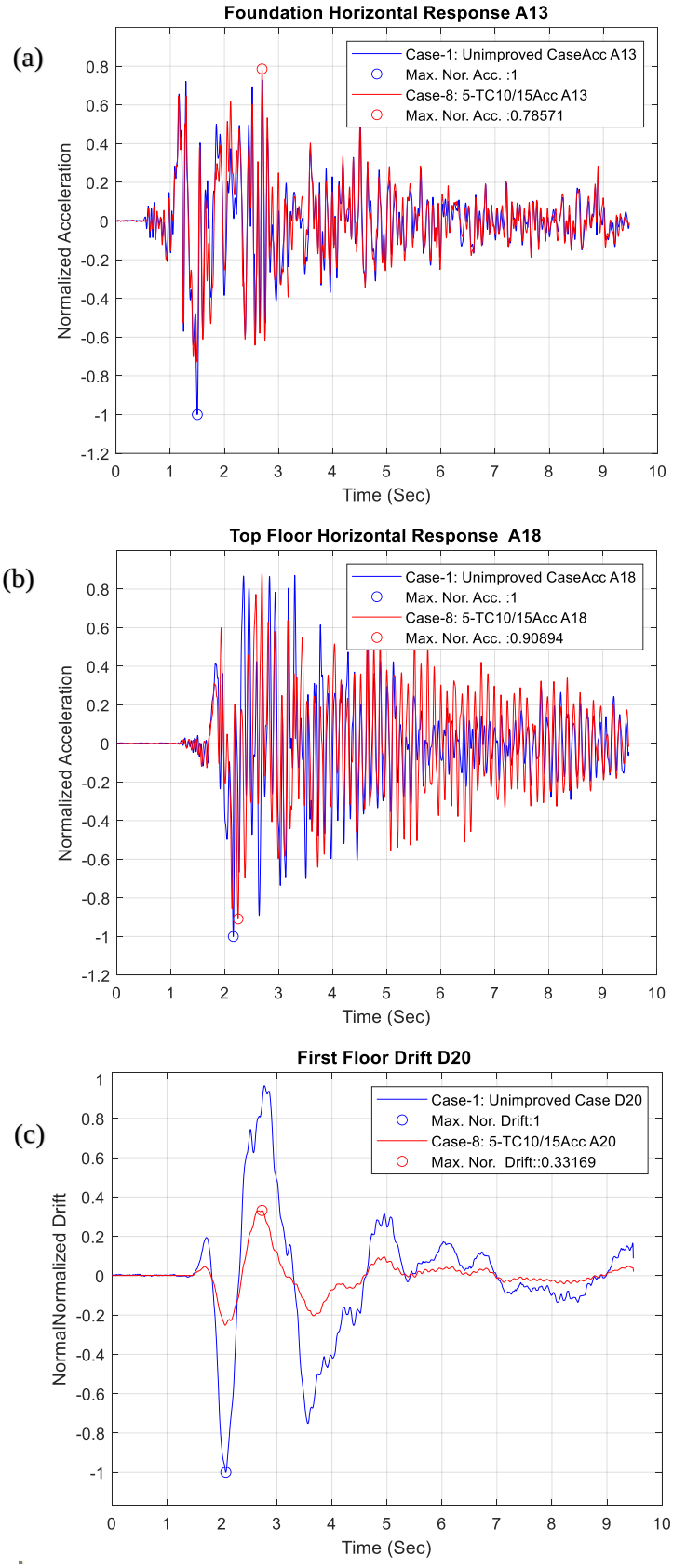



Figure 4. 23. (a) FHR, (b) TFHR, (c) FFD of 5-TC10/15 under Kocaeli Earthquake Motion

Table 4.19. Results of 5-TC10/15 under Kocaeli Earthquake Motion

| 5-TC10/15 - Kocaeli EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,02 | 0,20 | 0,07 | 0,47 | 0,06 | 0,40 | 0,05 | 0,38 | 0,05 | 0,45 | 0,08 | 0,56 |
| 5-TC10/15 | 0,02 | 0,15 | 0,06 | 0,36 | 0,07 | 0,49 | 0,04 | 0,35 | 0,04 | 0,37 | 0,07 | 0,51 |
| % Reduction | 5 | 21 | 17 | 24 | -26 | -21 | 18 | 7 | 21 | 17 | 9 | 9 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0148 | 0,0863 | 0,0006 | 0,0115 | 0,0018 | 0,0188 | 0,0007 | 0,0093 | 0,0002 | 0,0039 |
| 5-TC10/15 | * | * | 0,0040 | 0,0286 | 0,0005 | 0,0046 | 0,0008 | 0,0071 | 0,0006 | 0,0058 | 0,0003 | 0,0029 |
| % Reduction | * | * | 73 | 67 | 22 | 60 | 55 | 62 | 15 | 38 | 29 | 26 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,64 | | 2,87 | | 2,16 | | 1,36 | | 1,53 | | 2,71 | |
| 5-TC10/15 | 0,77 | | 2,24 | | 2,79 | | 1,20 | | 1,30 | | 2,56 | |
| % Reduction | -20 | | 22 | | -29 | | 12 | | 15 | | 6 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,06 | | 1,04 | | 1,04 | | 1,50 | | 1,00 | | 1,04 | |

- **5- TC10 /15 against El Centro Earthquake Motion**

Case results are shown in Figure. 4.23 and, Table. 4.20.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 1-10%. Moreover, the inter-story drift ratio showed a critical reduction of 70-74%. Besides, peak spectral acceleration decreased generally. Period lengthening could be observed except foundation and $4^{th}$ floor.

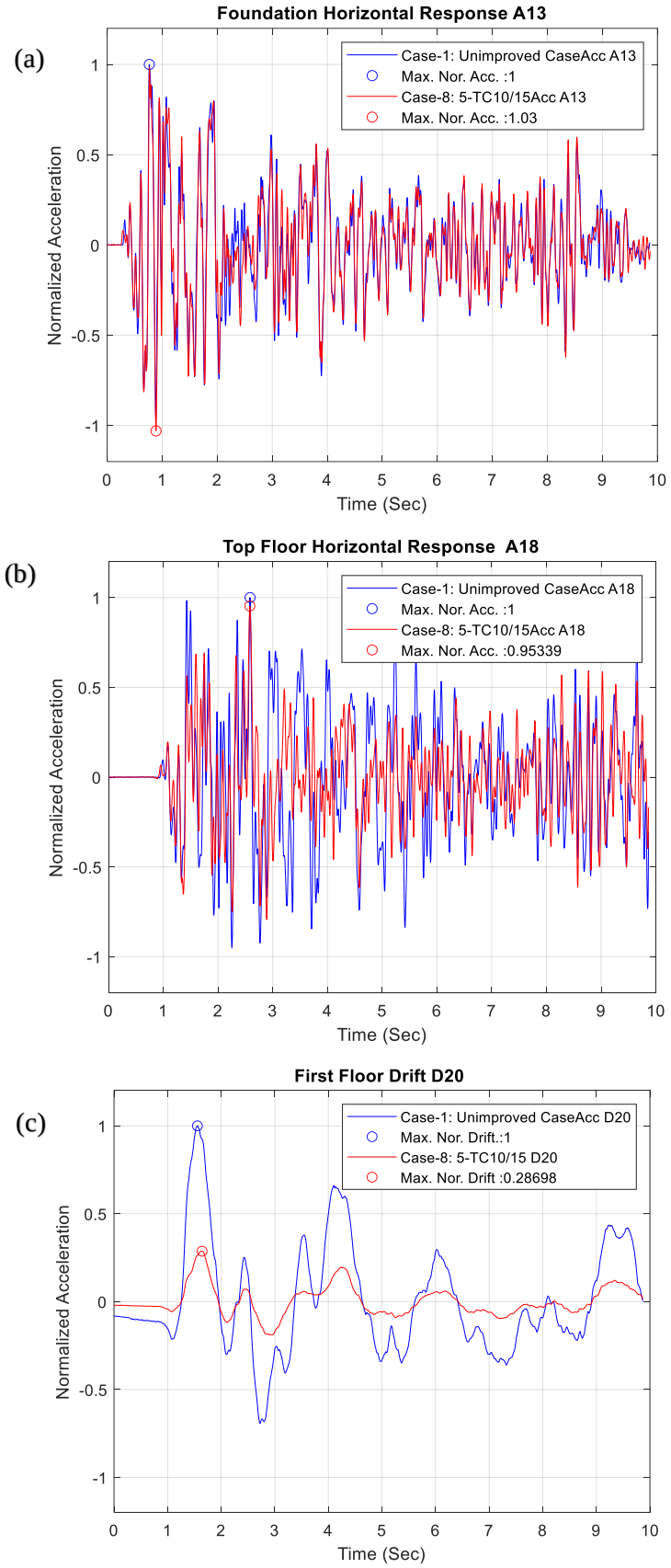



Figure 4.24.(a) FHR, (b) TFHR, (c) FFD of 5-TC10/15 under El Centro Earthquake Motion

Table 4.20. Results of 5-TC10/15 under El Centro Earthquake Motion

| 5-TC10/15 - El Centro EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,03 | 0,20 | 0,06 | 0,33 | 0,05 | 0,32 | 0,07 | 0,34 | 0,07 | 0,32 | 0,09 | 0,43 |
| 5-TC10/15 | 0,03 | 0,21 | 0,04 | 0,33 | 0,04 | 0,31 | 0,04 | 0,31 | 0,03 | 0,29 | 0,05 | 0,41 |
| % Reduction | 17 | -3 | 27 | 1 | 17 | 2 | 41 | 10 | 53 | 10 | 42 | 5 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0177 | 0,0926 | 0,0010 | 0,0062 | 0,0023 | 0,0108 | 0,0013 | 0,0090 | 0,0008 | 0,0021 |
| 5-TC10/15 | * | * | 0,0040 | 0,0266 | 0,0002 | 0,0018 | 0,0007 | 0,0032 | 0,0004 | 0,0023 | 0,0001 | 0,0020 |
| % Reduction | * | * | 77 | 71 | 76 | 71 | 70 | 70 | 67 | 74 | 87 | 60 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,81 | | 1,73 | | 1,46 | | 1,48 | | 1,50 | | 1,80 | |
| 5-TC10/15 | 0,81 | | 1,37 | | 1,73 | | 1,30 | | 0,83 | | 1,61 | |
| % Reduction | 1 | | 21 | | -18 | | 12 | | 45 | | 10 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,00 | | 1,04 | | 1,04 | | 1,13 | | 0,25 | | 1,00 | |

- **5-TC10/15 under Kobe Earthquake Motion**

Case results are shown in Figure 4.24 and Table 4.21.

According to test results, foundation horizontal acceleration response was affected negatively by improvement, but this improvement has positive effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 13-31%. Moreover, the inter-story drift ratio showed a critical reduction of 64-89%. Besides, peak spectral acceleration decreased generally. Except 3$^{rd}$ floor, period lengthening was observed for all models.

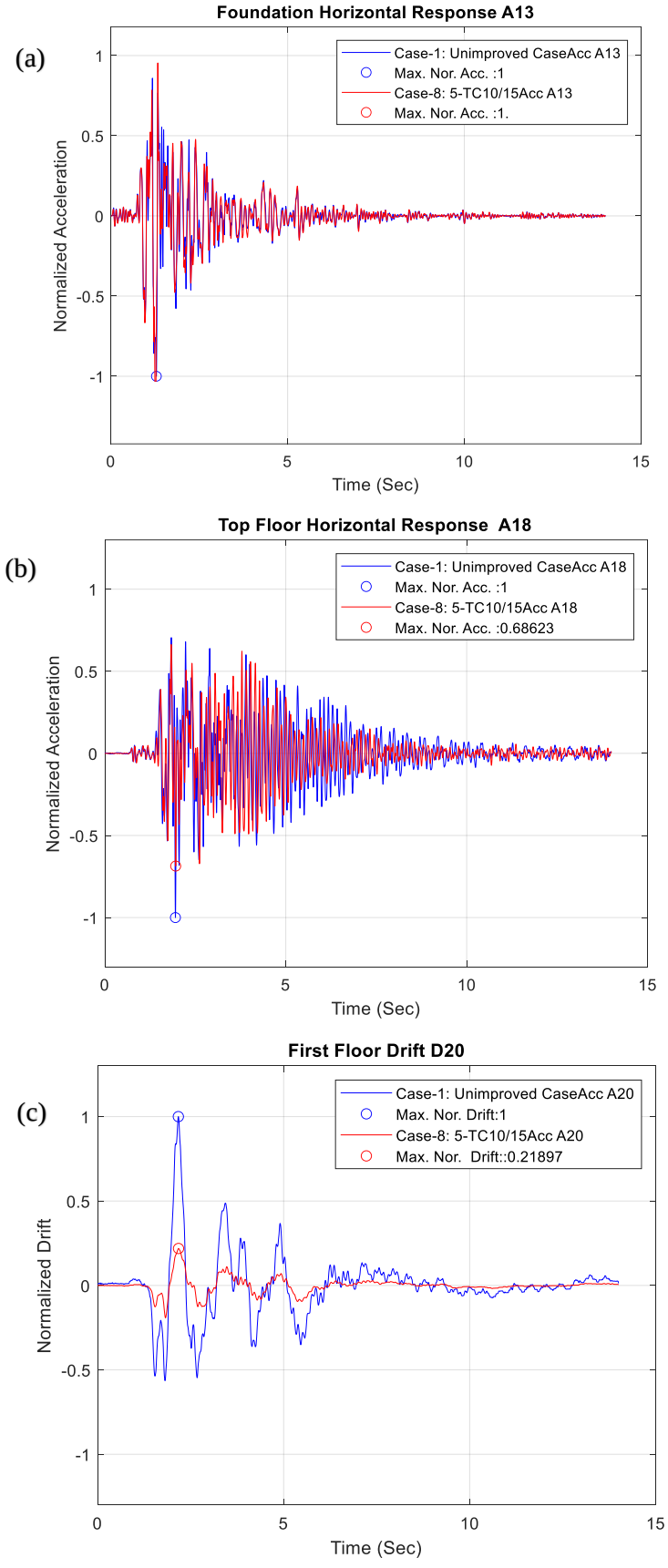



Figure 4. 25. (a) FHR, (b) TFHR, (c) FFD of 5-TC10/15 under Kobe Earthquake Motion

Table 4.21. Results of 5-TC10/15 under Kobe Earthquake Motion

| 5-TC10/15 - Kobe EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,05 | 0,56 | 0,11 | 0,70 | 0,10 | 0,91 | 0,09 | 0,91 | 0,09 | 0,62 | 0,13 | 1,07 |
| 5-TC10/15 | 0,04 | 0,72 | 0,08 | 0,90 | 0,09 | 0,79 | 0,06 | 0,65 | 0,05 | 0,48 | 0,09 | 0,74 |
| % Reduction | 16 | 27 | 26 | 29 | 7 | 13 | 38 | 28 | 40 | 23 | 26 | 31 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0107 | 0,0856 | 0,0025 | 0,0135 | 0,0037 | 0,0247 | 0,0029 | 0,0209 | 0,0018 | 0,0155 |
| 5-TC10/15 | * | * | 0,0022 | 0,0186 | 0,0003 | 0,0031 | 0,0006 | 0,0071 | 0,0006 | 0,0075 | 0,0003 | 0,0039 |
| % Reduction | * | * | 79 | 78 | 87 | 77 | 83 | 71 | 80 | 64 | 83 | 75 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 1,67 | | 4,10 | | 3,81 | | 5,12 | | 2,52 | | 3,84 | |
| 5-TC10/15 | 1,83 | | 4,01 | | 5,22 | | 2,97 | | 2,35 | | 4,72 | |
| % Reduction | -9 | | 2 | | -37 | | 42 | | 7 | | -23 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 2,07 | | 1,04 | | 1,50 | | 1,00 | | 2,27 | | 1,04 | |

### 4.2.8. Case 9: TC10 with 10 cm Thickness (5-TC 10/ 10) as GSI Material

In Case 9, 5-story model foundation was surrounded with 10 cm thickness GRM includes 10% Tire Crumb. In this test, all selected earthquake motions were applied. However, the results of Kobe El Centro, Kocaeli earthquakes are presented here.

- **5-TC10/10 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.25 and Table 4.22.

According to test results, foundation horizontal acceleration response was affected negatively by improvement, but this improvement has positive effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 13-31%. Moreover, the inter-story drift ratio showed a critical reduction of 64-89%. Besides, peak spectral acceleration decreased generally. Period lengthening was observed except 3rd floor.

