

Article

Development of Geotechnical Seismic Isolation System in the Form of Vertical Barriers: Effectiveness and Perspective

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Abstract: This paper discusses the concept of geotechnical seismic isolation (GSI) systems, characterized by new principles of action, to reduce seismic loads on buildings. The advantages and disadvantages of GSIs and their environmental and economic reliability are analyzed. The aim of the study is to develop a geotechnical seismic isolation system in the form of vertical barriers, using a rubber–soil mixture (RSM). The novelty of the work lies in the definition of effective structural and technical solutions of vertical seismic barriers made of RSM, characterized by reliability in providing seismic isolation. The ground and superstructure interactions are modeled in PLAXIS 2D software from 2021, using the finite element method, using the accelerogram of the Kobe and Northridge earthquakes. The results confirm the positive impact of using an RSM as an effective GSI geometrical. The results show that the GSI system using an RSM reduces horizontal accelerations by 60%. Significant acceleration reductions of 40–60% are also observed when the thickness and depth of GSI seismic barriers are increased. The results of the study contribute to the substantiation of methodology and scientific and technical efficiency of geotechnical seismic isolation as an economically favorable design alternative to the traditional seismic isolation system.



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1. Introduction

The recent earthquake in Gaziantep and Sehitkamil, Turkey, in 2023 reminded us of the destructive power of earthquakes. Underground tremors of magnitude 7.8 killed more than 50,000 people and destroyed more than 160,000 buildings. According to the United Nations, 1.5 million people are homeless.

According to the available data on damage caused by earthquakes in the past, almost all of the damage to people is caused by building collapse. The main cause of human casualties is the collapse of multistory residential buildings. Such a disaster has made us look back and reassess the earthquake resistance and safety of existing buildings, which are characterized by high vulnerability in terms of their resilience.

The Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) highlights the importance of scientific research to develop innovative approaches, including the development of seismic isolation systems and damping devices, in addressing the global challenges caused by earthquakes [1,2].

Nowadays, high-tech typical support isolators such as rubber bearings, pendulum friction bearings, elastomeric bearings, lead–rubber bearings, and dampers are often used in civil engineering practice. Traditional base isolation systems used in construction practice, such as elastomeric, lead–rubber [3] and single concave bearings [4], sliding elements

and friction-pendulum systems [5], and sliding isolation devices [6], are quite expensive economically and are technically difficult to install, and also technologically difficult for the seismic isolation of objects of existing buildings. However, the alternative methods and means of seismic protection and seismic isolation, which reduce the intensity of seismic loads, developed to date, do not find their application due to the complexity of structural solutions and technology of their devices.

Modern earthquake-resistant buildings equipped with various active seismic protection systems provide a high level of seismic resistance, allowing buildings and structures to withstand earthquakes of designed intensity in many cases. At the same time, it is not uncommon for critical long objects with seismic protection systems to be destroyed, especially those exposed to Rayleigh surface waves, the main component of the seismic wave. This forces the development of alternative seismic protection methods that reduce the effects of exposure in the built-up areas. Such methods include the seismic barrier method. The basic idea of seismic barriers is to protect the area occupied by a building or group of buildings from seismic waves. The need for protection against surface seismic waves is confirmed by numerous examples of foundation structures failing due to significant bending vibrations associated with the passage of Rayleigh waves. Depending on the nature of seismic waves most likely to occur in a particular region, different types of seismic barriers can be proposed to increase the earthquake resistance of buildings and structures or a group of buildings and structures from collapse and even damage.

Therefore, the development of new technologies of seismic protection and seismic isolation, characterized by new principles of action and better modified properties of geomaterial, to reduce inertial seismic loads on buildings and structures, is a task of paramount importance.

Discussions regarding a simple and reliable seismic isolation system concept, known as a geotechnical seismic isolation (GSI) system, have attracted attention in recent years as a cost-effective design alternative to the traditional base isolation system [7,8]. The term GSI was originally introduced by Tsang [9] in the last decade to refer to a unique layer under the building foundation designed to dissipate seismic energy. Seismic isolation in the GSI system is achieved by using engineered soils with high damping properties and low shear modulus surrounding the building foundation at a limited depth [10–14]. The main advantage of this method is that partial energy dissipation occurs within the soil itself before the seismic wave reaches the foundation and superstructure [15,16]. Recently, research on GSI methods has been gradually extended to seismic protection of bridge structures and pile-supported bridge piers [17,18]. The GSI system placed vertically between the retaining wall and the backfill soil as a seismic buffer system acts as a protective layer with high flexibility and energy absorption capacity, and prevents soil liquefaction [19,20].

The basic idea of a GSI is to improve the foundation soil in such a way that the seismic energy is partially dissipated within the GSI before being transmitted to the structure [21–24]. GSIs made of geofoam, gravel–sand mixtures, and other materials have been proposed to evaluate the seismic energy dissipation efficiency [25–29]. Also, GSI devices from single or multiple trenches of rigid materials have been considered [30,31]. Among other materials proposed to improve subgrade soils, gravel–rubber mixtures (GRMs) have attracted considerable research attention due to their good static and dynamic properties: low specific gravity, wide range of elastic properties, low shear modulus, and high damping (similar) [32–34]. In addition, their use has immediate benefits as an end-of-life recycling (ELT) of tires, the disposal of which has become a serious ecological problem worldwide in recent years. The use of shredded tires has great potential in geotechnical engineering programs, where rubber–soil mixtures (RSMs) are often used in backfilling excavation slots, reinforcing road embankment soils, and retaining walls. The geotechnical application of recycled rubber can lead to solving the environmental and economic benefits of this technology [35].

Laboratory and field studies of the environmental aspects of this technology have shown that concentrations of metallic components and organic matter, leaching limits, and

extraction toxicity are well below standards in US protocols. This further confirms that recycled tire scrap is not a hazardous secondary raw material [9].