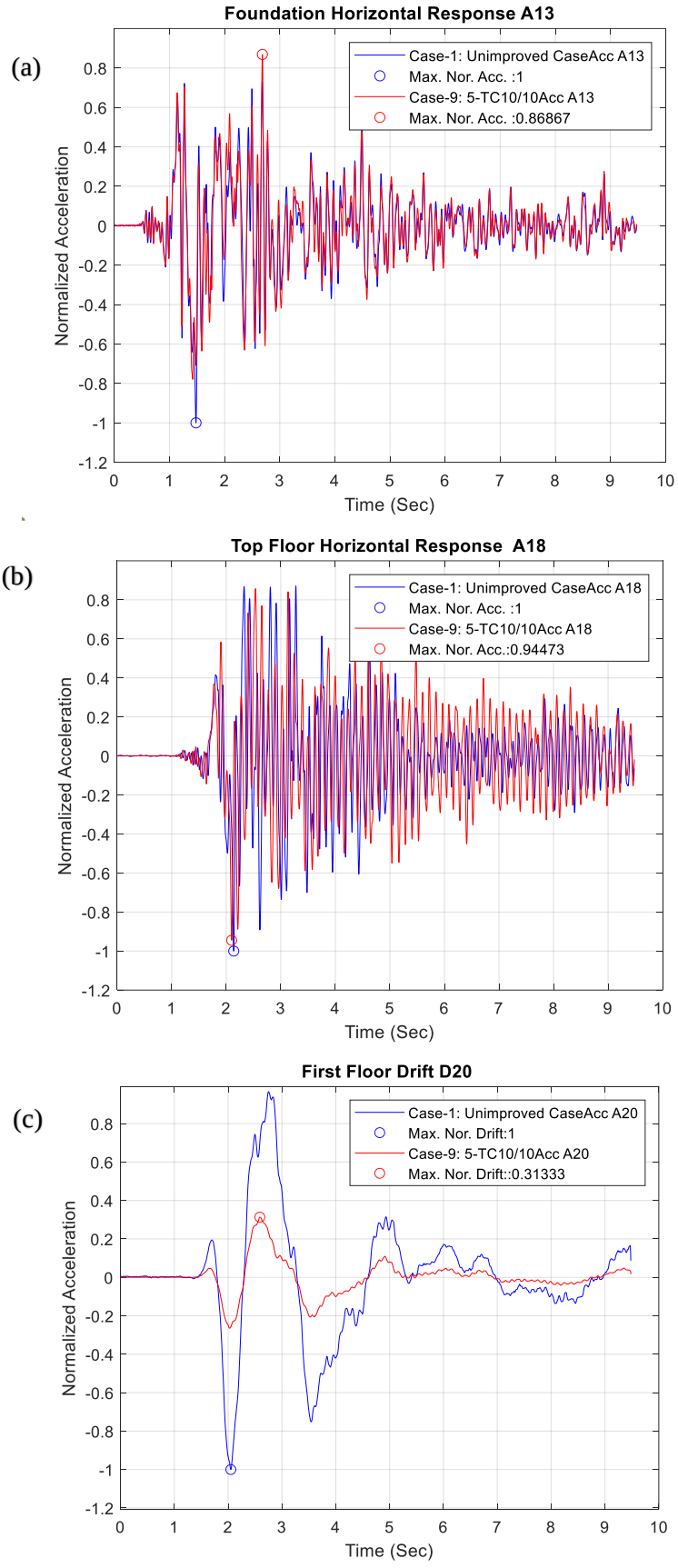



Figure 4.26. (a) FHR, (b) TFHR, (c) FFD of 5-TC10/10 under Kocaeli Earthquake Motion

Table 4.22. Results of 5-TC10/10 under Kocaeli Earthquake Motion

| 5-TC10/10 - Kocaeli EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,02 | 0,20 | 0,07 | 0,47 | 0,06 | 0,40 | 0,05 | 0,38 | 0,05 | 0,45 | 0,08 | 0,56 |
| 5-TC10/10 | 0,02 | 0,17 | 0,06 | 0,36 | 0,08 | 0,46 | 0,04 | 0,38 | 0,04 | 0,36 | 0,07 | 0,53 |
| % Reduction | 5 | 13 | 17 | 24 | -27 | -15 | 16 | 1 | 19 | 18 | 7 | 6 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,01483 | 0,08634 | 0,00063 | 0,01151 | 0,00180 | 0,01882 | 0,00069 | 0,00931 | 0,00010 | 0,00395 |
| 5-TC10/10 | * | * | 0,00393 | 0,02696 | 0,00040 | 0,00437 | 0,00071 | 0,00567 | 0,00047 | 0,00486 | 0,00014 | 0,00159 |
| % Reduction | * | * | 73 | 69 | 36 | 62 | 60 | 70 | 33 | 48 | 45 | 60 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,64 | | 2,87 | | 2,16 | | 1,36 | | 1,53 | | 2,71 | |
| 5-TC10/10 | 0,73 | | 2,34 | | 2,95 | | 1,34 | | 1,35 | | 2,69 | |
| % Reduction | -14 | | 18 | | -37 | | 1 | | 12 | | 1 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,06 | | 1,04 | | 1,00 | | 1,50 | | 1,00 | | 1,04 | |

- **5- TC10 / 10 against El Centro Earthquake Motion**

Case results are shown in Figure 4.23 and, Table .4.20.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 1-24%. Moreover, the inter-story drift ratio showed a critical reduction of 33-70%. Besides, peak spectral acceleration decreased generally. Period lengthening was observed except 2$^{nd}$ and 4$^{th}$ floors.

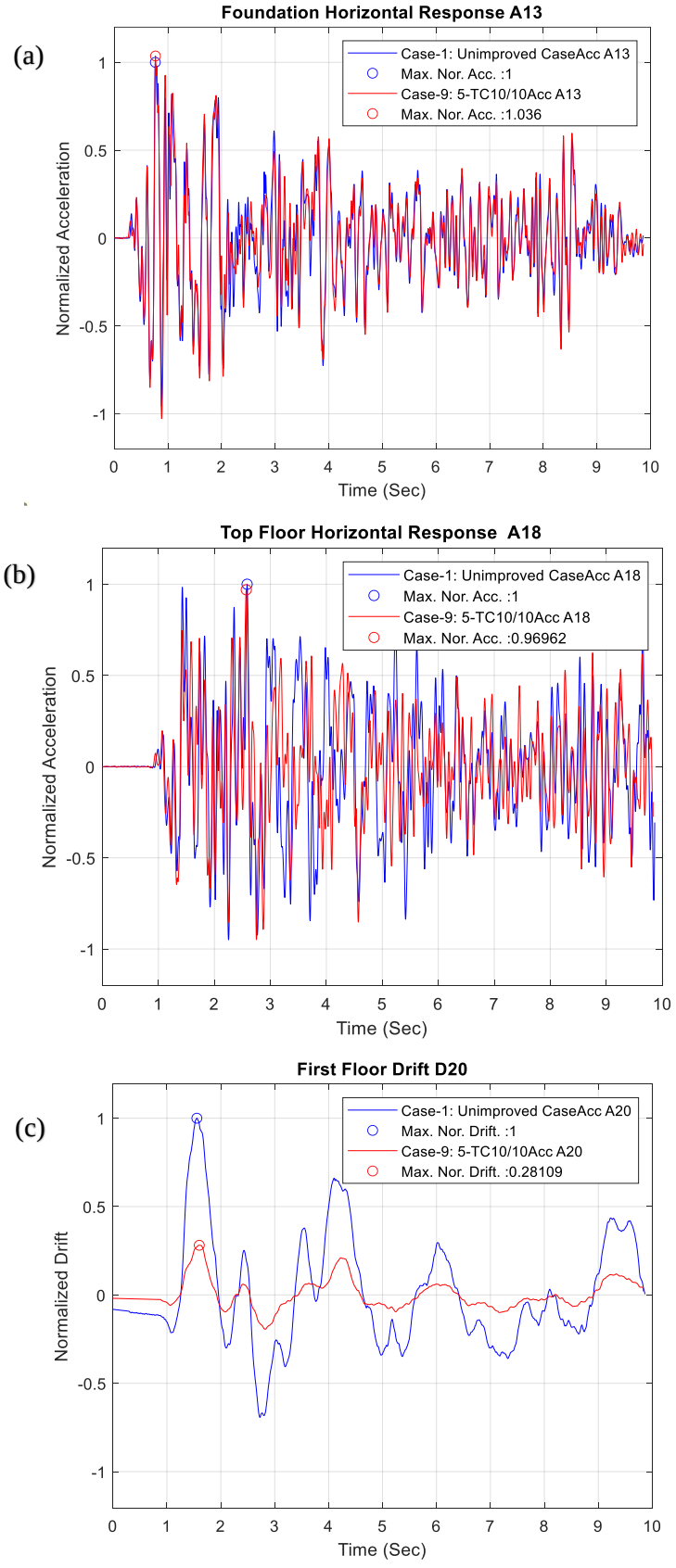



Figure 4.27. (a) FHR, (b) TFHR, (c) FFD of 5-TC10/10 under El Centro Earthquake Motion

Table 4.23. Results of 5-TC10/10 under El Centro Earthquake Motion

| 5-TC10/10 - El Centro EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,03 | 0,20 | 0,06 | 0,33 | 0,05 | 0,32 | 0,07 | 0,34 | 0,07 | 0,32 | 0,09 | 0,43 |
| 5-TC10/10 | 0,03 | 0,21 | 0,05 | 0,35 | 0,05 | 0,32 | 0,04 | 0,29 | 0,04 | 0,31 | 0,06 | 0,41 |
| % Reduction | 15 | -4 | 22 | -5 | 6 | -2 | 36 | 15 | 44 | 5 | 34 | 3 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,01771 | 0,09259 | 0,00096 | 0,00619 | 0,00228 | 0,01081 | 0,00126 | 0,00904 | 0,00078 | 0,00212 |
| 5-TC10/10 | * | * | 0,00395 | 0,02612 | 0,00022 | 0,00184 | 0,00064 | 0,00381 | 0,00036 | 0,00215 | 0,00001 | 0,00038 |
| % Reduction | * | * | 78 | 72 | 77 | 70 | 72 | 65 | 71 | 76 | 99 | 82 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 0,81 | | 1,73 | | 1,46 | | 1,48 | | 1,50 | | 1,80 | |
| 5-TC10/10 | 0,85 | | 1,64 | | 2,10 | | 1,23 | | 1,04 | | 1,99 | |
| % Reduction | -5 | | 5 | | -43 | | 17 | | 30 | | -11 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 1,00 | | 1,04 | | 1,04 | | 1,04 | | 0,25 | | 1,00 | |

- **5-TC10/10 under Kobe Earthquake Motion**

Case results are shown in Figure 4.27 and Table 4.24.

According to test results, foundation horizontal acceleration response was affected negatively by improvement, but this improvement has positive effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 11-37%. Moreover, the inter-story drift ratio showed a critical reduction of 66-88%. Besides, peak spectral acceleration decreased generally. Period lengthening was observed except 1$^{st}$ and 3$^{rd}$ floors.

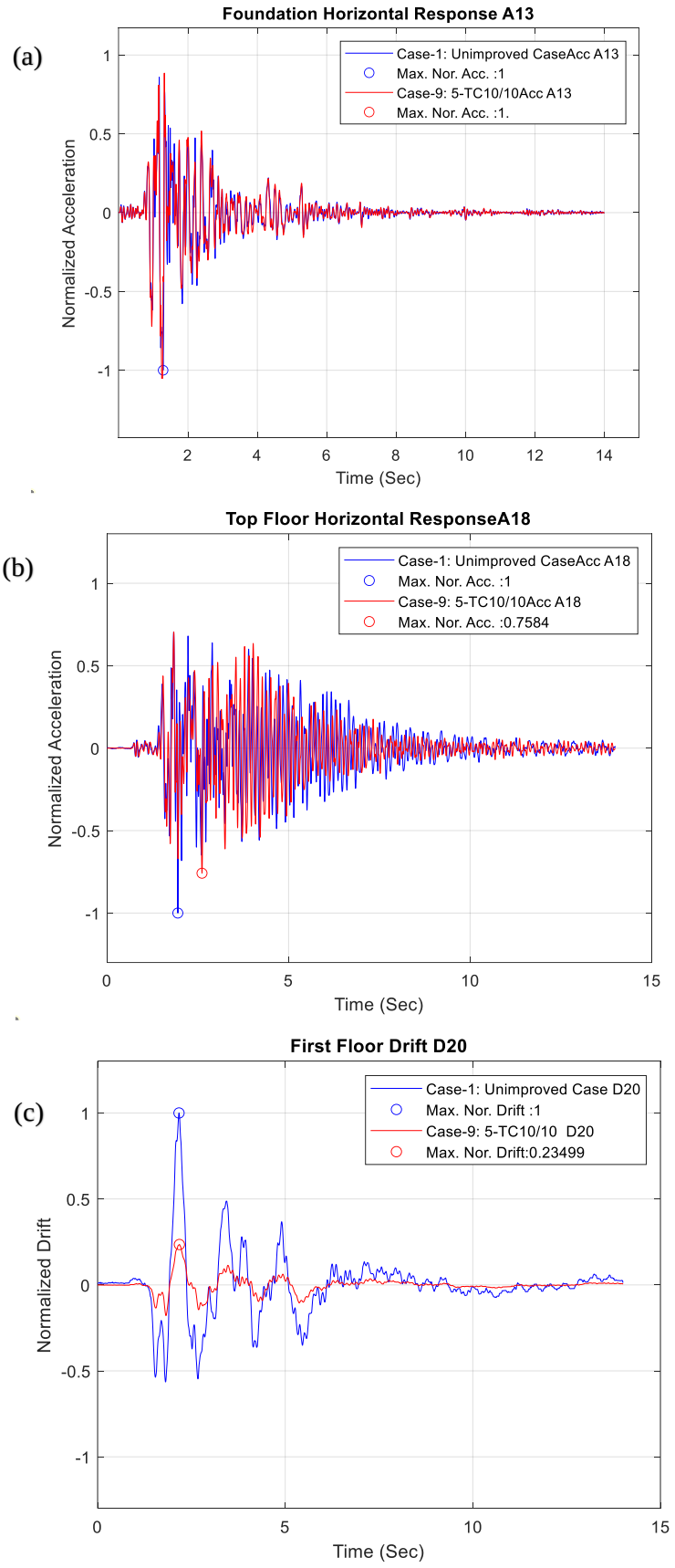



Figure 4. 28. (a) FHR, (b) TFHR, (c) FFD of 5-TC10/10 under Kobe Earthquake Motion

Table 4.24. Results of 5-TC10/10 under Kobe Earthquake Motion

| 5-TC10/10 - Kobe EQ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | | Floor-4 | | Floor-5 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | | | | | |
| 5-Sand | 0,05 | 0,56 | 0,11 | 0,70 | 0,10 | 0,91 | 0,09 | 0,91 | 0,09 | 0,62 | 0,13 | 1,07 |
| 5-TC10/10 | 0,05 | 0,76 | 0,09 | 0,88 | 0,10 | 0,81 | 0,06 | 0,57 | 0,06 | 0,51 | 0,10 | 0,81 |
| % Reduction | 13 | 35 | 22 | -27 | -1 | 11 | 36 | 37 | 34 | 18 | 20 | 24 |
| Interstory Drift Ratio | | | | | | | | | | | | |
| 5-Sand | * | * | 0,0107 | 0,0856 | 0,0025 | 0,0135 | 0,0037 | 0,0247 | 0,0029 | 0,0209 | 0,0018 | 0,0155 |
| 5-TC10/10 | * | * | 0,0023 | 0,0200 | 0,0003 | 0,0034 | 0,0007 | 0,0071 | 0,0006 | 0,0070 | 0,0003 | 0,0045 |
| % Reduction | * | * | 79 | 77 | 87 | 74 | 81 | 71 | 79 | 66 | 82 | 71 |
| Peak Spectral Acceleration (g) | | | | | | | | | | | | |
| 5-Sand | 1,67 | | 4,10 | | 3,81 | | 5,12 | | 2,52 | | 3,84 | |
| 5-TC10/10 | 1,88 | | 4,22 | | 5,51 | | 2,78 | | 2,50 | | 5,01 | |
| % Reduction | -12 | | -3 | | -45 | | 46 | | 1 | | -30 | |
| Period Lengthening Ratio | | | | | | | | | | | | |
| Ratio | 2,07 | | 1,00 | | 1,50 | | 1,00 | | 2,27 | | 1,04 | |

## 4.3. Experimental Results without GSI for Three Story Model

3 story building model were generated for the first case that doesn't include any improvement material and method. By the way, the behavior of buildings without improvement can be observed. The experimental results of the control model were considered to compare the results of improved cases.

### 4.3.1. Case 10: Unisolated Case under Kocaeli Earthquake Motion

Figure 4.28, It was showed Horizontal Foundation Response (FHR), the Top Floor Horizontal Response (TFHR), and First Floor Drift (FFD) graphs.

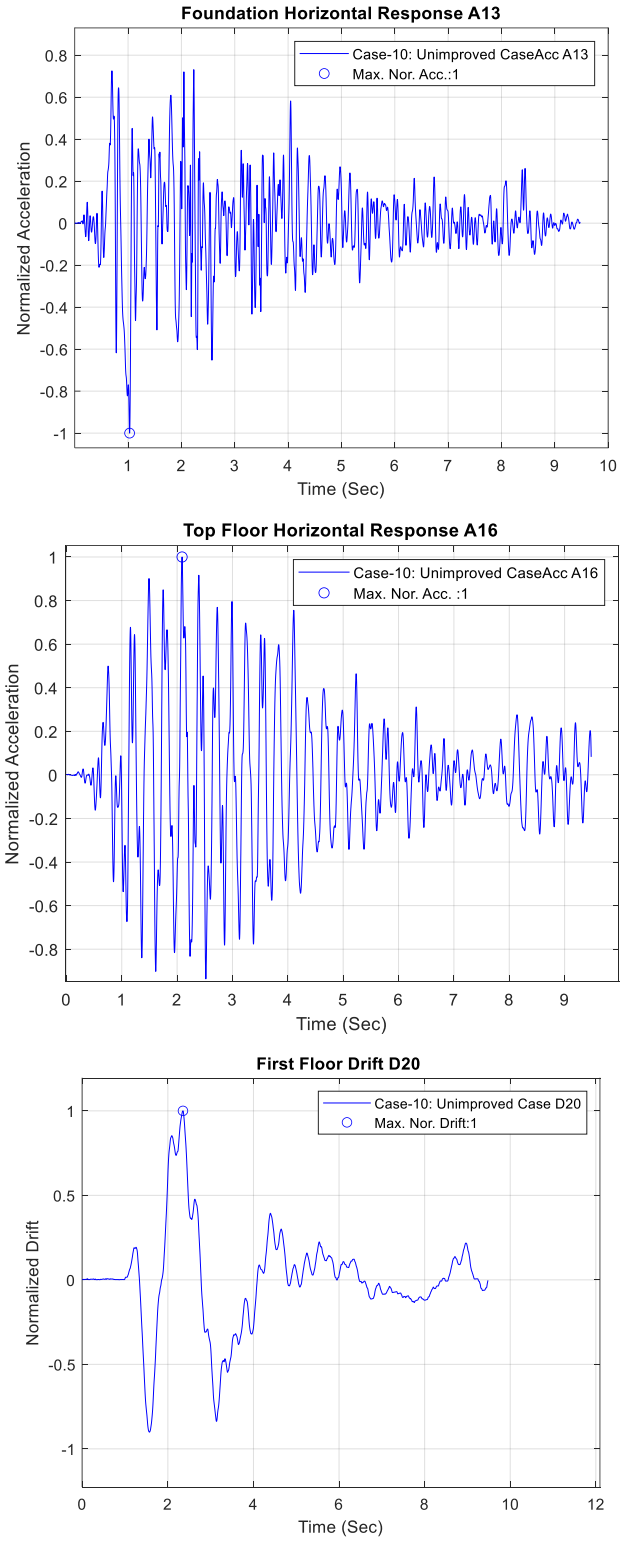



Figure 4. 29. (a) FHR, (b) TFHR, (c) FFD of 3-Sand under Kocaeli Earthquake Motion

### 4.3.2. Case 10: Unisolated Case under El Centro Earthquake Motion

Figure 4.29, It was showed Horizontal Foundation Response (FHR), the Top Floor Horizontal Response (TFHR), and First Floor Drift (FFD) graphs.

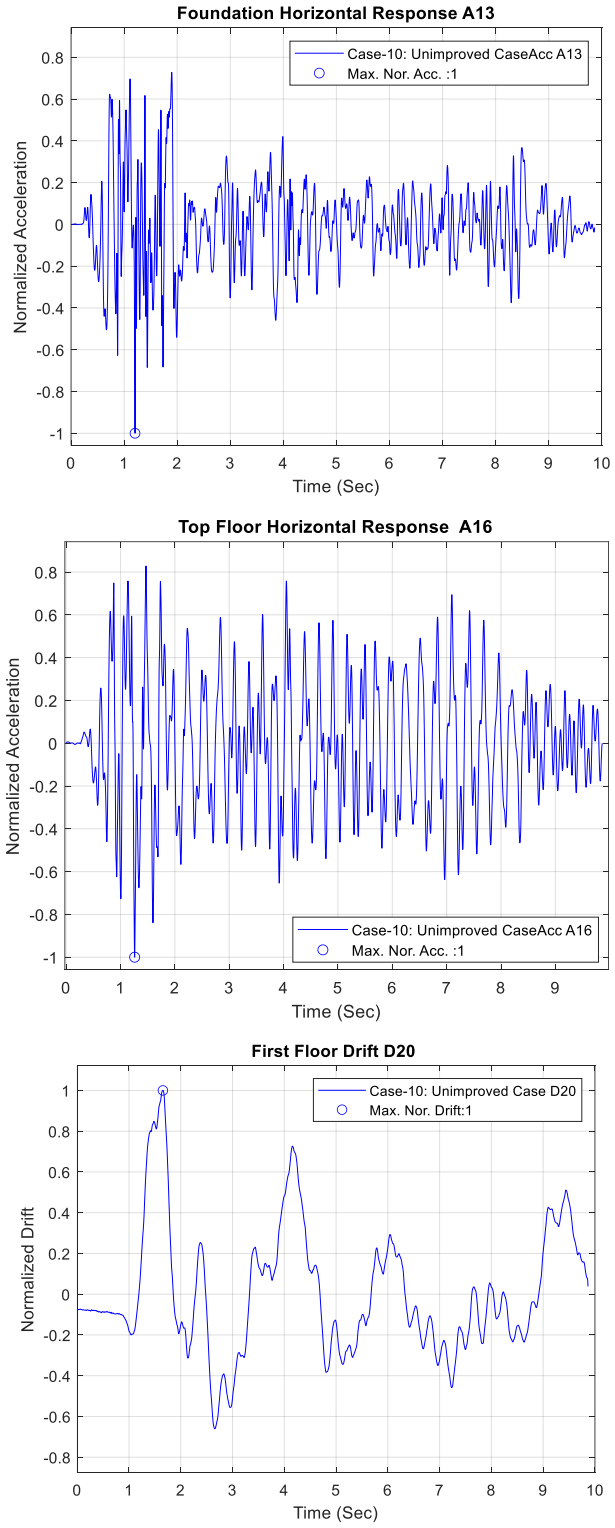
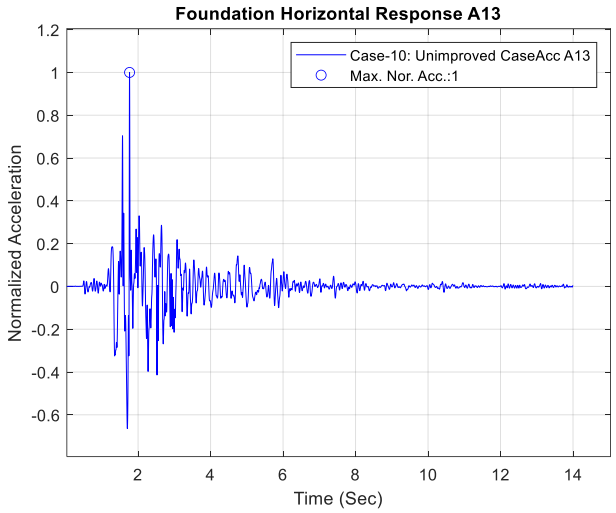


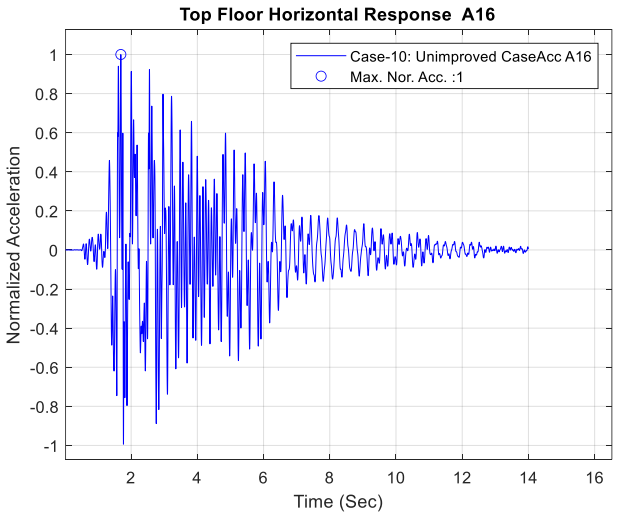

Figure 4.30. (a) FHR, (b) TFHR, (c) FFD of 3-Sand under El Centro Earthquake Motion

### 4.3.3. Case 10: Unisolated Case under Kobe Earthquake Motion

Figure 4.30, It was showed Horizontal Foundation Response (FHR), the Top Floor Horizontal Response (TFHR), and First Floor Drift (FFD) graphs.

(i)



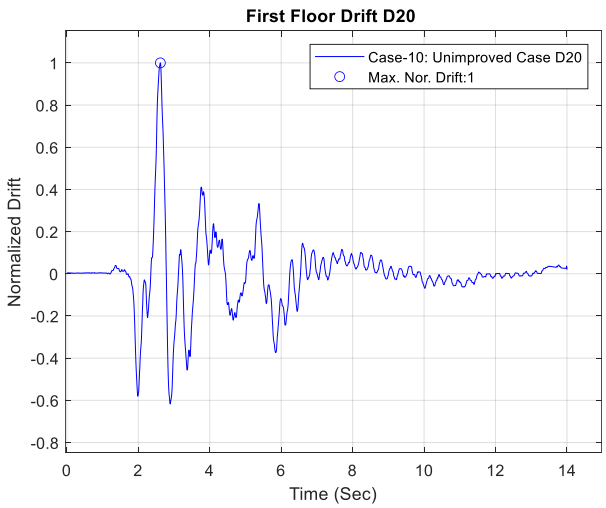




Figure. 4.31. (a) FHR, (b) TFHR, (c) FFD of 3-Sand under Kobe Earthquake Motion

## 4.4. Experimental Results of Isolated Cases for 3-Story Building Model

The results of tests are shown by comparing unimproved cases results with control model results.

### 4.4.1. Case 11: Only Gravel with 10 cm Thickness (3-TC0/10) as GSI Material

In Case 11, 3-story model foundation was surrounded with 10 cm thickness GRM includes 10% Tire Crumb. In this test, all selected earthquake motions were applied. However, the results of Kobe El Centro, Kocaeli earthquakes are presented here.

- **3-TC0/10 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.31 and Table 4.25.

According to test results, foundation horizontal acceleration response was affected negatively by improvement, but this improvement has positive effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 13-17%. Moreover, the inter-story drift ratio showed a critical reduction of 74-83%. Besides, peak spectral acceleration decreased generally. Period lengthening could be observed except 1$^{st}$ floor.

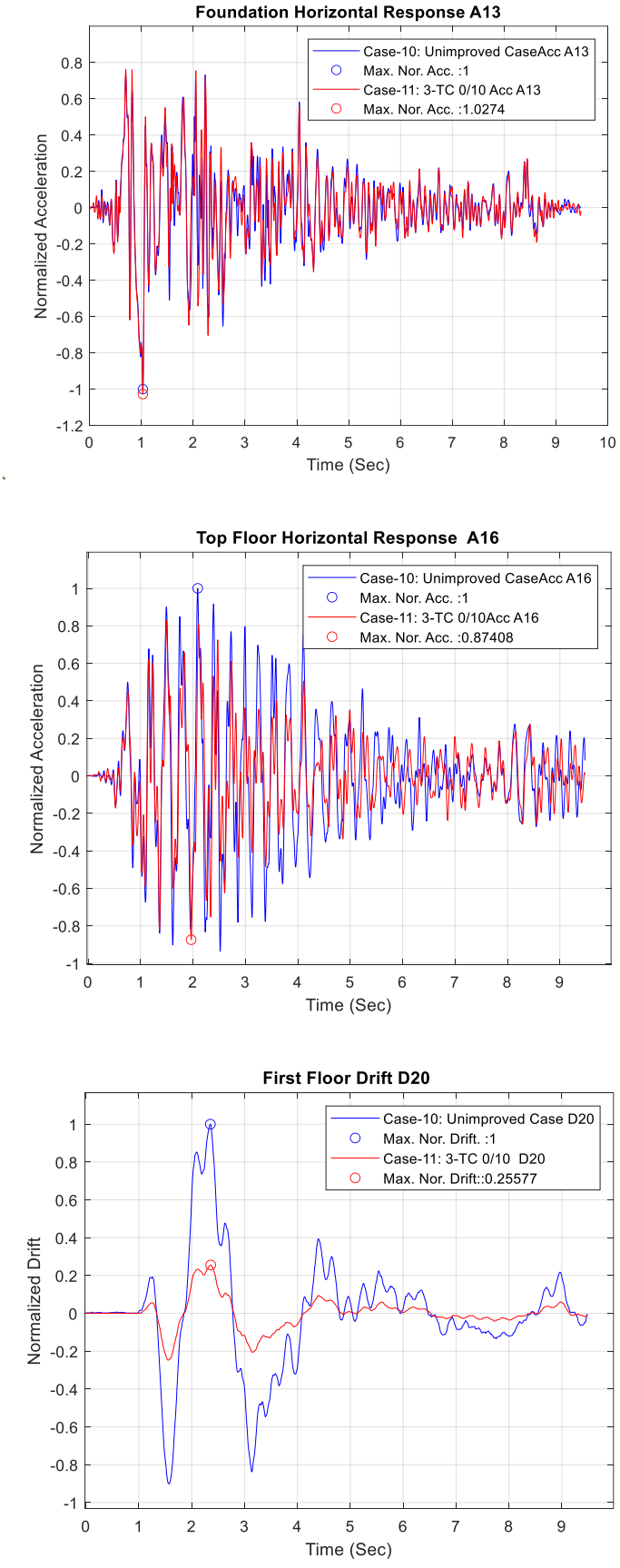



Figure 4.32. (a) FHR, (b) TFHR, (c) FFD of 3-TC0/10 under Kocaeli Earthquake Motion

Table 4.25. Results of 3-TC0/10 under Kocaeli Earthquake Motion

| 3- TC0/10 - Kocaeli EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-Sand | 0,02 | 0,18 | 0,06 | 0,37 | 0,05 | 0,35 | 0,08 | 0,49 |
| 3-TC0/10 | 0,02 | 0,18 | 0,04 | 0,30 | 0,04 | 0,29 | 0,06 | 0,43 |
| % Reduction | 1 | -3 | 37 | 17 | 5 | 16 | 27 | 13 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,0137 | 0,0840 | 0,0004 | 0,0060 | 0,0014 | 0,0112 |
| 3-TC0/10 | * | * | 0,0037 | 0,0215 | 0,0001 | 0,0013 | 0,0001 | 0,0019 |
| % Reduction | * | * | 73 | 74 | 73 | 78 | 90 | 83 |
| Peak Spectral Acceleration (g) | | | | | | | | |
| 3-Sand | 0,52 | | 2,03 | | 1,51 | | 2,76 | |
| 3-TC0/10 | 0,65 | | 1,72 | | 1,44 | | 1,98 | |
| % Reduction | -26 | | 15 | | 4 | | 28 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 1,00 | | 0,32 | | 3,44 | | 1,11 | |

- **3-TC0/10 under El Centro Earthquake Motion**

Case results are shown in Figure 4.32 and Table 4.26.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer.Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 4-32%. Moreover, the inter-story drift ratio showed a critical reduction of 33-70%. Besides, peak spectral acceleration decreased generally. Period lengthening couldn’t be observed except foundation.

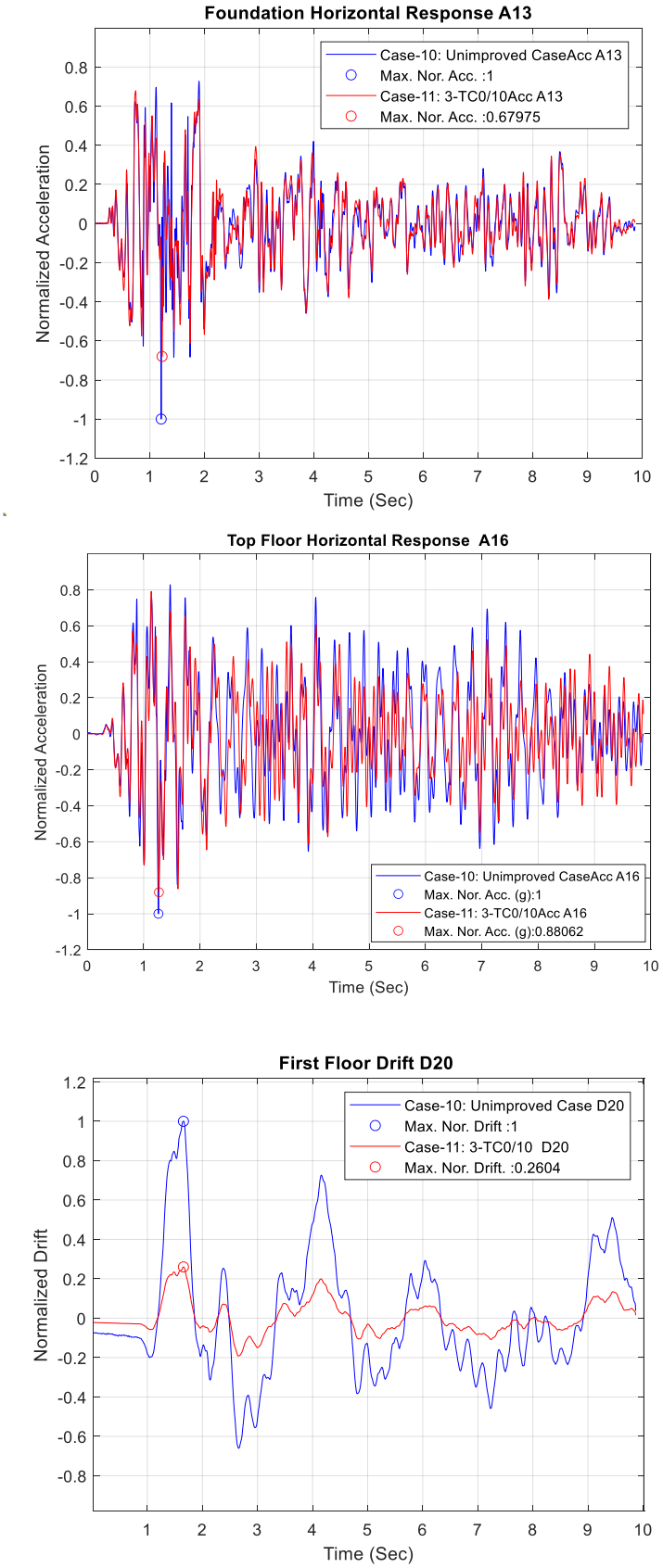



Figure 4.33. (a) FHR, (b) TFHR, (c) FFD of 3-TC0/10 under El Centro Earthquake Motion

Table 4.26. Results of 3-TC0/10 under El Centro Earthquake Motion

| 3- TC0/10 - El Centro EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-Sand | 0,03 | 0,31 | 0,08 | 0,53 | 0,06 | 0,48 | 0,11 | 0,71 |
| 3-TC0/10 | 0,03 | 0,21 | 0,07 | 0,41 | 0,07 | 0,46 | 0,09 | 0,63 |
| % Reduction | 3 | 32 | 13 | 22 | -3 | 4 | 15 | 12 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,01640 | 0,09938 | 0,00205 | 0,00594 | 0,00080 | 0,01665 |
| 3-TC0/10 | * | * | 0,00438 | 0,02579 | 0,00019 | 0,00180 | 0,00028 | 0,00332 |
| % Reduction | * | * | 73 | 74 | 91 | 70 | 65 | 80 |
| Peak Spectral Acceleration (g) | | | | | | | | |
| 3-Sand | 0,87 | | 2,12 | | 2,32 | | 2,85 | |
| 3-TC0/10 | 0,83 | | 2,42 | | 1,55 | | 2,59 | |
| % Reduction | 5 | | -14 | | 33 | | 9 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 2,57 | | 0,31 | | 1,00 | | 0,31 | |

- **3-TC0/10 under Kobe Earthquake Motion**

Case results are shown in Figure 4.33 and Table 4.27.

According to test results, foundation horizontal acceleration response was affected positively by improvement, but this improvement has negative effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 4-32%. Moreover, the inter-story drift ratio showed a critical reduction of 70-80%. Besides, peak spectral acceleration decreased generally. Period lengthening couldn't be observed except foundation.