According to the researchers, the effectiveness of GSI systems depends on many factors. GSI system designs must take into account the geological conditions of the site and the effects of geodynamic processes such as seismic faults. The results of the study show the significant influence of the presence of a fault under the building on the failure of the building structure [36,37]. Also, special attention is paid to the frequency characteristics of the building and the soil mass, where the resonance effect can significantly affect the building behavior under strong surface vibrations [38]. This question requires detailed study when creating GSI systems of different shapes from geomaterials.

This paper presents the effectiveness of vertical seismic barriers consisting of rubber-soil mixture (RSM) on the seismic response of reinforced concrete moment-resisting frames, which are considered typical for frame buildings, designed according to Kazakhstan seismic standards similar to Euro Code 8 [39]. The frame structures and underlying soil profiles are modeled as a single system with direct consideration of soil-structure interaction phenomena. As for the mixture of rubber and soil, the rubber content is 30% by weight and its mechanical properties were determined by experiments carried out at the Laboratory of Soil Dynamics and Geotechnical Seismic Engineering of Aristotle University of Thessaloniki [40,41]. Dynamic analyses of soil-structure systems are performed considering the variation of RSM layer thickness, inlet traffic characteristics, and building height. The effects of RSM layers were investigated in terms of foundation-level acceleration, base shear force, maximum inter-story drift, foundation deformation, and soil stress distribution beneath the foundation of the structure. Analyses of theoretical and experimental studies show that the GSI system has the potential to significantly reduce seismic hazard.

The aim of this study is to develop a geotechnical seismic isolation system in the form of vertical barriers, with different geometrical characteristics (thickness, height, location from the building), using RSM. The novelty of the work consists of determination of effective constructive and technical solutions of vertical seismic barriers from RSMs, which are characterized by reliability in providing seismic isolation of construction objects. In addition, the seismic barriers are located outside the buildings, which will not cause damage to the protected facility. Also, locating the barrier below the Earth's surface, in the groundmass, will not incur operational maintenance costs. Only after strong displacements of the massif, after strong earthquakes, in case of geometrical disturbances, is an additional row of vertical barrier built. The use of RSMs is considered by experts to provide durability, termite resistance, fire safety, and non-gassing [9].

The proposed system of geotechnical seismic isolation also allows us to control the behavior of structures of existing buildings under seismic effects and to minimize the risk of their destruction. Devices of this system are aimed at solving practical problems oriented on existing construction technologies with the use of modified soil-composite materials.

The developed methodology of design and creation of geotechnical seismic isolation systems, and the results of computational and experimental modeling of seismic isolation systems efficiency assessment will become a research, analytical, and design basis for the development of new ways to ensure the seismic resistance of construction objects.

The results of a feasibility study of organizational and technological reliability of the system device in construction and operational periods will allow the application of this system in increasing the preservation and protection of architectural monuments.

Based on the numerical modeling carried out, screen-barrier shapes, their geometric parameters, dimensions, and material and location of the damping screen-barrier relative to the building will be developed.

2. Materials and Methods

In this paper, a nonlinear dynamic transient analysis is performed on a two-dimensional finite element model of the soil-foundation-building system in the PLAXIS software package to determine the optimum fill size of vertical barriers using RSMs. The PLAXIS program

is a specialized two-dimensional computer program based on the finite element method, which is used to calculate the deformation and stability of various geotechnical objects. The input of geometry of soil layers, structure, loads, and boundary conditions is based on CAD drawing procedures that provide detailed and accurate modeling of the real situation.

The reinforced concrete frame of the buildings is modeled in accordance with Code of Rules of the Republic of Kazakhstan Euro Norms 1992 (CR RK EN) [42]. Static loads on the design scheme were taken according to CR RK 1991 (CR RK—Code of Rules of the Republic of Kazakhstan) [43].

The parameters of the building frame and engineering–geological conditions of the site on PLAXIS are presented in Figure 1.

Property	Unit	Value	Property	Unit	Value
Material set			Stiffness		
Identification		Стена 0.2m	E'	kN/m ²	60.00E3
Comments			ν' (nu)		0.3000
Colour		RGB 0, 0, 255	Alternatives		
Material type		Elastic	G	kN/m ²	23.08E3
Properties			E_{oed}	kN/m ²	80.77E3
Isotropic		☒	Strength		
EA_1	kN/m	6.120E6	c'_{ref}	kN/m ²	45.00
EA_2	kN/m	6.120E6	ϕ' (phi)	°	31.00
EI	kN m ² /m	20.40E3	ψ (psi)	°	0.000
d	m	0.2000	Velocities		
w	kN/m/m	25.00	V_s	m/s	98.78
ν (nu)		0.2500	V_p	m/s	184.8

(a)

(b)

Figure 1. Modeling parameters for input to PLAXIS: (a) building frame parameters; (b) site geotechnical conditions parameters.

When performing finite element calculations, the boundary conditions are assigned. Seismic waves that are generated within and outside the design scheme can propagate over long distances, so the boundaries of the design scheme must correctly reflect the real conditions that need to be modeled [44].

The soil array is modeled in two dimensions with two degrees of freedom using a three-node plane deformation formulation of a bilinear isoparametric triangular element [45]. Regarding the dimensions of the soil profiles, the depth is assumed to be 30 m and the width differs for the three frame models to allow for free-field conditions and “quasi-transparency” at the profile boundaries. In this case, the width of the ground profile is defined as 120 for a high-rise building, respectively. The grid geometry is based on the concept of allowing transverse wave propagation at or below a certain frequency, which will place the optimum number within the length of the selected transverse wave. Figure 2 shows the GSI calculation diagram for a nine-story building, space frame system.