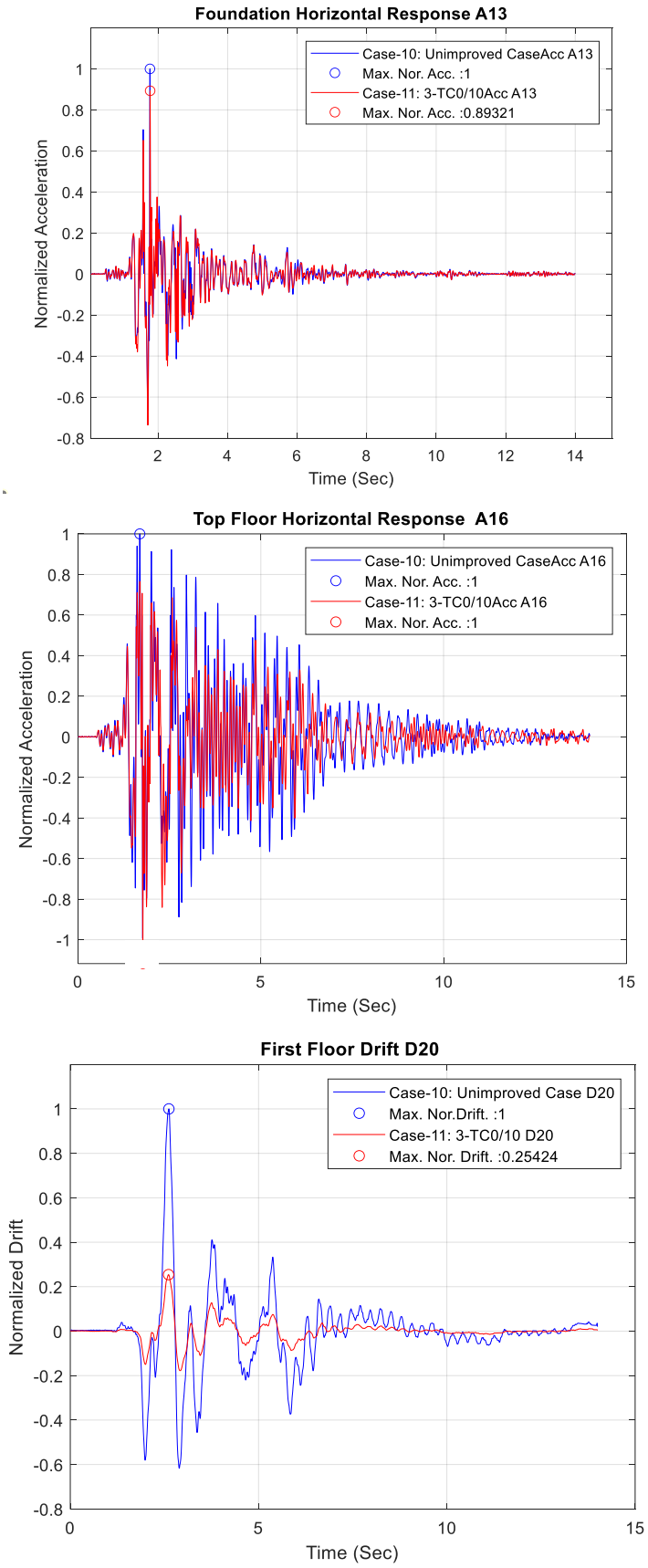



Figure 4.34. (a) FHR, (b) TFHR, (c) FFD of 3-TC0/10 under Kobe Earthquake Motion

Table 4.27. Results of 3-TC0/10 under Kobe Earthquake Motion

| 3- TC0/10 - Kobe EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-Sand | 0,04 | 0,88 | 0,08 | 0,79 | 0,08 | 0,71 | 0,10 | 0,83 |
| 3-TC0/10 | 0,04 | 0,79 | 0,06 | 0,77 | 0,06 | 0,58 | 0,08 | 0,93 |
| % Reduct. | -3 | 11 | 21 | 1 | 26 | 18 | 21 | 12 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,00958 | 0,09616 | 0,00689 | 0,02089 | 0,00239 | 0,03900 |
| 3-TC0/10 | * | * | 0,00260 | 0,02446 | 0,00077 | 0,00707 | 0,00100 | 0,00951 |
| % Reduction | * | * | 73 | 75 | 89 | 66 | 58 | 76 |
| Peak Spectral Acc. (g) | | | | | | | | |
| 3-Sand | 1,94 | | 2,78 | | 3,51 | | 3,35 | |
| 3-TC0/10 | 1,78 | | 2,57 | | 1,98 | | 2,38 | |
| % Reduction | 8 | | 7 | | 44 | | 29 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 1,00 | | 0,73 | | 0,76 | | 5,47 | |

### 4.4.2. Case 12: Only Gravel with 15 cm Thickness (3-TC0/15) as GSI Material

In Case 12, 3-story model foundation was surrounded with 15 cm thickness GRM includes 10% Tire Crumb. In this test, all selected earthquake motions were applied. However, the results of Kobe El Centro, Kocaeli earthquakes are presented here.

- **3-TC0/15 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.34 and Table 4.28. According to test results, foundation horizontal acceleration response was affected negatively by GSI system, but this improvement has positive effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 1-35%. Moreover, the inter-story drift ratio showed a important reduction of 63-80%. Besides, peak spectral acceleration decreased generally. Period lengthening was observed except foundation and 1$^{st}$ floor.

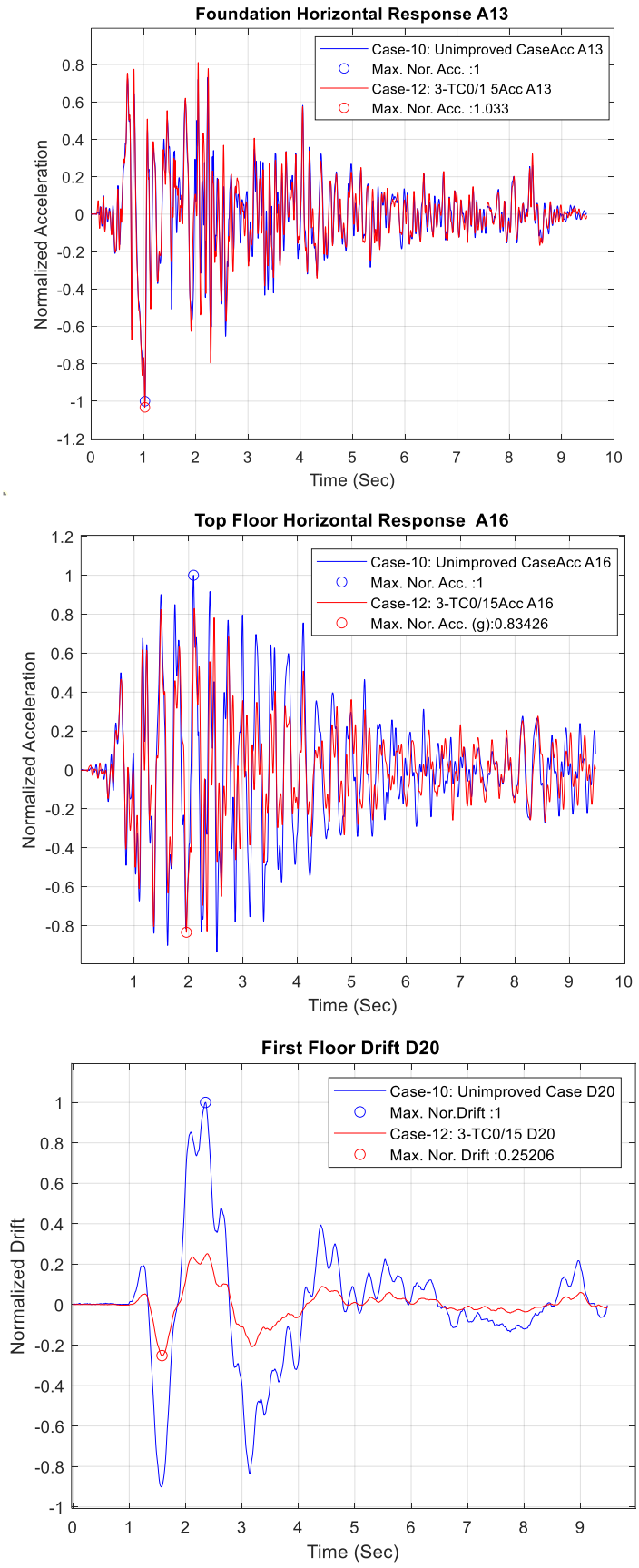



Figure 4.35. (a) FHR, (b) TFHR, (c) FFD of 3-TC0/15 under Kocaeli Earthquake Motion

Table 4.28. Results of 3-TC0/15 under Kocaeli Earthquake Motion

| 3- TC0/15 - Kocaeli EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-Sand | 0,02 | 0,18 | 0,06 | 0,37 | 0,05 | 0,35 | 0,08 | 0,49 |
| 3-TC0/ 15 | 0,02 | 0,19 | 0,04 | 0,34 | 0,05 | 0,29 | 0,06 | 0,41 |
| % Reduction | 0 | -3 | 35 | 9 | 1 | 18 | 24 | 17 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,0137 | 0,0840 | 0,0004 | 0,0060 | 0,0014 | 0,0112 |
| 3-TC0/15 | * | * | 0,0036 | 0,0212 | 0,0001 | 0,0015 | 0,0003 | 0,0025 |
| % Reduction | * | * | 74 | 75 | 63 | 75 | 80 | 77 |
| Peak Spectral Acceleration (g) | | | | | | | | |
| 3-Sand | 0,52 | | 2,03 | | 1,51 | | 2,76 | |
| 3-TC0/15 | 0,71 | | 1,80 | | 1,50 | | 2,05 | |
| % Reduction | -37 | | 12 | | 0 | | 26 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 1,00 | | 0,32 | | 3,50 | | 1,09 | |

- **3-TC0/15 under El Centro Earthquake Motion**

Case results are shown in Figure 4.35 and Table 4.29.

According to test results, foundation horizontal acceleration response was affected negatively by improvement, but this improvement has positive effect on first-floor horizontal response. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 1-35%. Moreover, the inter-story drift ratio showed a critical reduction of 63-80%. Besides, peak spectral acceleration decreased generally. Period lengthening was observed at the foundation level.

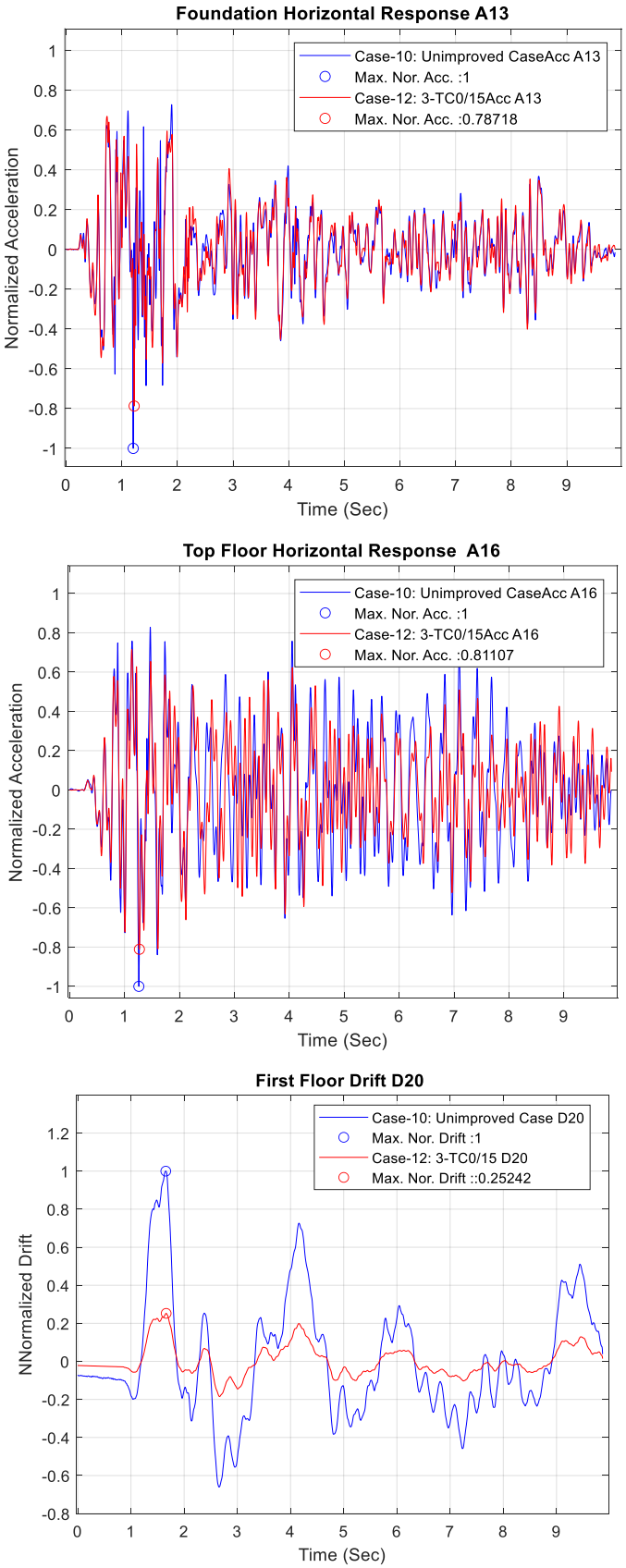



Figure 4.36. (a) FHR, (b) TFHR, (c) FFD of 3-TC0/15 under El Centro Earthquake Motion

Table 4.29. Results of 3-TC0/15 under El Centro Earthquake Motion

| 3- TC0/15 - El Centro EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-Sand | 0,03 | 0,31 | 0,08 | 0,53 | 0,06 | 0,48 | 0,11 | 0,71 |
| 3-TC0/15 | 0,03 | 0,24 | 0,07 | 0,42 | 0,07 | 0,46 | 0,09 | 0,58 |
| % Reduction | 3 | 21 | 13 | 21 | -4 | 4 | 15 | 19 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,0164 | 0,0994 | 0,0020 | 0,0059 | 0,0008 | 0,0167 |
| 3-TC0/15 | * | * | 0,0043 | 0,0249 | 0,0002 | 0,0017 | 0,0004 | 0,0037 |
| % Reduction | * | * | 74 | 75 | 90 | 72 | 45 | 78 |
| Peak Spectral Acceleration (g) | | | | | | | | |
| 3-Sand | 0,87 | | 2,12 | | 2,32 | | 2,85 | |
| 3-TC0/15 | 0,82 | | 2,41 | | 1,62 | | 2,50 | |
| % Reduction | 6 | | -13 | | 30 | | 12 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 2,57 | | 0,31 | | 1,00 | | 0,31 | |

- **3-TC0/15 under Kobe Earthquake Motion**

Case results are shown in Figure 4.36 and Table 4.30.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer.Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 4-23%. Moreover, the inter-story drift ratio showed a critical reduction of 70-76%. Besides, peak spectral acceleration decreased generally. Period lengthening couldn't be observed except 1$^{st}$ floor.

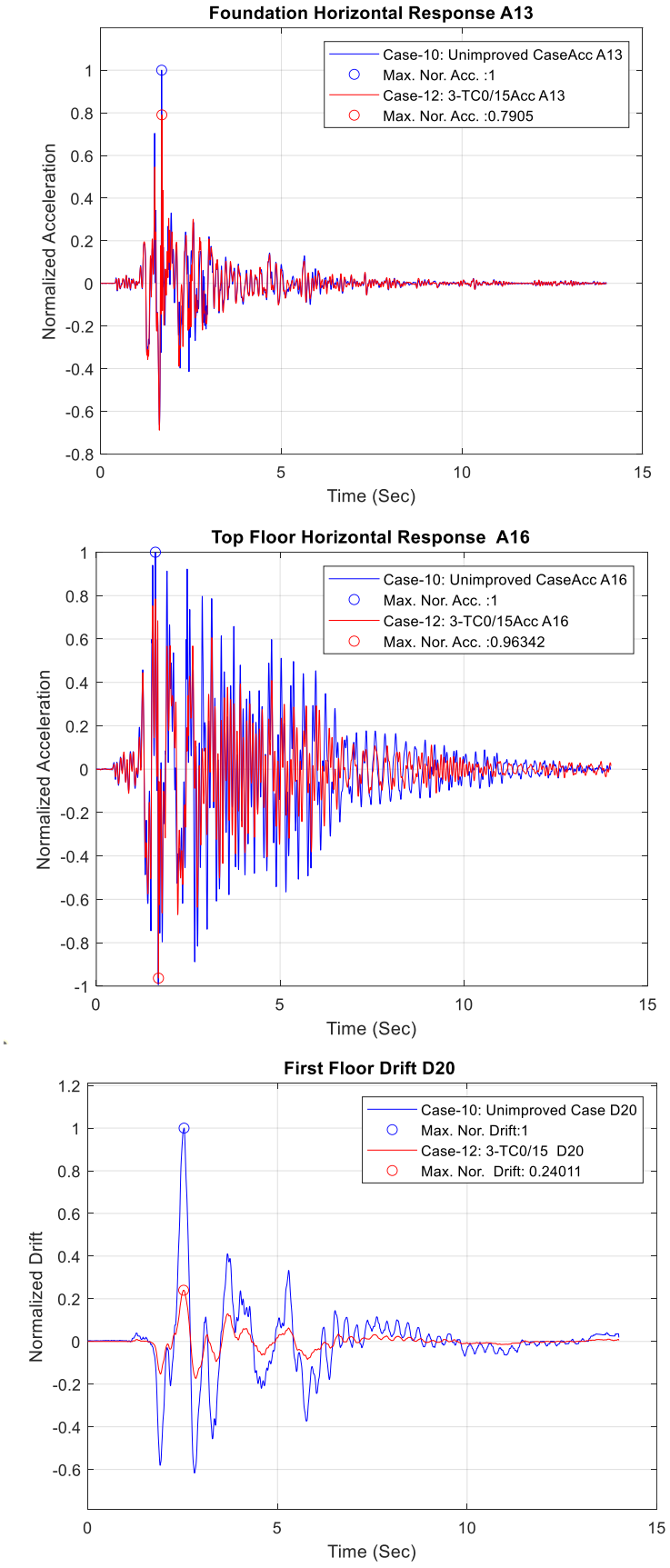



Figure 4.37. (a) FHR, (b) TFHR, (c) FFD of 3-TC0/15 under Kobe Earthquake Motion

Table 4. 30. Results of 3-TC0/15 under Kobe Earthquake Motion

| 3- TC0/15 - Kobe EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-Sand | 0,04 | 0,88 | 0,08 | 0,79 | 0,08 | 0,71 | 0,10 | 0,83 |
| 3-TC0/ 15 | 0,04 | 0,70 | 0,06 | 0,79 | 0,06 | 0,55 | 0,08 | 0,80 |
| % Reduction | 3 | 21 | 23 | -1 | 30 | 23 | 25 | 4 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,0096 | 0,0962 | 0,0069 | 0,0209 | 0,0024 | 0,0390 |
| 3-TC0/15 | * | * | 0,0025 | 0,0231 | 0,0008 | 0,0062 | 0,0010 | 0,0108 |
| % Reduction | * | * | 74 | 76 | 89 | 70 | 57 | 72 |
| Peak Spectral Acc. (g) | | | | | | | | |
| 3-Sand | 1,94 | | 2,78 | | 3,51 | | 3,35 | |
| 3-TC0/15 | 1,62 | | 2,52 | | 1,92 | | 2,43 | |
| % Reduction | 16 | | 9 | | 45 | | 28 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 0,88 | | 1,55 | | 0,88 | | 1,00 | |

### 4.4.3. Case 13: TC 30 with 10 cm Thickness (3-TC 30/ 10) as GSI Material

In Case 13, 3-story model foundation was surrounded with 10 cm thickness GRM includes 30% Tire Crumb. The results of Kobe El Centro, Kocaeli earthquake observations are presented in the following section.

- **3-TC30/10 under Kocaeli Earthquake Motion**

Case results are shown Figure 4.37 and Table 4.31. According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer.Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 2-26%. Moreover, the inter-story drift ratio showed a critical reduction of 25-69%. Besides, peak spectral acceleration decreased on upper floors. Period lengthening wasn't observed.