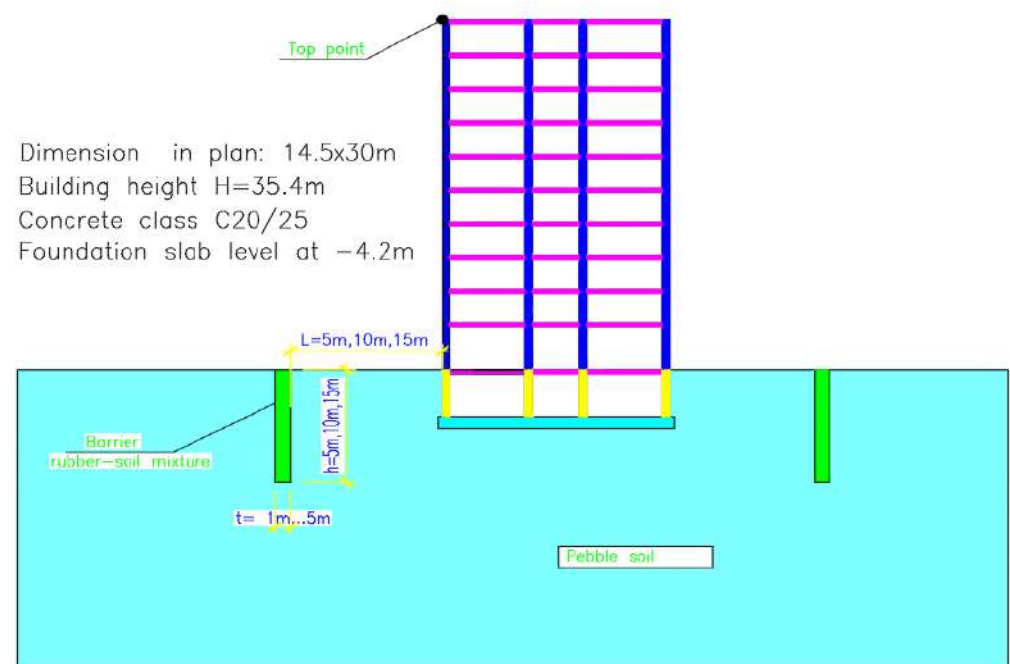


Figure 2. Calculation scheme of the GSI system.

The calculation scheme of the GSI system is modeled by finite element method for a depth of 30 m and a width of 120 m. The soil array is partitioned into $5 \times 5\text{ m}$ finite element meshes in a triangular shape. A finer mesh improves accuracy but takes more time to calculate (Figure 3).

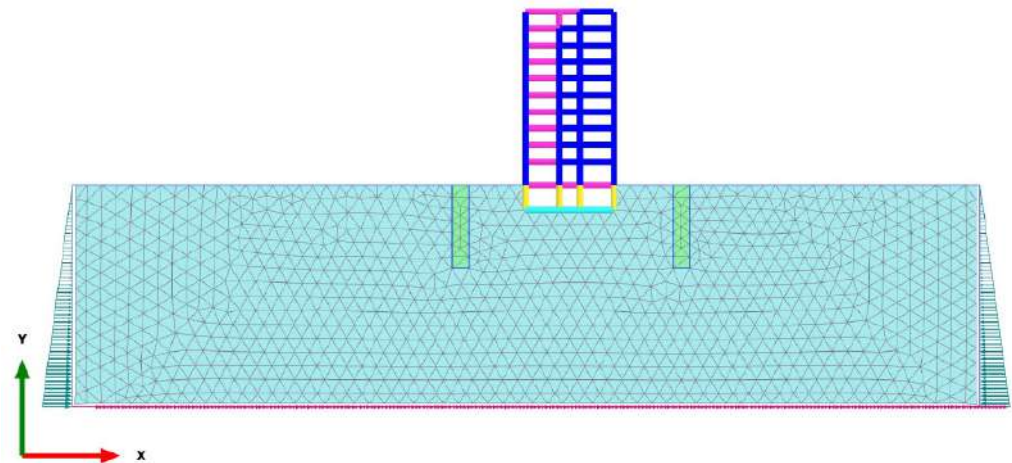


Figure 3. Calculation scheme of the GSI system in PLAXIS.

Extensive research has been carried out to investigate the fundamental engineering properties of RSMs such as shear strength, elastic modulus, and Poisson's ratio (for example, Edil and Bosscher, 1994). The density values of sand and RSM with 75% bulk rubber (abbreviated as RSM 75) selected for finite element modeling are 17.4 and 9.5 kN/m^3 , respectively. Considering the fact that Poisson's ratio has little effect on the results, different values for different materials were considered irrelevant and a Poisson's ratio value of 0.3 was chosen. These parameters [9] were used in order to compare and contrast the results of the study.

The dynamic properties of RSM have been investigated by [37]. The maximum values of shear modulus ($G_{\max}$) (at very small shear strains (10^{-5} – $10^{-3}\%$)) adopted for sand and RSM 75 are 222 and 7.5 MPa , respectively. The strain-dependent $G/G_{\max}$ ratio (shear

modulus degradation) and damping ratio are shown in Figure 4. As can be seen from the graph of dependence of shear modulus on the amplitude of shear strains (Figure 4a), sand with rubber addition shows a decrease in shear modulus at small strains. Also, the damping curve (Figure 4b) shows the improvement of damping index with increasing percentage of rubber content. A large uncertainty in estimating the dynamic properties of soil materials is unavoidable, so a tolerance of about plus or minus 10% is allowed when modeling the degradation of shear modulus and attenuation [9].