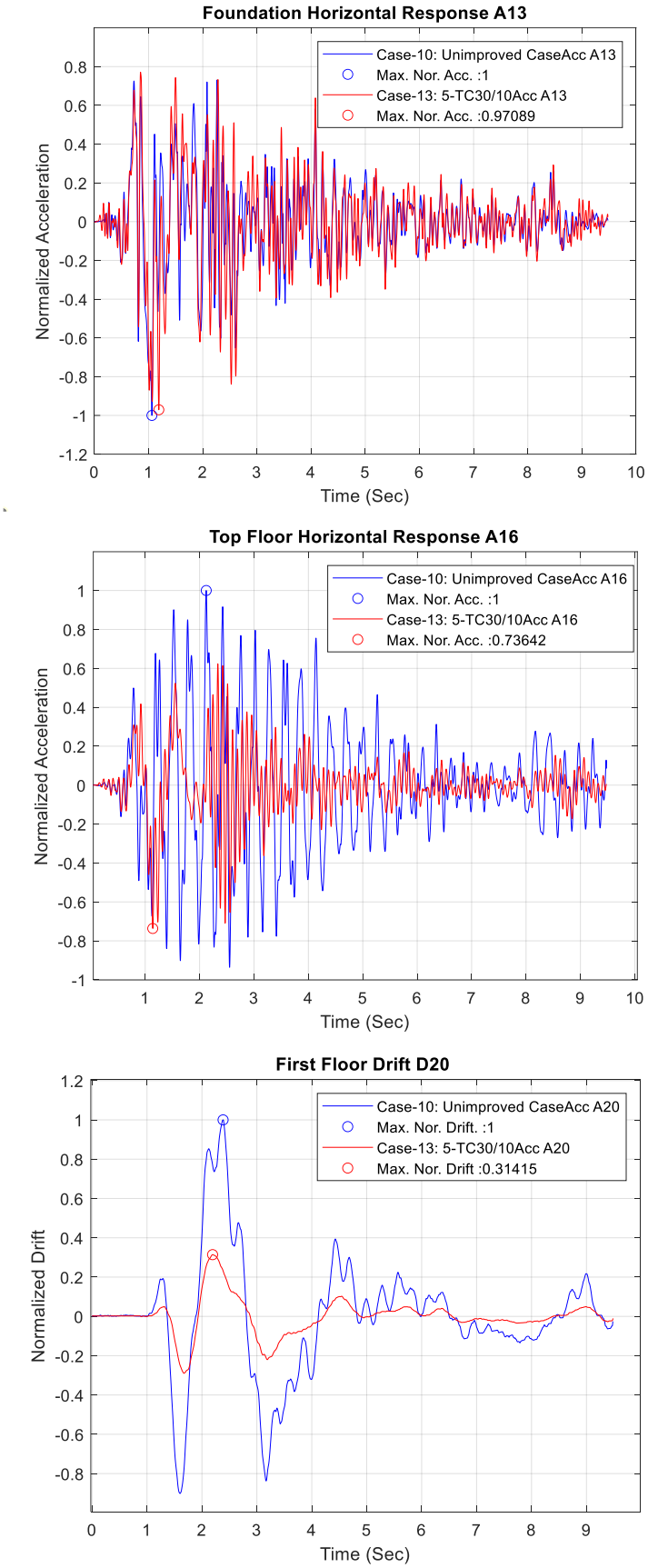



Figure 4.38. (a) FHR, (b) TFHR, (c) FFD of 3-TC30/10 under Kocaeli Earthquake Motion

Table 4. 31. Results of 3-TC30/10 under Kocaeli Earthquake Motion

| 3- TC30/10 - Kocaeli EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-San | 0,02 | 0,18 | 0,06 | 0,37 | 0,05 | 0,35 | 0,08 | 0,49 |
| 3-TC30 // 10 | 0,02 | 0,17 | 0,04 | 0,36 | 0,04 | 0,27 | 0,05 | 0,36 |
| % Reduction | 25 | 3 | 30 | 2 | 24 | 24 | 43 | 26 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,0137 | 0,0840 | 0,0004 | 0,0060 | 0,0014 | 0,0112 |
| 3-TC30/10 | * | * | 0,0048 | 0,0264 | 0,0006 | 0,0045 | 0,0008 | 0,0066 |
| % Reduction | * | * | 65 | 69 | -50 | 25 | 43 | 41 |
| Peak Spectral Acceleration (g) | | | | | | | | |
| 3-Sand | 0,52 | | 2,03 | | 1,51 | | 2,76 | |
| 3-TC30/10 | 0,89 | | 2,44 | | 1,28 | | 2,21 | |
| % Reduction | -72 | | -20 | | 15 | | 20 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 1,00 | | 0,32 | | 1,00 | | 0,32 | |

- **3-TC 30 /10 Against El - Centro Earthquake Motion**

Case results are shown in Figure. 4.38 and, Table. 4.32.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer.Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 21-51%. Moreover, the inter-story drift ratio showed a critical reduction of 65-70%. Besides, peak spectral acceleration decreased for all models. Period lengthening wasn’t observed except foundation level.

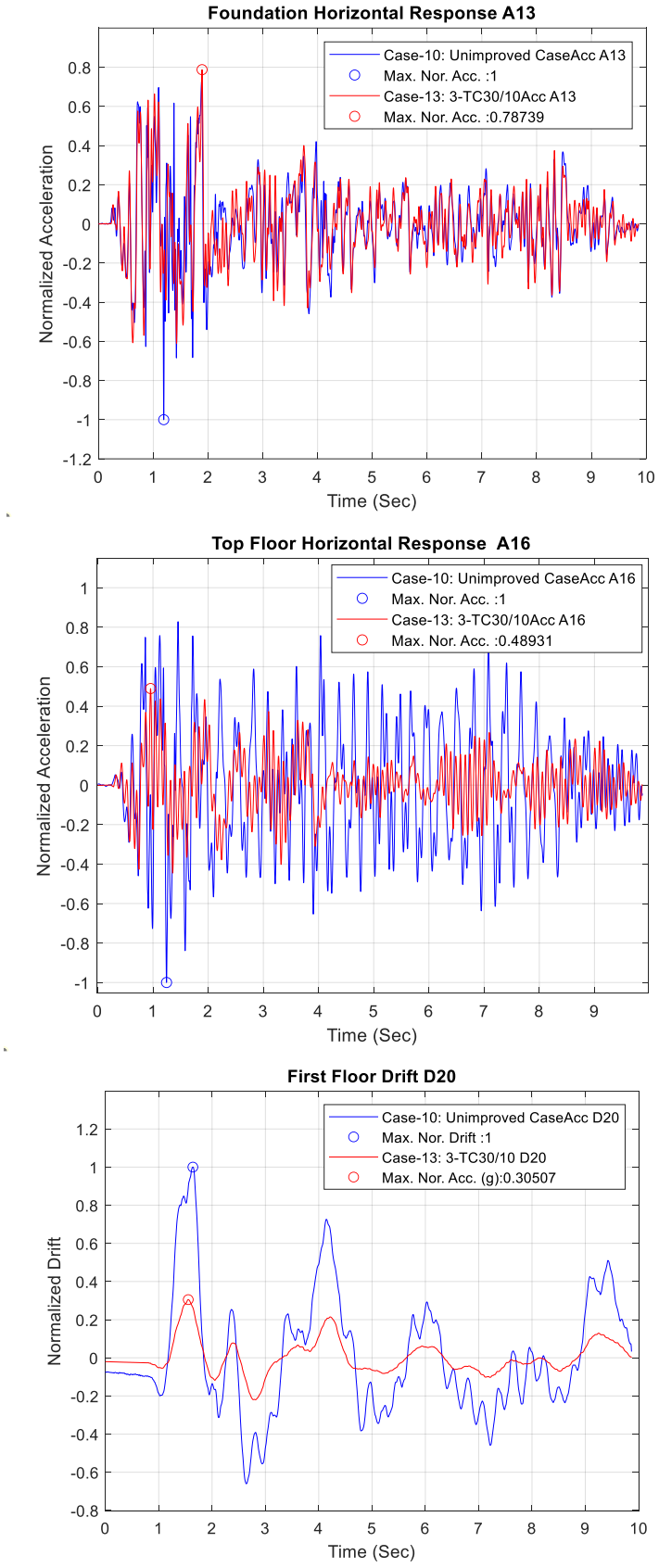



Figure 4.39. (a) FHR, (b) TFHR, (c) FFD of 3-TC30/10 under El Centro Earthquake Motion

Table 4. 32. Results of 3-TC30/10 under El Centro Earthquake Motion

| 3- TC30/10 - El Centro EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-Sand | 0,03 | 0,31 | 0,08 | 0,53 | 0,06 | 0,48 | 0,11 | 0,71 |
| 3-TC30/10 | 0,03 | 0,24 | 0,05 | 0,36 | 0,04 | 0,32 | 0,06 | 0,35 |
| % Reduction | -12 | 21 | 34 | 33 | 35 | 34 | 47 | 51 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,01640 | 0,09938 | 0,00205 | 0,00594 | 0,00080 | 0,01665 |
| 3-TC30/10 | * | * | 0,00538 | 0,03033 | 0,00052 | 0,00206 | 0,00094 | 0,00496 |
| % Reduction | * | * | 67 | 69 | 75 | 65 | 67 | 70 |
| Peak Spectral Acceleration (g) | | | | | | | | |
| 3-Sand | 0,87 | | 2,12 | | 2,32 | | 2,85 | |
| 3-TC30/10 | 0,79 | | 1,73 | | 1,17 | | 1,75 | |
| % Reduction | 9 | | 19 | | 50 | | 38 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 2,57 | | 0,33 | | 1,00 | | 0,31 | |

- **3-TC30/10 under Kobe Earthquake Motion**

Case results are shown in Figure 4.39 and Table 4.33.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer.Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 2-37%. Moreover, the inter-story drift ratio showed a critical reduction of 72-78%. Besides, peak spectral acceleration decreased for all model. Period lengthening was observed except 2$^{nd}$ floor.

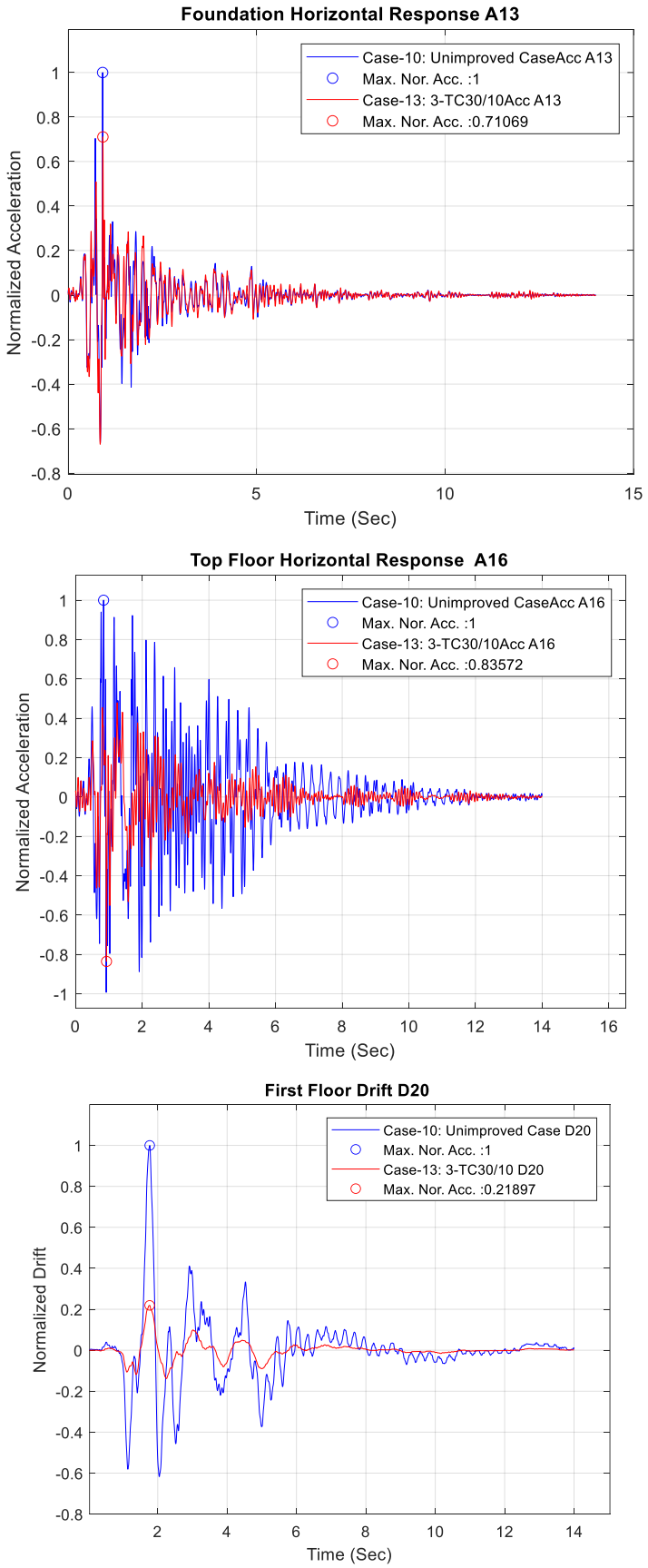



Figure 4. 40. (a) FHR, (b) TFHR, (c) FFD of 3-TC30/10 under Kobe Earthquake Motion

Table 4.33. Results of 3-TC30/10 under Kobe Earthquake Motion

| 3- TC30/10 - Kobe EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-Sand | 0,04 | 0,88 | 0,08 | 0,79 | 0,08 | 0,71 | 0,10 | 0,83 |
| 3-TC30/10 | 0,05 | 0,63 | 0,05 | 0,77 | 0,04 | 0,44 | 0,06 | 0,70 |
| % Reduction | -20 | 29 | 29 | 2 | 50 | 37 | 44 | 16 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,0096 | 0,0962 | 0,0069 | 0,0209 | 0,0024 | 0,0390 |
| 3-TC30/10 | * | * | 0,0028 | 0,0210 | 0,0007 | 0,0057 | 0,0011 | 0,0111 |
| % Reduction | * | * | 71 | 78 | 90 | 73 | 53 | 72 |
| Peak Spectral Acc. (g) | | | | | | | | |
| 3-Sand | 1,94 | | 2,78 | | 3,51 | | 3,35 | |
| 3-TC30/10 | 1,65 | | 2,05 | | 1,75 | | 1,76 | |
| % Reduction | 15 | | 26 | | 50 | | 47 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 3,87 | | 1,73 | | 0,65 | | 1,06 | |

### 4.4.4. Case 14: TC30 with 15 cm Thickness (3-TC30/10) as GSI Material

In Case 14, 3-story model foundation was surrounded with 15 cm thickness GRM includes 30% Tire Crumb. In this test, all selected earthquake motions were applied. However, the results of Kobe El Centro, Kocaeli earthquakes are presented here.

- **3-TC30/15 under Kocaeli Earthquake Motion**

Case results are shown in Figure 4.40 and Table 4.34. According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer.Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 3-29%. Moreover, the inter-story drift ratio showed a critical reduction of 15-65%. Besides, peak spectral acceleration decreased on upper floors. Period lengthening couldn’t be observed.

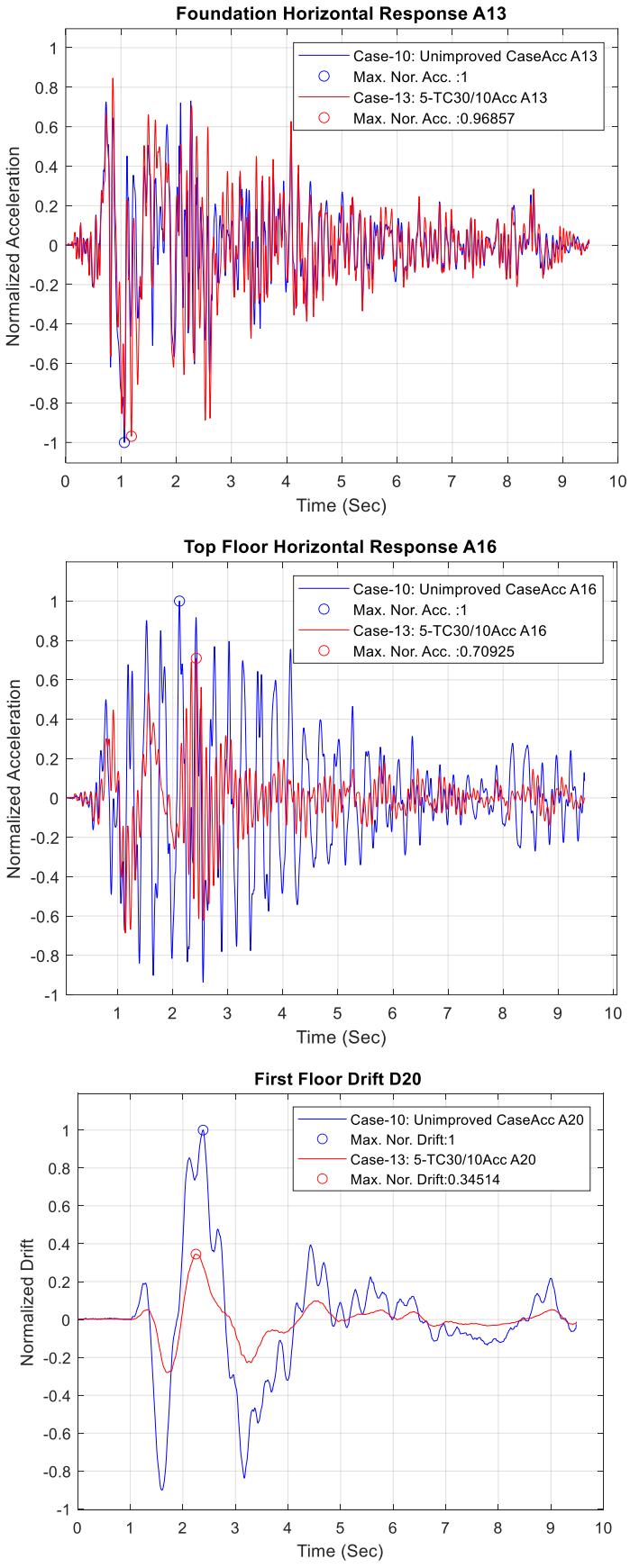



Figure 4.41. (a) FHR, (b) TFHR, (c) FFD of 3-TC30/15 under Kocaeli Earthquake Motion

Table 4. 34. Results of 3-TC30/15 under Kocaeli Earthquake Motion

| 3- TC30/15 - Kocaeli EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-Sand | 0,02 | 0,18 | 0,06 | 0,37 | 0,05 | 0,35 | 0,08 | 0,49 |
| 3-TC30/15 | 0,03 | 0,17 | 0,04 | 0,39 | 0,03 | 0,25 | 0,05 | 0,35 |
| % Reduction | -28 | 3 | 33 | -7 | 26 | 29 | 44 | 29 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,01371 | 0,08396 | 0,00037 | 0,00601 | 0,00139 | 0,01118 |
| 3-TC30/15 | * | * | 0,00493 | 0,02898 | 0,00066 | 0,00511 | 0,00095 | 0,00758 |
| % Reduction | * | * | 64 | 65 | -80 | 15 | 31 | 32 |
| Peak Spectral Acceleration (g) | | | | | | | | |
| 3-Sand | 0,52 | | 2,03 | | 1,51 | | 2,76 | |
| 3-TC30/15 | 0,95 | | 2,41 | | 1,25 | | 2,16 | |
| % Reduction | -84 | | -18 | | 17 | | 22 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 1,00 | | 0,32 | | 1,00 | | 0,32 | |

- **3-TC 30 /15 against El- Centro Earthquake Motion**

Case results are shown in Figure. 4.41 and Table. 4.35.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 19-53%. Moreover, the inter-story drift ratio showed a critical reduction of 56-73%. Besides, peak spectral acceleration decreased generally. Period lengthening couldn’t be observed except foundation.