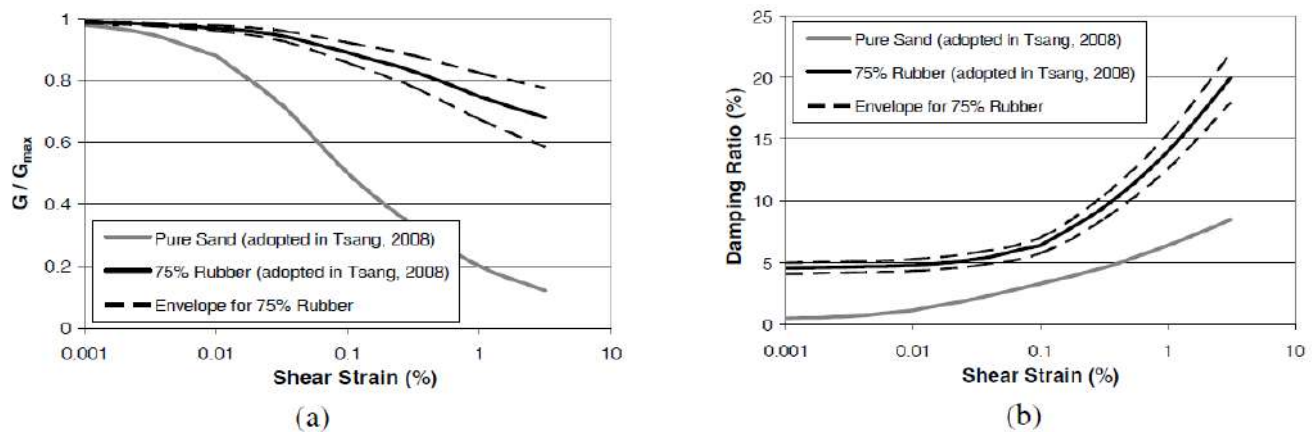


Figure 4. Shear modulus curves (a) and damping curves (taken from [9]) as a function of shear strain amplitude (b).

The dynamic properties of soils are well known for their significant dependence on shear deformation of soils. The PLAXIS computer program used in this study uses a commonly used equivalent linear method in which the nonlinear characteristics of soils can be captured using two strain-compatible material parameters, namely, secant shear modulus G and damping coefficient ξ .

We take RSM as the reference material, which is shown in Table 1.

Table 1. Physical and mechanical properties of RSM and soil.

Name	Specific Weight	Modulus of Elasticity	Poisson
RSM 75%	19.5 kN/m ³	7.5 MPA	0.3
Pebble soil	20.0 kN/m ³	60 MPA	0.3

The soil profile and foundation are modeled by solid finite elements, and the oscillator is modeled as a linear-elastic beam element with a concentrated mass at the top. A damping factor of 5% is considered, and damping proportional to mass and stiffness is used. The input motion is applied at the base of the model in the form of time acceleration diagrams representing the moving rock.

In SSI systems, it is common for the sway component of structural motion to dominate the response when the rigid superstructure is standing on “normal ground” [46].

For the purpose of modeling earthquake strength, we use the parameters of the accelerograms of the destructive Kobe (Japan, 1994) and Northridge (California, 1995) earthquakes, presented in Table 2.

Table 2. Earthquake tremor data used in the parametric study.

Name	Kobe	Northridge
Date of the earthquake	17 January 1994	17 January 1995
Magnitude	6.9	6.7
Peak horizontal acceleration	2.0	3.0

3. Results and Discussions

For calculation, we use the accelerogram of the Kobe and Northridge earthquakes in amplitude–frequency parameters typical of destructive earthquakes (Figure 5). The accelerogram of the Northridge earthquake is characterized by several high-amplitude and high-frequency parameters.

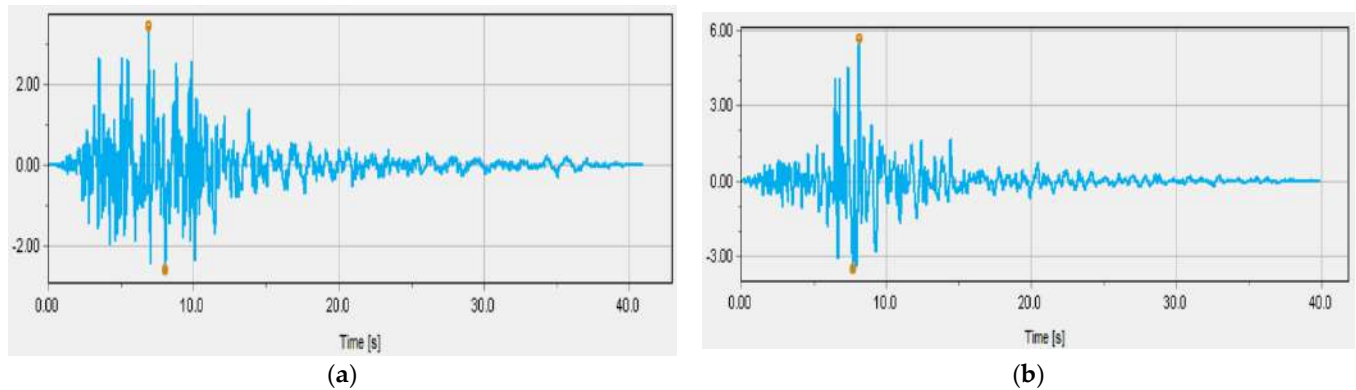


Figure 5. Earthquake accelerograms: (a) Kobe earthquake; (b) Northridge earthquake.

Each of these time diagrams is normalized relative to the maximum absolute acceleration of the control model, which used pebble soil as the base material.

In order to determine effective structural and technical solutions for vertical seismic barriers made of RSMs, computational and experimental modeling of the effect of the thickness, depth of the barrier, and its distance from the building on the dynamic behavior of buildings was carried out. The final results of the computational–experimental modeling are the indices of horizontal accelerations and the response spectrum to the upper points of the building.

3.1. Effect of Barrier Thickness

Comparison of the results of the response spectrum (Figure 6) of the building without a barrier and with the use of an RSM barrier shows the effect of the barrier on the horizontal accelerations at the roof level of the building. It was found that the values of RSM layer thicknesses from 1 to 3 m resulted in a percentage reduction in peak horizontal roof accelerations from 37 to 65%, respectively. The efficiency is probably due to the much larger amount of energy absorbed by the thicker barrier thickness.

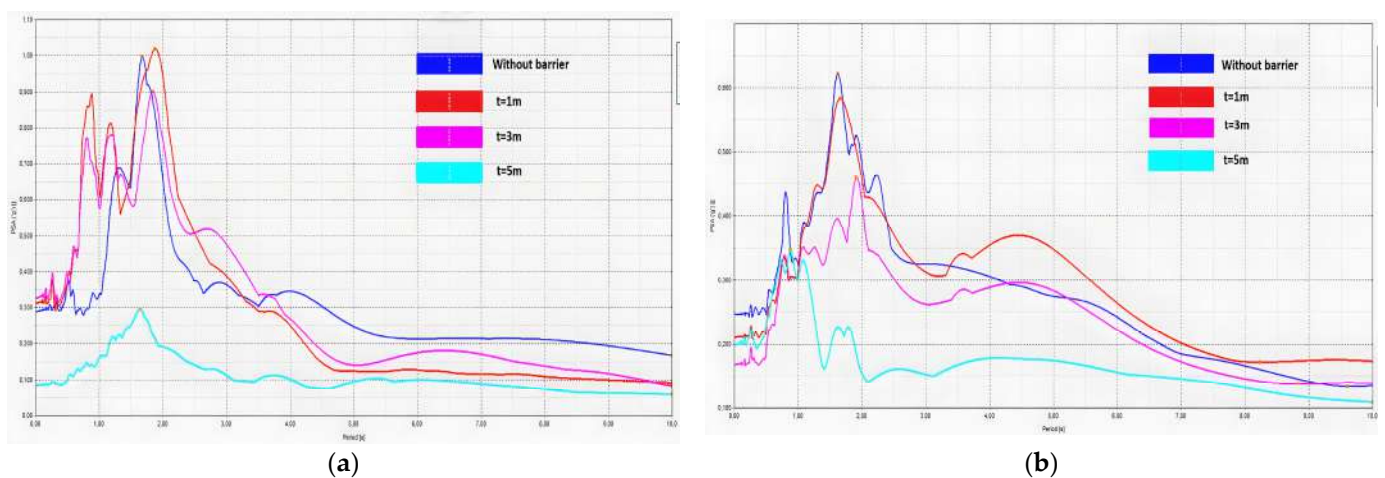


Figure 6. Horizontal acceleration response spectrum of the top point of the building without and with RSM barrier as a function of barrier thickness: (a) Kobe earthquake; (b) Northridge earthquake.

Experiments also found that as the thickness of the RSM layer increases from 3 to 5 m, the value of peak horizontal accelerations at the top point of the building decreases by up to 73%. This is probably due to the wavelength of the oscillation. According to experts, if the wavelength is larger than the barrier width, some of the wave energy passes through the barrier and the barrier efficiency decreases [47]. This effect is also due to wave energy dissipation.

As can be seen from Figure 6, the acceleration characteristics of the Kobe and Northridge earthquakes also affect the amplitude–frequency parameters of the accelerograms at the top of the building. The response spectrum of horizontal accelerations of the top point of the building according to the Kobe accelerogram (Figure 6a) has a large amplitude compared to the Northridge accelerogram, at the same time with rapid attenuation depending on the thickness of the barrier. The response spectrum from the Northridge accelerogram has a frequency character; apparently this is also related to the low-frequency parameters of this earthquake.

The results of horizontal accelerations of the top point of the building without barrier and with barriers of different thicknesses showed good parametric data for determining the derivation of barrier design parameters (Figure 7).

At a barrier thickness of 1 m (Figure 7a,b), the values of horizontal accelerations of the top point of the building without a barrier and with a barrier made of RSM are practically insignificant. While the acceleration for the building without barrier is 0.282 g and 0.241 g, the acceleration for the building with RSM barrier is 0.233 g and 0.251 g. The reduction in acceleration is 4–10%.

While a 3 m thick barrier (Figure 7c,d) reduces the acceleration of the top of the building to 0.51 g (Kobe) and 0.212 g (Northridge), a 5 m thick barrier (Figure 7e,f) reduces the acceleration of the top of the building to 0.050 g, which is a 60–70% reduction.

As can be seen from the graph of horizontal acceleration dynamics as a function of barrier thickness (Figure 8), the thickness parameters significantly affect the effectiveness of the geotechnical seismic isolation system. It is important to note that the results obtained were the most sensitive to the change in the thickness of the RSM, which is in agreement with the results obtained earlier in [48–50].

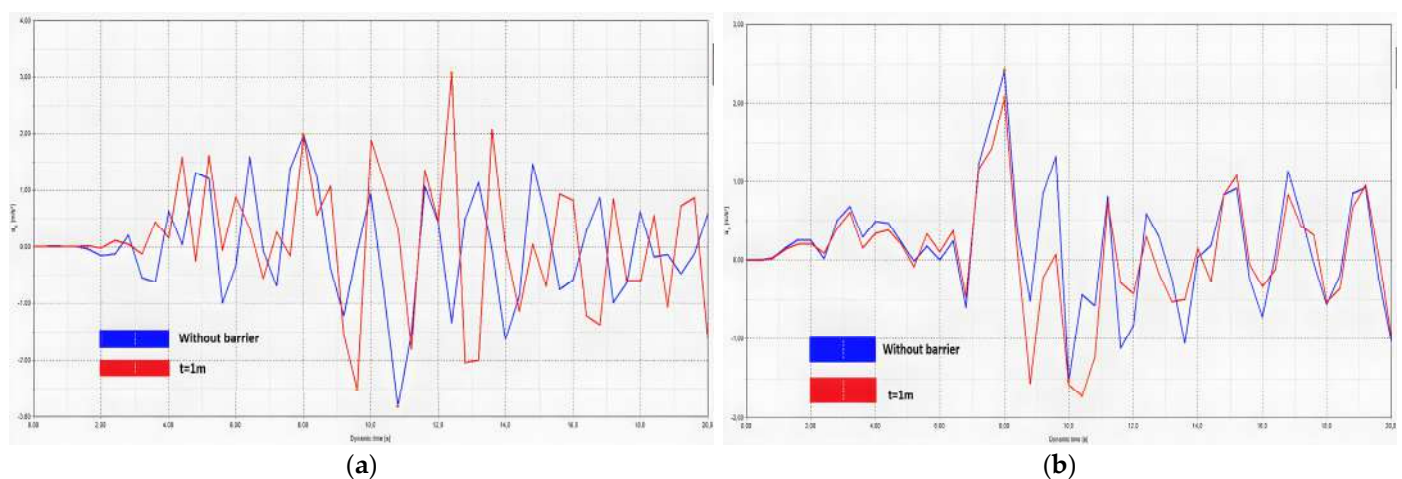


Figure 7. Cont.