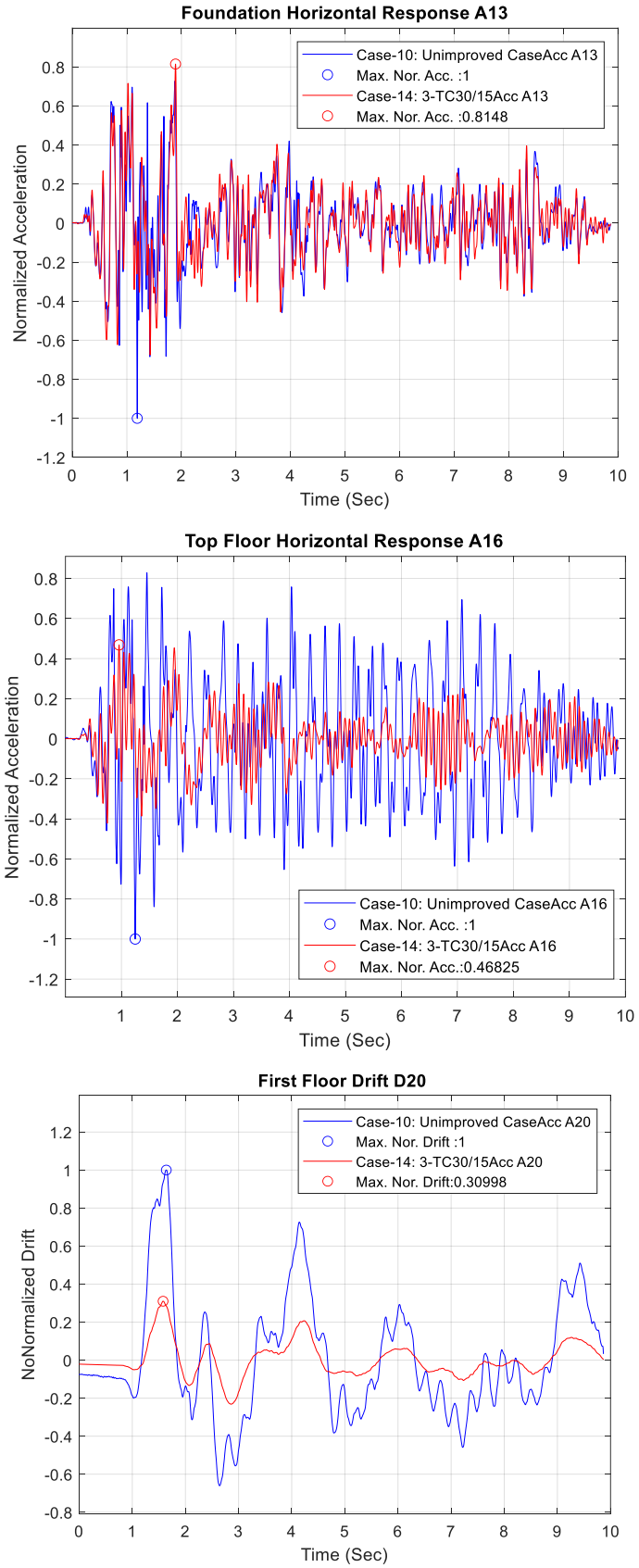



Figure 4.42. (a) FHR, (b) TFHR, (c) FFD of 3-TC30/15 under El Centro Earthquake Motion.

Table 4. 35. Results of 3-TC30/15 under El Centro Earthquake Motion

| 3- TC30/15 - El Centro EQ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-Sand | 0,03 | 0,31 | 0,08 | 0,53 | 0,06 | 0,48 | 0,11 | 0,71 |
| 3-TC30/15 | 0,03 | 0,25 | 0,05 | 0,35 | 0,04 | 0,31 | 0,05 | 0,33 |
| % Reduction | -14 | 19 | 38 | 34 | 39 | 35 | 50 | 53 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,01640 | 0,09938 | 0,00205 | 0,00594 | 0,00080 | 0,01665 |
| 3-TC30/15 | * | * | 0,00551 | 0,03090 | 0,00064 | 0,00261 | 0,00103 | 0,00442 |
| % Reduction | * | * | 66 | 69 | 69 | 56 | 59 | 73 |
| Peak Spectral Acceleration (g) | | | | | | | | |
| 3-Sand | 0,87 | | 2,12 | | 2,32 | | 2,85 | |
| 3-TC30/15 | 0,82 | | 1,63 | | 1,12 | | 1,65 | |
| % Reduction | 6 | | 23 | | 52 | | 42 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 2,57 | | 0,31 | | 1,00 | | 0,31 | |

- **3-TC30/15 under Kobe Earthquake Motion**

Case results are shown in Figure 4.42 and Table 4.36.

According to test results, foundation and first-floor horizontal acceleration response were affected positively by inclusion of the GRM layer. Also, first-floor drift decreased seriously. When examining acceleration values, the peak and RMS of accelerations of stories were decreased by 1-29%. Moreover, the inter-story drift ratio showed a critical reduction of 69-79%. Besides, peak spectral acceleration decreased generally. Period lengthening was observed except 2$^{nd}$ floor.

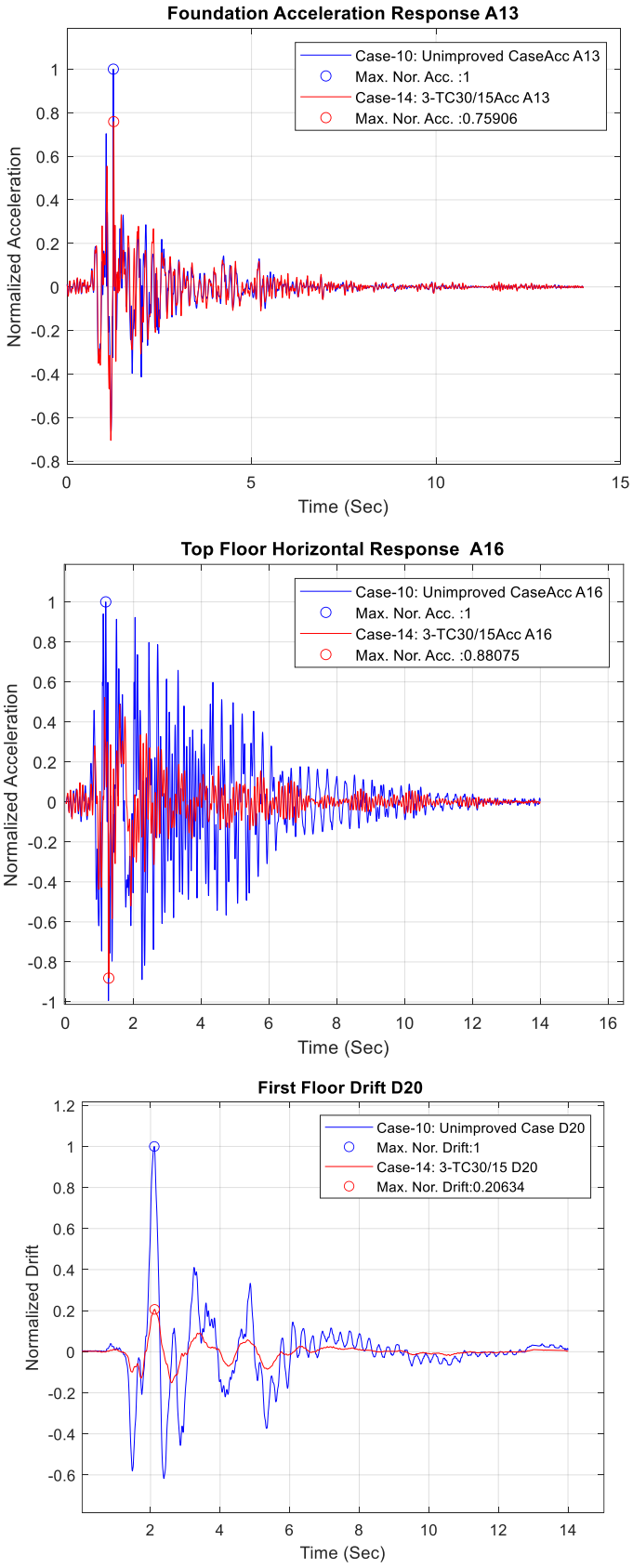



Figure 4. 43. (a) FHR, (b) TFHR, (c) FFD of 3-TC30/15 under Kobe Earthquake Motion

Table 4. 36. Results of 3-TC30/15 under Kobe Earthquake Motion

| **3- TC30/15 - Kobe EQ** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Foundation | | Floor-1 | | Floor-2 | | Floor-3 | |
| | RMS | Top | RMS | Top | RMS | Top | RMS | Top |
| Floor Accelerations (g) | | | | | | | | |
| 3-San | 0,04 | 0,88 | 0,08 | 0,79 | 0,08 | 0,71 | 0,10 | 0,83 |
| 3-TC 30 / 15 | 0,05 | 0,67 | 0,06 | 0,78 | 0,04 | 0,50 | 0,06 | 0,73 |
| % Reduction | -23 | 24 | 28 | 1 | 52 | 29 | 46 | 12 |
| Interstory Drift Ratio | | | | | | | | |
| 3-Sand | * | * | 0,0096 | 0,0962 | 0,0069 | 0,0209 | 0,0024 | 0,0390 |
| 3-TC30/15 | * | * | 0,0028 | 0,0199 | 0,0007 | 0,0065 | 0,0010 | 0,0106 |
| % Reduction | * | * | 71 | 79 | 89 | 69 | 56 | 73 |
| Peak Spectral Acc. (g) | | | | | | | | |
| 3-Sand | 1,94 | | 2,78 | | 3,51 | | 3,35 | |
| 3-TC30/15 | 1,70 | | 2,29 | | 1,83 | | 1,94 | |
| % Reduction | 12 | | 18 | | 48 | | 42 | |
| Period Lengthening Ratio | | | | | | | | |
| Ratio | 3,87 | | 1,73 | | 0,65 | | 1,06 | |

# 5. DISCUSSION

A series of shaking table tests were conducted with building models for examining the effect of rubber content in Gravel Rubber Mixture, the thickness of GSI, earthquake motions with different earthquake characteristics and number of building story on the proposed GSI system. According to test experimental program, 2 unisolated cases and 12 isolated cases with one rubber type, four rubber content, two thickness of Gravel Rubber Mixture (GRM) and two different story building model were used.

In this part of the thesis, the parameters of the top floor acceleration, foundation acceleration, top floor drift ratio, first-floor drift ratio, top floor peak spectral acceleration, foundation peak spectral acceleration, top floor period lengthening ratio, foundation period lengthening ratio under the three different earthquakes, Kocaeli Earthquake Motion, El Centro Earthquake Motion, and Kobe Earthquake Motion, are discussed for the 14 cases that are shown in Table 5.1.

Table 5. 1. Considered Cases for Experimental Study

| Cases | | | | | |
|---|---|---|---|---|---|
| Case Number | Storeys | Type of GRM | Rubber | Thickness of GRM (cm) | Code |
| 1 | 5 | Sand | 0 | 0 | 5-Sand |
| 2 | 5 | Gravel | 0 | 10 | 5-TC0/10 |
| 3 | 5 | Gravel | 0 | 15 | 5-TC0/15 |
| 4 | 5 | Crumb | 30 | 10 | 5-TC30/10 |
| 5 | 5 | Crumb | 30 | 15 | 5-TC30/15 |
| 6 | 5 | Crumb | 20 | 15 | 5-TC20/15 |
| 7 | 5 | Crumb | 20 | 10 | 5-TC20/10 |
| 8 | 5 | Crumb | 10 | 15 | 5-TC10/15 |
| 9 | 5 | Crumb | 10 | 10 | 5-TC10/10 |
| 10 | 3 | Sand | 0 | 0 | 3-Sand |
| 11 | 3 | Gravel | 0 | 10 | 3-TC0/10 |
| 12 | 3 | Gravel | 0 | 15 | 3-TC0/15 |
| 13 | 3 | Crumb | 30 | 10 | 3-TC30/10 |
| 14 | 3 | Crumb | 30 | 15 | 3-TC30/15 |

## 5.1. Discussion of Isolated Cases under Different Earthquake Motions

In this section, the results of the isolated cases were compared with the results of unisolated cases. The effectiveness of using GSI material as Gravel and Gravel Rubber Mixtures has been discussed.

### 5.1.1. Case 2: Only Gravel with 10 cm Thickness (5-TC0/10) as GSI Material

The foundation of 5 story building model was surrounded with only gravel with 10 cm thickness for second case. According to unimproved case, the reduction percent of performance criteria is given in Table 5.1. When comparing Case1 and Case 2, 5-TC0/10 is more effective in reduction of floor drift ratios. Within the scope of the peak spectral acceleration, any improvements are not observed. Except foundation period lengthening under Kobe Earthquake Motion, there has been no change in terms of period lengthening. The percent reduction in performance indicator parameters of Case 2 compared to control model is given in Table 5.2.

Table 5.2. Percentage (%) Reduction Obtained from the Parametric Study of Case 2

| Comparison of the Case 2 with Case 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Performance Criteria | Ground Motions | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 15 | -4 | 12 | -4 | 8 | 12 |
| | Foundation Acceleration | 0 | 21 | 1 | -2 | 0 | -17 |
| | Peak Floor Drift Ratio | 39 | 36 | 75 | 81 | 71 | 72 |
| | First Floor Drift Ratio | 72 | 73 | 73 | 72 | 74 | 75 |
| | Peak Floor Peak Spectral Acceleration | -3,9 | | -8 | | -22 | |
| | Foundation Peak Spectral Acceleration | -3,9 | | -3 | | -2 | |

### 5.1.2. Case 3: Only Gravel with 15 cm Thickness (5-TC0/15) as GSI Material

The foundation of 5 story building model was surrounded with only gravel with 15 cm thickness for third case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.3. When comparing Case1 and Case 3, 5-TC0/15 is effective in reduction of performance criteria on floor drift ratios. Within the scope of the peak the spectral acceleration, any improvements are not observed. Except foundation peak period lengthening under Kobe Earthquake Motion, there has been no change in terms of period lengthening.

Table 5.3. Percentage (%) Reduction Obtained from the Parametric Study of Case 3

| Comparison of the Case 3 with Case 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Performance Criteria | Ground Motions | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 2 | -3 | 2 | 22 | 4 | 5 |
| | Foundation Acceleration | 0 | 15 | -5 | -9 | 0 | -13 |
| | Peak Floor Drift Ratio | 32 | 38 | 75 | 81 | 74 | 52 |
| | First Floor Drift Ratio | 66 | 69 | 73 | 72 | 74 | 75 |
| | Peak Floor Peak Spectral Acceleration | -6 | | -20 | | -29 | |
| | Foundation Peak Spectral Acceleration | -5 | | -8 | | -2 | |

### 5.1.3. Case 4: TC30 with 10 cm Thickness (5-TC 30/10) as GSI Material

5 story model foundation was surrounded with 70% gravel and 30% Tire Crumb with 10 cm thickness for fourth case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.4. When comparing Case1 and Case 4, 5-TC30/10 is effective in reduction of performance criteria on accelerations and floor drift ratios. Within the scope of the peak the spectral acceleration, improvements for top floor peak spectral acceleration are observed. Except top floor and foundation peak period lengthening under Kobe Earthquake Motion, there has been no change in terms of period lengthening.

Table 5.4. Percentage (%) Reduction Obtained from the Parametric Study of Case 4

| Comparison of the Case 4 with Case 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Performance Criteria** | **Ground Motions** | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 32 | 24 | 33 | 13 | 38 | 35 |
| | Foundation Acceleration | 8 | 24 | 7 | -10 | 2 | -29 |
| | Peak Floor Drift Ratio | 18 | 17 | 29 | 81 | 71 | 55 |
| | First Floor Drift Ratio | 69 | 65 | 75 | 71 | 76 | 79 |
| | Peak FloorPeak Spectral Acceleration | 23 | | 8 | | 14 | |
| | Foundation Peak Spectral Acceleration | -16 | | 3 | | -16 | |

### 5.1.4. Case 5: TC30 with 15 cm Thickness (5-TC 30/15) as GSI Material

5 story model foundation was surrounded with 70% gravel and 30% Tire Crumb with 15 cm thickness for fifth case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.5. When comparing Case1 and Case 5, 5-TC30/15 is effective in reduction of performance criteria on accelerations and floor drift ratios. Within the scope of the peak the spectral acceleration, improvements for top floor peak spectral acceleration are observed. Except top floor and foundation peak period lengthening under Kobe Earthquake Motion, there has been no change in terms of period lengthening.