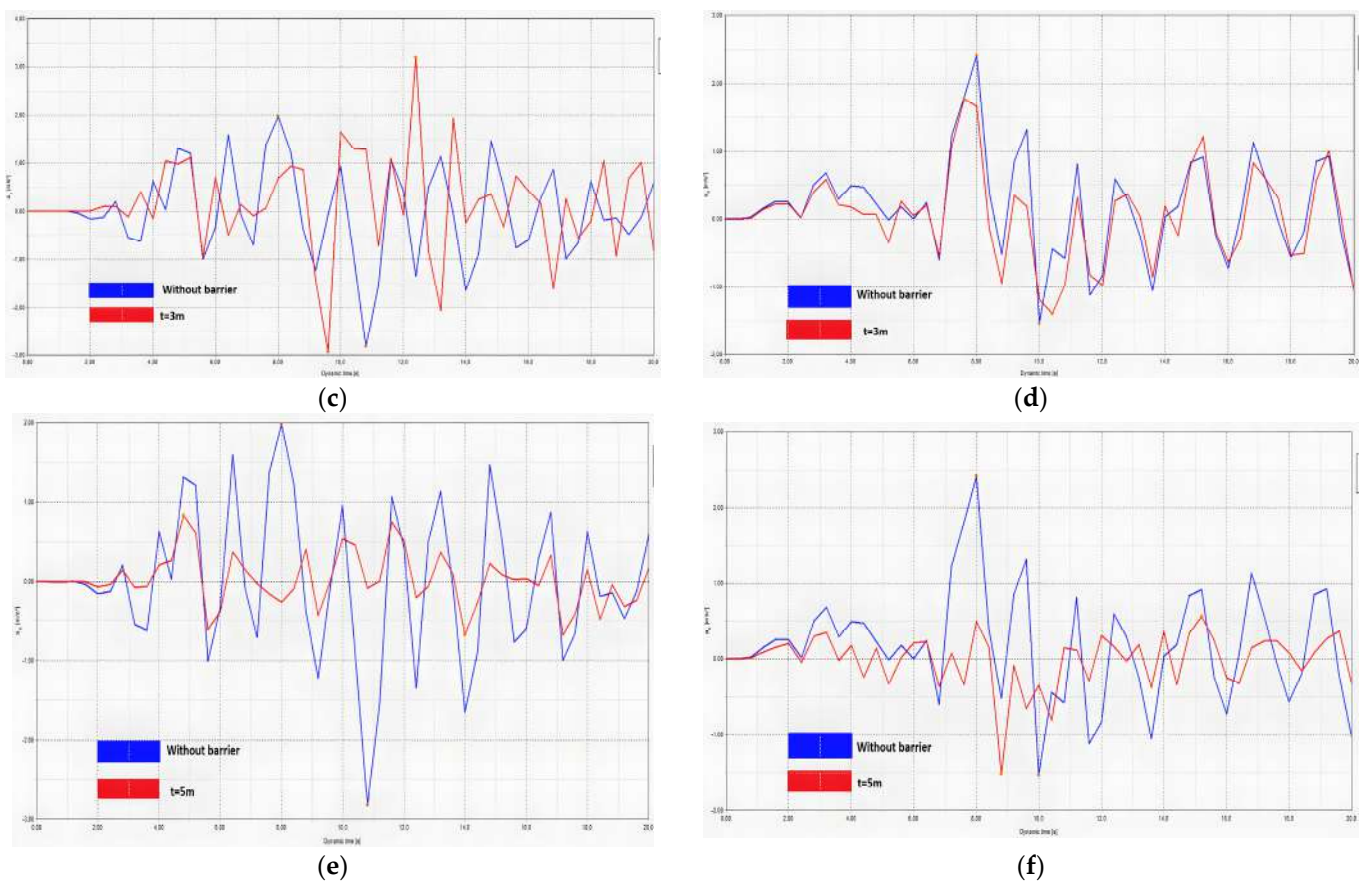


Figure 7. Time-normalized horizontal accelerations of the top point of the building obtained from the parametric study as a function of the thickness of the RSM barrier: (a) barrier thickness 1 m, Kobe earthquake; (b) barrier thickness 1 m, Northridge earthquake; (c) barrier thickness 3 m, Kobe earthquake; (d) barrier thickness 3 m, Northridge earthquake; (e) barrier thickness 5 m, Kobe earthquake; (f) barrier thickness 5 m, Northridge earthquake.

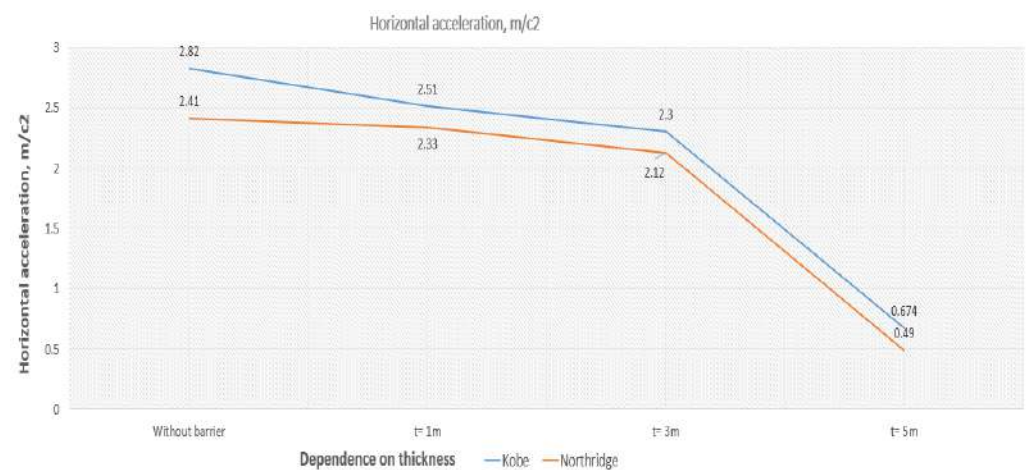


Figure 8. Graph of horizontal acceleration dynamics dependence on barrier thickness.