Table 5.5. Percentage (%) Reduction Obtained from the Parametric Study of Case 5

| Comparison of the Case 5 with Case 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Performance Criteria | Ground Motions | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 36 | 32 | 37 | 22 | 40 | 38 |
| | Foundation Acceleration | -6 | 23 | 4 | -12 | 1 | -31 |
| | Peak Floor Drift Ratio | 80 | 40 | 16 | 36 | 70 | 54 |
| | First Floor Drift Ratio | 69 | 69 | 75 | 72 | 78 | 78 |
| | Peak FloorPeak Spectral Acceleration | 33 | | 11 | | 15 | |
| | Foundation Peak Spectral Acceleration | -29 | | 1 | | -21 | |

### 5.1.5. Case 6: TC 20 with 15 cm Thickness (5-TC 20/ 15) as GSI Material

5 story model foundation was surrounded with 80% gravel and 20% Tire Crumb with 15 cm thickness for sixth case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.6. When comparing Case1 and Case 6, 5-TC20/15 is effective in reduction of performance criteria on accelerations and floor drift ratios. Within the scope of the peak the spectral acceleration, improvements for top floor peak spectral acceleration are observed. Except top floor and foundation peak period lengthening under Kobe Earthquake Motion, there has been no change in terms of period lengthening.

Table 5.6. Percentage (%) Reduction Obtained from the Parametric Study of Case 6

| Comparison of the Case 6 with Case 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Performance Criteria | Ground Motions | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 15 | 19 | 40 | 17 | 32 | 38 |
| | Foundation Acceleration | -12 | 21 | 10 | -3 | 7 | -23 |
| | Peak Floor Drift Ratio | 24 | 25 | 36 | 31 | 76 | 62 |
| | First Floor Drift Ratio | 66 | 66 | 75 | 71 | 78 | 80 |
| | Peak FloorPeak Spectral Acceleration | 15 | | 18 | | -3 | |
| | Foundation Peak Spectral Acceleration | -7 | | 5 | | -10 | |

### 5.1.6. Case 7: TC 20 with 10 cm Thickness (5-TC 20/ 10) as GSI Material

5 story model foundation was surrounded with 80% gravel and 20% Tire Crumb with 10 cm thickness for seventh case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.7. When comparing Case1 and Case 7, 5-TC20/10 is effective in reduction of performance criteria on accelerations and floor drift ratios. Within the scope of the peak the spectral acceleration, improvements for top floor peak spectral acceleration are observed. Except top floor and foundation peak period lengthening under Kobe Earthquake Motion, there has been no change in terms of period lengthening.

Table 5.7. Percentage (%) Reduction Obtained from the Parametric Study of Case 7

| Comparison of the Case 7 with Case 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Performance Criteria** | **Ground Motions** | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 20 | 15 | 43 | 10 | 31 | 36 |
| | Foundation Acceleration | 7 | 23 | 18 | -4 | 15 | -24 |
| | Peak Floor Drift Ratio | 18 | 10 | 57 | 36 | 81 | 89 |
| | First Floor Drift Ratio | 72 | 65 | 77 | 70 | 79 | 80 |
| | Peak FloorPeak Spectral Acceleration | 13 | | 10 | | -19 | |
| | Foundation Peak Spectral Acceleration | -11 | | 1 | | -10 | |

### 5.1.7. Case 8: TC 10 with 15 cm Thickness (5-TC 10/ 15) as GSI Material

5 story model foundation was surrounded with 90% gravel and 10% Tire Crumb with 15 cm thickness for eighth case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.8. When comparing Case1 and Case 8, 5-TC10/15 is effective in reduction of performance criteria on accelerations and floor drift ratios. Within the scope of the peak the spectral acceleration, improvements for top floor peak spectral acceleration are observed. Except top floor and foundation peak period lengthening under Kobe Earthquake Motion, there has been no change in terms of period lengthening.

Table 5. 8. Percentage (%) Reduction Obtained from the Parametric Study of Case 8

| Comparison of the Case 8 with Case 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Performance Criteria | Ground Motions | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 9 | 9 | 42 | 5 | 26 | 31 |
| | Foundation Acceleration | 5 | 21 | 17 | -3 | 16 | 27 |
| | Peak Floor Drift Ratio | 29 | 26 | 87 | 60 | 83 | 75 |
| | First Floor Drift Ratio | 73 | 67 | 77 | 71 | 79 | 78 |
| | Peak FloorPeak Spectral Acceleration | 6 | | 10 | | -23 | |
| | Foundation Peak Spectral Acceleration | -20 | | 1 | | -9 | |

### 5.1.8. Case 9: TC10 with 10 cm Thickness (5-TC 10/ 10) as GSI Material

5 story model foundation was surrounded with 90% gravel and 10% Tire Crumb with 10 cm thickness for ninth case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.9. When comparing Case1 and Case 9, 5-TC10/10 is effective in reduction of performance criteria on accelerations and floor drift ratios. Within the scope of the peak the spectral acceleration, improvements for top floor peak spectral acceleration are observed. Except top floor and foundation peak period lengthening under Kobe Earthquake Motion, there has been no change in terms of period lengthening.

Table 5.9. Percentage (%) Reduction Obtained from the Parametric Study of Case 9

| Comparison of the Case 9 with Case 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Performance Criteria** | **Ground Motions** | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 7 | 6 | 34 | 3 | 20 | 24 |
| | Foundation Acceleration | 5 | 13 | 15 | -4 | 13 | 35 |
| | Peak Floor Drift Ratio | 45 | 60 | 99 | 82 | 82 | 71 |
| | First Floor Drift Ratio | 73 | 69 | 78 | 72 | 79 | 77 |
| | Peak FloorPeak Spectral Acceleration | 1 | | -11 | | -30 | |
| | Foundation Peak Spectral Acceleration | -14 | | -5 | | -12 | |

### 5.1.9. Case 11: Only Gravel with 10 cm Thickness (3-TC0/10) as GSI Material

The foundation of 3 story building model was surrounded with only gravel with 10 cm thickness for eleventh case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.10. When comparing Case10 and Case 11, 3-TC0/10 is effective in reduction of performance criteria on accelerations and floor drift ratios. Within the scope of the peak the spectral acceleration, improvements for top floor peak spectral acceleration are observed. Top floor and foundation peak period lengthening improved under Earthquake Motions.

Table 5.10. Percentage (%) Reduction Obtained from the Parametric Study of Case 11 Compared to Case 10

| Comparison of the Case 11 with Case 10 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Performance Criteria** | **Ground Motions** | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 27 | 13 | 15 | 12 | 21 | 12 |
| | Foundation Acceleration | 1 | -3 | 3 | 32 | -3 | 11 |
| | Peak Floor Drift Ratio | 90 | 83 | 65 | 80 | 58 | 76 |
| | First Floor Drift Ratio | 73 | 74 | 73 | 74 | 73 | 75 |
| | Peak FloorPeak Spectral Acceleration | 28 | | 9 | | 29 | |
| | Foundation Peak Spectral Acceleration | -26 | | 5 | | 8 | |

### 5.1.10. Case 12: Only Gravel with 15 cm Thickness (3-TC0/15) as GSI Material

The foundation of 3 story building model was surrounded with only gravel with 15 cm thickness for twelfth case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.11. When comparing Case10 and Case 12, 3-TC0/15 is effective in reduction of performance criteria on accelerations and floor drift ratios. Within the scope of the peak the spectral acceleration, improvements for foundation and top floor peak spectral acceleration are observed. Top floor and foundation peak period lengthening improved under all Earthquake Motions.

Table 5.11. Percentage (%) Reduction Obtained from the Parametric Study of Case 12 Compared to Case 10

| Comparison of the Case 12 with Case 10 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Performance Criteria | Ground Motions | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 24 | 17 | 15 | 19 | 25 | 4 |
| | Foundation Acceleration | 0 | -3 | 3 | 21 | 3 | 21 |
| | Peak Floor Drift Ratio | 80 | 77 | 45 | 78 | 57 | 72 |
| | First Floor Drift Ratio | 74 | 75 | 74 | 75 | 74 | 76 |
| | Peak FloorPeak Spectral Acceleration | 26 | | 12 | | 28 | |
| | Foundation Peak Spectral Acceleration | -37 | | 6 | | 16 | |

### 5.1.11. Case 13: TC 30 with 10 cm Thickness (3-TC 30/ 10) as GSI Material

The foundation of 3 story building model was surrounded with 70% gravel and 30% Tire Crumb with 10 cm thickness for thirteenth case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.12. When comparing Case10 and Case 13, 3-TC30/10 is effective in reduction of performance criteria on accelerations and floor drift ratios. Within the scope of the peak the spectral acceleration, improvements for foundation and top floor peak spectral acceleration are observed. Top floor and foundation peak period lengthening improved under El Centro and Kobe Earthquake Motions.

Table 5.12. Percentage (%) Reduction Obtained from the Parametric Study of Case 13 Compared to Case 10

| Comparison of the Case 13 with Case 10 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Performance Criteria | Ground Motions | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 43 | 26 | 47 | 51 | 44 | 16 |
| | Foundation Acceleration | 25 | 3 | -12 | 21 | -20 | 29 |
| | Peak Floor Drift Ratio | 43 | 41 | 67 | 70 | 53 | 72 |
| | First Floor Drift Ratio | 65 | 69 | 67 | 69 | 71 | 78 |
| | Peak FloorPeak Spectral Acceleration | 20 | | 38 | | 47 | |
| | Foundation Peak Spectral Acceleration | 72 | | 9 | | 15 | |

### 5.1.12. Case 14: TC30 with 15 cm Thickness (3-TC30/10) as GSI Material

The foundation of 3 story building model was surrounded with 70% gravel and 30% Tire Crumb with 15 cm thickness for fourteenth case. According to unimproved case, the reduction percent of performance criteria can be seen in Table 5.13. When comparing Case10 and Case 14, 3-TC30/15 is effective in reduction of performance criteria on accelerations and floor drift ratios. Within the scope of the peak the spectral acceleration, improvements for foundation and top floor peak spectral acceleration are observed. Top floor and foundation peak period lengthening improved under El Centro and Kobe Earthquake Motions.

Table 5.13. Percentage (%) Reduction Obtained from the Parametric Study of Case 14 Compared to Case 10

| Comparison of the Case 14 with Case 10 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Performance Criteria** | **Ground Motions** | | | | | |
| | | Kocaeli EQ | | El Centro EQ | | Kobe EQ | |
| | | RSM | Peak | RSM | Peak | RSM | Peak |
| Reduction (%) | Peak Floor Acceleration | 44 | 29 | 50 | 53 | 46 | 12 |
| | Foundation Acceleration | -28 | 3 | -14 | 19 | -23 | 24 |
| | Peak Floor Drift Ratio | 31 | 32 | 59 | 73 | 56 | 73 |
| | First Floor Drift Ratio | 64 | 65 | 66 | 69 | 71 | 79 |
| | Peak FloorPeak Spectral Acceleration | 22 | | 42 | | 42 | |
| | Foundation Peak Spectral Acceleration | 84 | | 6 | | 12 | |

## 5.2. Discussion on Effects of Rubber Content, GRM Thickness and Story Number

The effects of the proposed GSI system by using Gravel and GRM were investigated in this part according to Kocaeli, El Centro and Kobe Earthquake Motions. Inferences obtained from experimental results are given below.

### 5.2.1. Comparison of the cases under Kocaeli Earthquake Motion

In this section, the results of all cases examined under Kocaeli Earthquake Motion are gathered in Table 5.14. According to cases, these results were evaluated.

When comparing peak values, maximum percent reductions are 32% for top floor acceleration, 24% for foundation acceleration, 83% for top floor drift ratio and 75% for first floor drift ratio. Also, it was founded that the maximum percent reductions are 44% for top floor acceleration, 8% for foundation acceleration, 90% for top floor drift ratio and 74% for first floor drift ratio when considering RMS values.

It was not observed a straight relation between GRM Content and the effectivity of GSI system. Studies showed that improvement including 30% tire crumb is the most effective option for 5 story building model. However, another option including only gravel is more appropriate for 3 story building model.

The thickness of GRM is another important parameter on the GSI system. When considering 10 cm thickness, experiments showed that samples including 30% Tire Crumb is more suitable for 5 story buildings. Also, only gravel as GSI material is more beneficial for 3 story building model. The same behavior is valid for cases including 15 cm Gravel or GRM thickness.

When examining the usage of only gravel, results showed that generally Case-11 and Case 12 are better than Case 2 and Case 3 according to experimental results in Table 5.14. Thus, it can be comment like that only gravel is more beneficial for 3 story model than 5 story model. But this situation is vice-versa for GSI including tire crumb.

As a summary, the most improved case for 5 story building model is 5-TC30/15 under Kocaeli Earthquake Motion. In this case, reductions are up to 32% for top floor acceleration, 23% for foundation acceleration, 40% for top floor drift ratio, 69% for first floor drift ratio and 23% for top floor peak spectral acceleration. Also, 3-TC0/10 is seen as the most effective case among 3 story building models. In this method, reductions in 13% for top floor acceleration, 83% for top floor drift ratio, 74% for first floor drift ratio and 28% for top floor spectral peak acceleration are obtained.

Table 5. 14. Percentage (%) Reduction Obtained from the Parametric Study for all Cases under Kocaeli Earthquake Motion

| Kocaeli Earthquake Motion | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Performance Criteria** | **Case 1 & Case 2** | **Case 1 & Case 3** | **Case 1 & Case 4** | **Case 1 & Case 5** | **Case 1 & Case 6** | **Case 1 & Case 7** | **Case 1 & Case 8** | **Case 1 & Case 9** | **Case 10 & Case 11** | **Case 10 & Case 12** | **Case 10 & Case 13** | **Case 10 & Case 14** |
| | | Isolation Type | 5-TC0/10 | 5-TC0/15 | 5-TC30/10 | 5-TC30/15 | 5-TC20/15 | 5-TC20/10 | 5-TC10/15 | 5-TC10/10 | 3-TC0/10 | 3-TC0/15 | 3-TC30/10 | 3-TC30/15 |
| | | Thickness | 10 | 15 | 10 | 15 | 15 | 10 | 15 | 10 | 10 | 15 | 10 | 15 |
| | | Number of Story | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 3 | 3 | 3 | 3 |
| Reduction (%) | Peak | Top Floor Acceleration | -4 | -3 | 24 | 32 | 19 | 15 | 9 | 6 | 13 | 17 | 26 | 29 |
| | | Foundation Acceleration | 21 | 15 | 24 | 23 | 21 | 23 | 21 | 13 | -3 | -3 | 3 | 3 |
| | | Top Floor Drift Ratio | 36 | 38 | 17 | 40 | 25 | 10 | 26 | 60 | 83 | 77 | 41 | 32 |
| | | First Floor Drift Ratio | 73 | 69 | 65 | 69 | 66 | 65 | 67 | 69 | 74 | 75 | 69 | 65 |
| | RMS | Top Floor Acceleration | 15 | 2 | 32 | 36 | 15 | 20 | 9 | 7 | 27 | 24 | 43 | 44 |
| | | Foundation Acceleration | 0 | 0 | 8 | -6 | -12 | 7 | 5 | 5 | 1 | 0 | 25 | -28 |
| | | Top Floor Drift Ratio | 39 | 32 | 18 | 80 | -24 | 18 | 29 | 45 | 90 | 80 | 43 | 31 |
| | | First Floor Drift Ratio | 72 | 66 | 69 | 69 | 66 | 72 | 73 | 73 | 73 | 74 | 65 | 64 |
| | | Top FloorPeak Spectral Acceleration | -3,9 | -6 | 23 | 33 | 15 | 13 | 6 | 1 | 28 | 26 | 20 | 22 |
| | | Foundation Peak Spectral Acceleration | -3,9 | -5 | -16 | -29 | -7 | -11 | -20 | -14 | -26 | -37 | 72 | 84 |

### 5.2.2. Comparison of the cases under El Centro Earthquake Motion

In this section, the results of all cases under El Centro Earthquake Motion are given in Table 5.15. According to experimental results, all cases were evaluated.

When comparing peak values, maximum percent reductions are 52% for top floor acceleration, 32% for foundation acceleration, 82% for top floor drift ratio and 75% for first floor drift ratio. Also, it was founded that the maximum percent reductions are 50% for top floor acceleration, 18% for foundation acceleration, 99% for top floor drift ratio and 78% for first floor drift ratio when considering RMS values.

It was not observed a direct relation between GRM Content and the effectiveness of improvement method. Studies showed that improvement including 20% tire crumb is the most effective option for 5 story building model. However, another option including 30% tire crumb and 70% gravel is more appropriate for 3 story building model.

The thickness of GRM is another important parameter on the improvement of soil. When considering 10 cm thickness, experiments showed that samples including 30% Tire Crumb is more effective for 5 story and 3 story buildings. The method including 20% Tire crumb is more effective among cases including 15 cm Gravel or GRM thickness.

When examining the usage of only gravel, results showed that generally Case 11 and Case 12 are better than Case 2 and Case 3 according to Table 5.14. Thus, only gravel is more beneficial for 3 story model than 5 story model. Also, this situation is valid for samples including tire crumb.

As a summary, the most improved case among 5 story building model tests is 5-TC20/10 under El Centro Earthquake Motion. In this case, reductions are up to 10% for top floor acceleration, 36% for top floor drift ratio, 70% for first floor drift ratio and 10% for top floor peak spectral acceleration. Also, 3-TC30/15 is found as the most effective case among 3 story building models. In this method, reductions are 53% for top floor acceleration, 19% for foundation acceleration, 73% for top floor drift ratio, 69% for first floor drift ratio and 42% for top floor peak spectral acceleration.

Table 5.15. Reduction Obtained from the Parametric Study for all Cases under El Centro Earthquake Motion

| El Centro Earthquake Motion | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Performance Criteria** | **Case 1 & Case 2** | **Case 1 & Case 3** | **Case 1 & Case 4** | **Case 1 & Case 5** | **Case 1 & Case 6** | **Case 1 & Case 7** | **Case 1 & Case 8** | **Case 1 & Case 9** | **Case 10 & Case 11** | **Case 10 & Case 12** | **Case 10 & Case 13** | **Case 10 & Case 14** |
| | | Isolation Type | 5-TC0/10 | 5-TC0/15 | 5-TC30/10 | 5-TC30/15 | 5-TC20/15 | 5-TC20/10 | 5-TC10/15 | 5-TC10/10 | 3-TC0/10 | 3-TC0/15 | 3-TC30/10 | 3-TC30/15 |
| | | Thickness | 10 | 15 | 10 | 15 | 15 | 10 | 15 | 10 | 10 | 15 | 10 | 15 |
| | | Number of Story | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 3 | 3 | 3 | 3 |
| Reduction (%) | Peak | Top Floor Acceleration | -4 | -22 | 13 | 22 | 17 | 10 | 5 | 3 | 12 | 19 | 51 | 53 |
| | | Foundation Acceleration | -2 | -9 | -10 | -12 | -3 | -4 | -3 | -4 | 32 | 21 | 21 | 19 |
| | | Top Floor Drift Ratio | 81 | 81 | 81 | 36 | 31 | 36 | 60 | 82 | 80 | 78 | 70 | 73 |
| | | First Floor Drift Ratio | 72 | 72 | 71 | 72 | 71 | 70 | 71 | 72 | 74 | 75 | 69 | 69 |
| | RMS | Top Floor Acceleration | 12 | 2 | 33 | 37 | 40 | 43 | 42 | 34 | 15 | 15 | 47 | 50 |
| | | Foundation Acceleration | 1 | -5 | 7 | 4 | 10 | 18 | 17 | 15 | 3 | 3 | -12 | -14 |
| | | Top Floor Drift Ratio | 75 | 75 | 29 | 16 | 36 | 57 | 87 | 99 | 65 | 45 | 67 | -29 |
| | | First Floor Drift Ratio | 73 | 73 | 75 | 75 | 75 | 77 | 77 | 78 | 73 | 74 | 67 | 66 |
| | | Top FloorPeak Spectral Acceleration | -8 | -20 | 8 | 11 | 18 | 10 | 10 | -11 | 9 | 12 | 38 | 42 |
| | | Foundation Peak Spectral Acceleration | -3 | -8 | 3 | 1 | 5 | 1 | 1 | -5 | 5 | 6 | 9 | 6 |

### 5.2.3. Comparison of the cases under Kobe Earthquake Motion

In this section, the results of all cases examined under Kobe Earthquake Motion are gathered in Table 5.15. According to cases, these results were evaluated.