It can be seen from the results of the study that the dynamics of horizontal accelerations are significantly dependent on the damping properties of the geomaterial and the thickness of the barrier. A thicker barrier is effective in absorbing and scattering seismic waves, which increases the level of protection and reduces the risk of damage. Due to the larger

volume of RSM, the effectiveness of the barrier increases in reducing the amplitude of seismic effects and increases protection against damage.

3.2. Effect of Barrier Depth

The design and engineering of RSM barriers were considered to determine the effectiveness of the depth or height of vertical seismic barriers on the degree of reduction in earthquake input motion. The extent to which the input motion amplification is reduced during an earthquake also depends on the depth of the RSM barrier. A numerical analysis was carried out to obtain the effective barrier height, and the RSM barrier depth was varied between 5 m, 10 m, and 15 m. As can be seen from the horizontal acceleration response spectrum (Figure 9), the acceleration values for the GSI system decrease with increasing barrier depth up to 15 m, which indicates a sufficiently high effect of reflection and absorption of energy of wave processes.

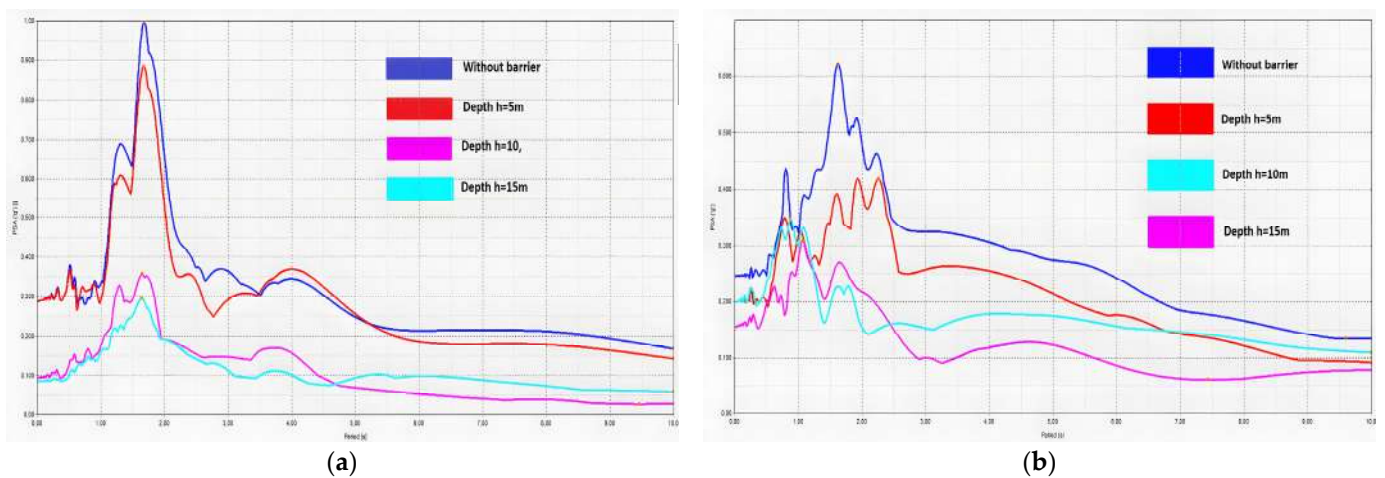


Figure 9. Horizontal acceleration response spectrum of the top point of a building without and with RSM barrier as a function of barrier depth: (a) Kobe earthquake; (b) Northridge earthquake.

The response spectrum of the horizontal acceleration response of the top point of the building from the two accelerograms (Figure 9) shows that as a function of the barrier depth, there is a sharp decrease in the amplitude of the Kobe oscillation, whereas for the low-frequency Northridge parameters, the response is moderate. This is reflected in the duration of the low-frequency oscillation at different barrier depths.

According to experts, the effectiveness of seismic isolation is also observed when the depth of the barrier increases. The results of the RSM barrier experiment showed that for a 5 m barrier depth (Figure 10a,b) the acceleration reduction is 0.281 g and 0.195 g, while for a 10 m barrier (Figure 10c,d) the acceleration reduction is 0.092 g and 0.057 g. When the barrier depth is increased from 10 m to 15 m, no significant difference in the SSI + GSI period is observed (Figure 10e,f). The results show that the value of reduction in horizontal accelerations of the top point of the building when the barrier is 15 m deep is 60–70%, which indicates the effectiveness of the GSI system with RSM.

As can be seen from the graph of the dynamics of horizontal accelerations dependence on the depth of the barrier (Figure 11), the lowest decrease is observed when using a barrier depth of 5 m, intermediate results are obtained at a depth of 10 m, and the best results are obtained when using a depth of 15 m. Typical reduction values in these cases are 5–30%, 10–40%, and 15–45%, respectively. This follows from the fact that the 15 m depth is the most ductile of the three depths and has the greatest propensity for large inelastic deformations. As a result, it reaches its shear strength faster, dissipates more energy during an earthquake, and provides greater seismic isolation capacity for the entire system. The decrease in the base period becomes more significant as the barrier depth increases from 10 m to 15 m. The influence of barrier depth parameters on the value of horizontal accelerations has been

noted by other researchers [48]. According to experts, surface waves, depending on the seismic properties of the soils, are reflected or absorbed by barriers, or they jump them at depth.