When comparing peak values, maximum percent reductions are 38% for top floor acceleration, 29% for foundation acceleration, 89% for top floor drift ratio and 80% for first floor drift ratio. The maximum percent reductions are obtained as 46% for top floor acceleration, 16% for foundation acceleration, 83% for top floor drift ratio and 79% for first floor drift ratio when considering RMS values.

It was not found a straight relation between GRM content and the effectiveness of improvement method. Studies showed that case with 30% tire crumb addition is the most effective option for 5 story building model. However, another case including only gravel is more appropriate for 3 story building model.

The thickness of GRM is another important parameter on the improvement of soil. When considering 10 cm thickness, experiments showed that cases including 30% Tire Crumb is more suitable for 5 story buildings. Also, cases including only gravel are more beneficial for 3 story building model. The same behavior is valid for cases including 15 cm Gravel or GRM thickness.

When examining the usage of only gravel, results showed that generally Case 11 and Case 12 are better than Case 2 and Case 3 in Table 5.15. Thus, it can be comment like that only gravel is more beneficial for 3 story model than 5 story model. Also, this situation is valid for cases including tire crumb.

As a summary, the most improved case that is among 5 story building model test is 5-TC30/15 under Kobe Earthquake Motion. In this case, reductions are up to 38% for top floor acceleration, -31% for foundation acceleration, 54% for top floor drift ratio, 78% for first floor drift ratio and 15% for top floor peak spectral acceleration. Also, it can be selected 3-TC30/10 as the most effective case that is among 3 story building models. In this method, reductions are 16% for top floor acceleration, 29% for foundation acceleration, 72% for top floor drift ratio, 78% for first floor drift ratio and 47% for top floor peak spectral acceleration.

Table 5. 16. Reduction Obtained from the Parametric Study for all Cases under Kobe Earthquake Motion

| Kobe Earthquake Motion | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Performance Criteria** | **Case 1 & Case 2** | **Case 1 & Case 3** | **Case 1 & Case 4** | **Case 1 & Case 5** | **Case 1 & Case 6** | **Case 1 & Case 7** | **Case 1 & Case 8** | **Case 1 & Case 9** | **Case 10 & Case 11** | **Case 10 & Case 12** | **Case 10 & Case 13** | **Case 10 & Case 14** |
| | | Isolation Type | 5-TC0/10 | 5-TC0/15 | 5-TC30/10 | 5-TC30/15 | 5-TC20/15 | 5-TC20/10 | 5-TC10/15 | 5-TC10/10 | 3-TC0/10 | 3-TC0/15 | 3-TC30/10 | 3-TC30/15 |
| | | Thickness | 10 | 15 | 10 | 15 | 15 | 10 | 15 | 10 | 10 | 15 | 10 | 15 |
| | | Number of Story | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 3 | 3 | 3 | 3 |
| Reduction (%) | Peak | Top Floor Acceleration | 12 | 5 | 35 | 38 | 38 | 36 | 31 | 24 | 12 | 4 | 16 | 12 |
| | | Foundation Acceleration | -17 | -13 | -29 | -31 | -23 | -24 | 26 | 35 | 11 | 21 | 29 | 24 |
| | | Top Floor Drift Ratio | 72 | 52 | 55 | 54 | 62 | 89 | 75 | 71 | 76 | 72 | 72 | 73 |
| | | First Floor Drift Ratio | 75 | 75 | 79 | 78 | 80 | 80 | 78 | 77 | 75 | 76 | 78 | 79 |
| | RMS | Top Floor Acceleration | 8 | 4 | 38 | 40 | 32 | 31 | 26 | 20 | 21 | 25 | 44 | 46 |
| | | Foundation Acceleration | 0 | 0 | 2 | 1 | 7 | 15 | 16 | 13 | -3 | 3 | -20 | -23 |
| | | Top Floor Drift Ratio | 71 | 74 | 71 | 70 | 76 | 81 | 83 | 82 | 58 | 57 | 53 | 56 |
| | | First Floor Drift Ratio | 74 | 74 | 76 | 78 | 78 | 79 | 79 | 79 | 73 | 74 | 71 | 71 |
| | | Top Floor Peak Spectral Acceleration | -22 | -29 | 14 | 15 | -3 | -19 | -23 | -30 | 29 | 28 | 47 | 42 |
| | | Foundation Peak Spectral Acceleration | -2 | -2 | -16 | -21 | -10 | -10 | -9 | -12 | 8 | 16 | 15 | 12 |

## 5.3. Seismic Demand

In this section, the situation of seismic demand reduction and period shifting for the selected cases under different earthquake motions was investigated.

### 5.3.1. Case1 and Case-5 (5-TC30/15) Top Floor Response Spectrum under Kocaeli Earthquake Motion.

When comparing unisolated case with isolated case including 70% Gravel and 30% Rubber having 15 cm thickness for 5 story model, decrease in spectral acceleration, and period shifting on the building model under Kocaeli earthquake motion was obtained.

This condition causes decreasing in seismic demand and a lengthening of the fundamental period. Thus, the behavior of the building model becomes more resistant to earthquake motions. The reduction of spectral acceleration under the scaled Kocaeli earthquake motion is 25% and the corresponding period lengthening ratio were calculated as 1,04%. (Figure 5.1)

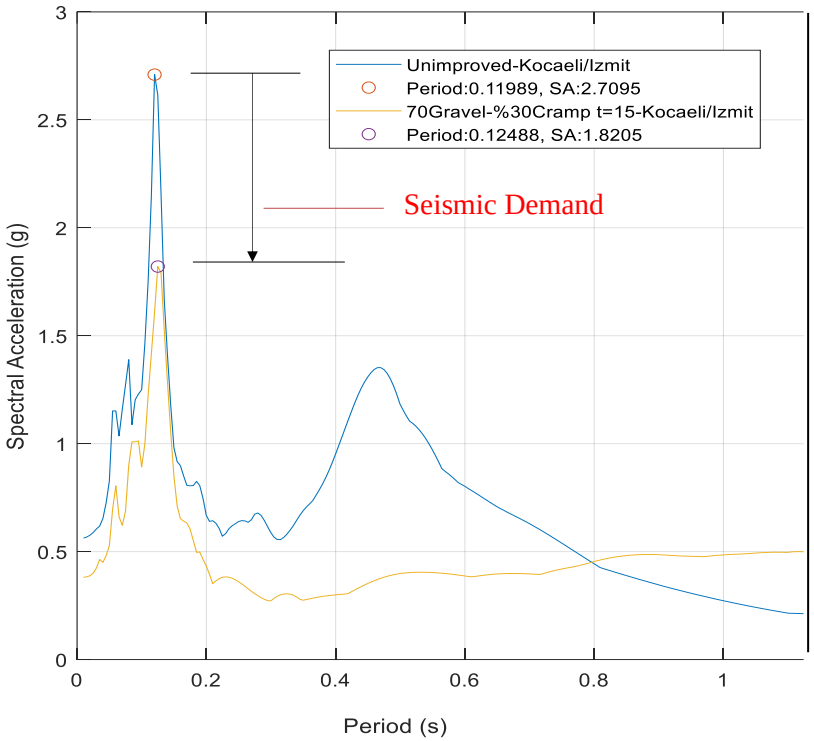



Figure 5.1. Effect of GSI on the Seismic Demand of the 5 Story Building Model under Kocaeli Earthquake Motion.

### 5.3.2. Case 1 and Case 5 (5-TC30/15) Top Floor Response Spectrum under El-Centro Earthquake Motion

When comparing the unisolated case with the isolated case including 70% Gravel and 30% Rubber and having 15 cm thickness for 5 story model, decrease in spectral acceleration, and an increasing of the period on the building model under El Centro earthquake motion was obtained. This condition causes decreasing in seismic demand and a lengthening of the period. Thus, the behavior of the building model becomes more resistant to earthquake motions. The reduction of spectral acceleration under the scaled El Centro earthquake motion is 11% and the corresponding period lengthening ratio were calculated as 1.04%. (Figure 5.2)

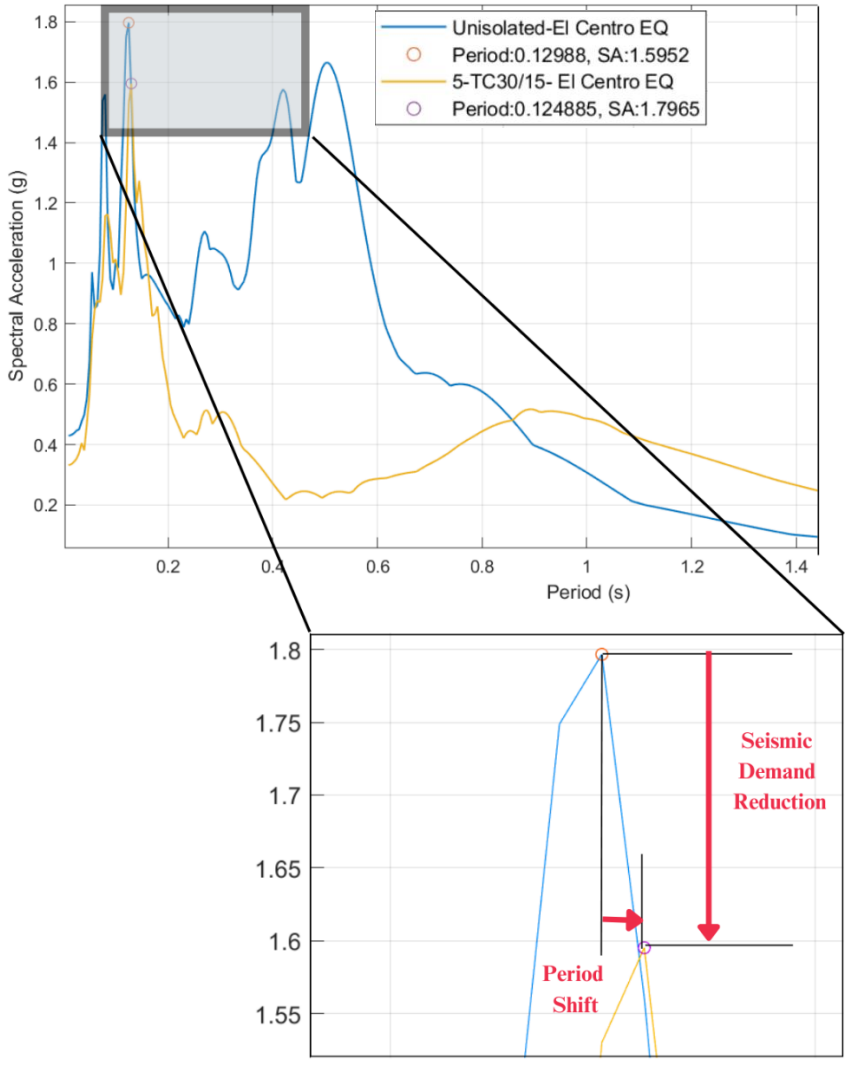



Figure 5.2. Effect of GSI on the Seismic Demand of the Building Model under El Centro Earthquake Motion

### 5.3.3. Case 1 and Case 5 (5-TC30/15) Top Floor Response Spectrum under Kobe Earthquake Motion

When comparing the unisolated case with the improved case including 70% Gravel and 30% Rubber and having 15 cm thickness for 5 story model, it was observed decrease in spectral acceleration, and an lengthening of the story period on the building model foundation under Kobe earthquake motion. This condition causes decreasing in seismic demand and a lengthening of the system period. Thus, the behavior of the building model motion becomes more resistant to earthquake motions. The reduction of spectral acceleration under the scaled Kobe earthquake motion is 15% and the corresponding period lengthening ratio were calculated as 1.16%. (Figure 5.3)

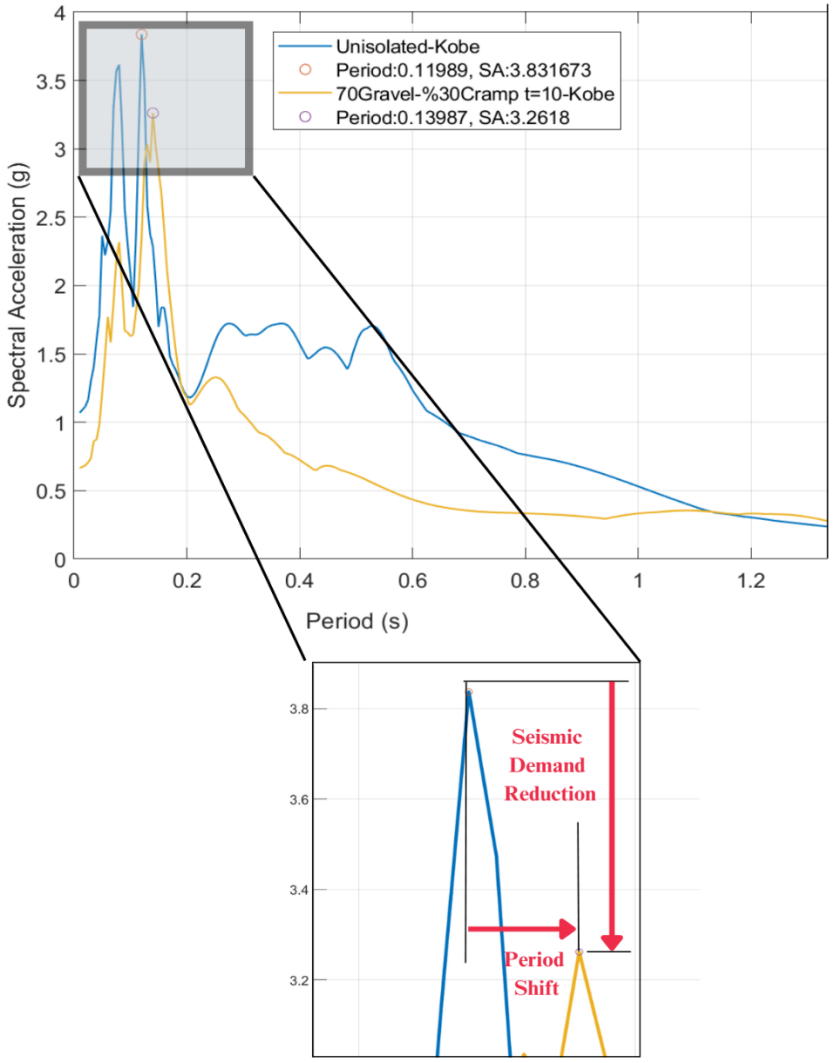



Figure 5.3. Effect of GSI on the Seismic Demand of the Building Model under Kobe Earthquake Motion

# 6. CONCLUSIONS

In this thesis, a new geotechnical seismic isolation material as Gravel Rubber Mixtures (GRM) was proposed. The effectiveness of GRM on the seismic performance of low and medium rise buildings was investigated by shaking table experiments. In this system, the GRM surrounds the foundations of the buildings at "t" thickness. Comparative studies were carried out to determine the effects of the main factors such as the gravel contents, the thickness of the GRM layer and the number of stories on the seismic performance of the building models. Shake table tests were carried out under different earthquake excitations for two control models simulating low and medium-rise buildings without geotechnical seismic isolation. For this purpose, low and medium-rise buildings were simulated using 1/10 scaled 3 and 5 story building models. The effectiveness of the GSI material was obtained by comparing the isolated models with the control models. The main results of this study are summarized as follows:

- Although there are some differences in effects of Gravel and GRM as GSI material on seismic performance of 3 and 5 story building models, the effects of Gravel and GRM are generally effective. Therefore, the proposed GSI system may be suitable for both 3 and 5 story buildings.
- From all comparative test results, reductions in top floor accelerations up to 53%, foundation accelerations up to 32%, first floor drifts up to 80%, and top floor drifts up to 99% were obtained. It shows that seismic response of the building models under Kocaeli, El Centro and Kobe earthquake motions are improved.
- According to the result of this thesis, it was found that the most effective case is TC 30/15 which has 30% rubber content with 15 cm thickness of GSI material for 5 story building model and cases (TC0/10 and TC0/15) including only gravel have seismic improvement effect on 3 story building as well. While comparing these results with previous studies on GSI, it was seen that there is consistency among the GSI systems.
- One of the key parameters affecting the performance of the GSI system is found as the thickness of the GSI layer. When considering the most efficient cases having 10 cm and 15 cm thickness of GSI, it was obtained that the

performance of 15 cm thickness of GSI is close to 10 cm thickness of GSI. Results obtained in this thesis showed that the thickness parameter doesn't play a vital role in the effectiveness of GRM.

- In this study, it was obtained that the use of GRM as a GSI material causes decreasing in the seismic demand of building model up to 25% and a lengthening of the period by up to 3,87%. It shows that seismic response of the model structures under earthquake motions are improved.
- According to all the performed test results, it was found that surrounding building foundations with only Gravel or GRM as GSI materials increases seismic performance of building model. Also, the most effective case is TC30/15 including 30% rubber content with the thickness of 15 cm GSI material. It may cause the decrease in earthquake hazards by improving seismic performance of the building model.

This thesis is preliminary study for evaluation of Gravel and GRM effectivity as geotechnical isolation material for low and medium rise buildings by performing a series of shaking table tests and the first study in the literature. In studies that will be conducted in the future, the effect of Gravel and GRM may be searched by using different parameters.

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