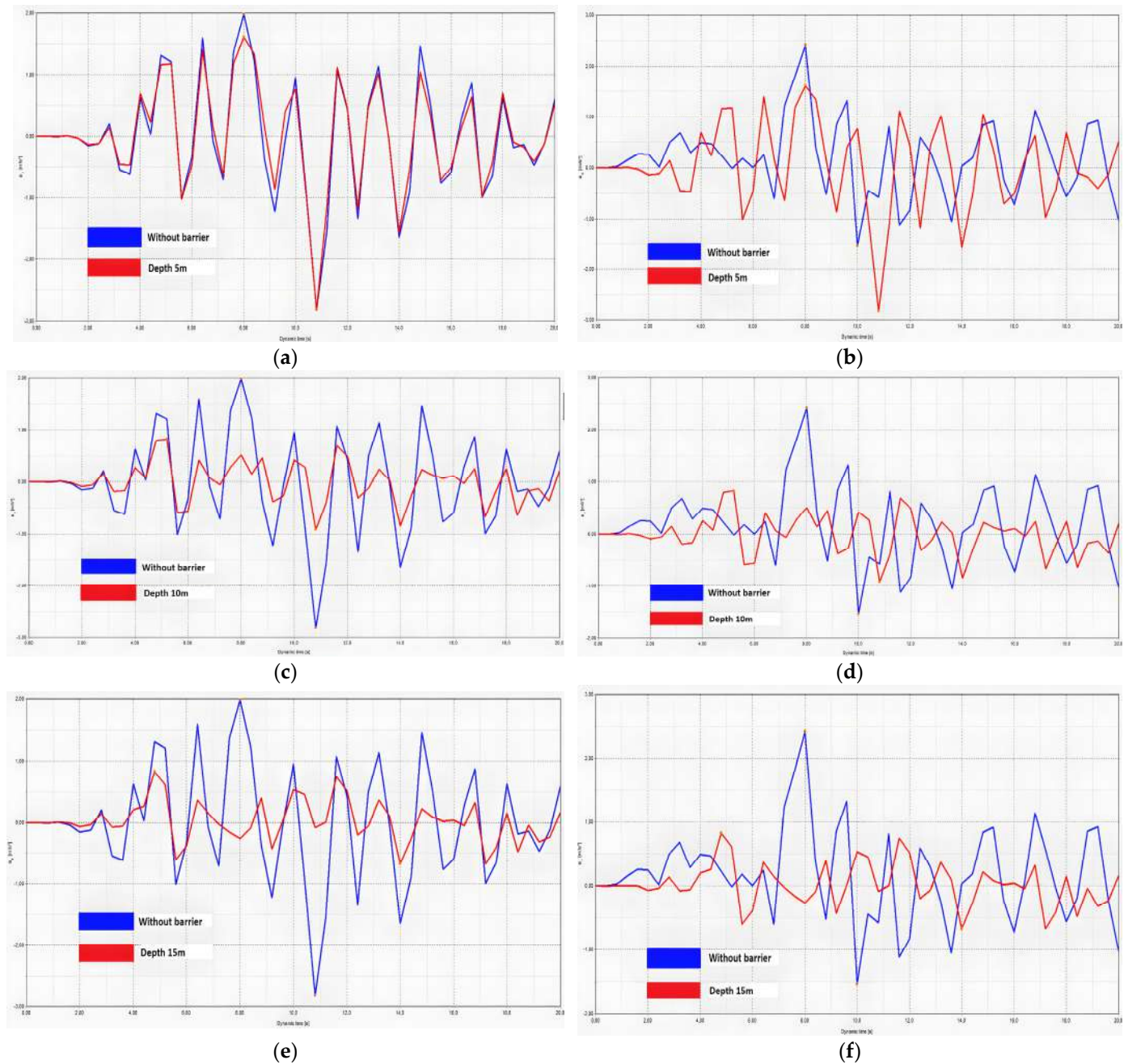


Figure 10. Time-normalized horizontal accelerations at the top of the building obtained from the parametric study as a function of the barrier RSM depth: (a) barrier depth 5 m, Kobe earthquake; (b) barrier depth 5 m, Northridge earthquake; (c) barrier depth 10 m, Kobe earthquake; (d) barrier depth 10 m, Northridge earthquake; (e) barrier depth 15 m, Kobe earthquake; (f) barrier depth 15 m, Northridge earthquake.

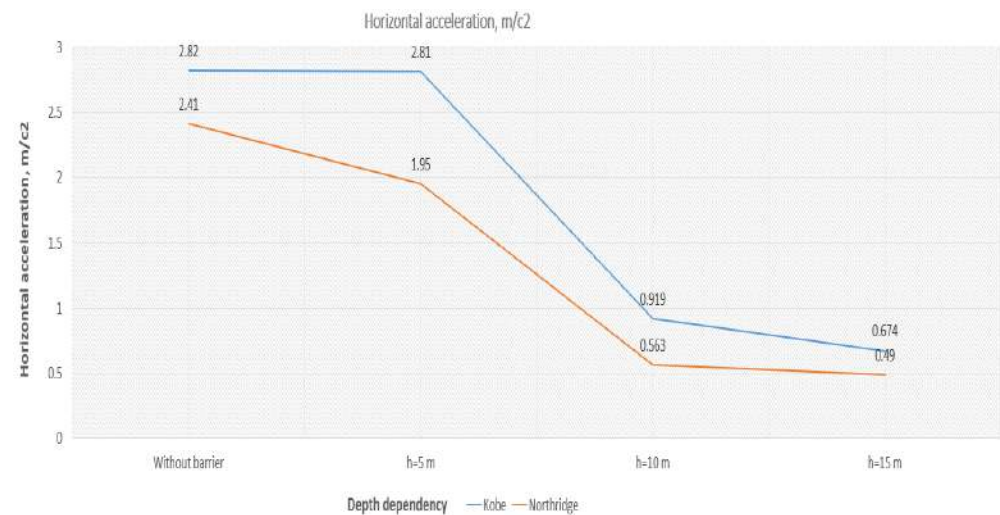


Figure 11. Graph of horizontal acceleration dynamics as a function of barrier depth.

3.3. Effect of Distance from the Building

The degree of reduction in earthquake input motion was considered in terms of the location of seismic barriers from the RSM away from the building. The minimum distance of the barrier from the building shall be determined from the stress–strain condition of the foundation from the load of the aboveground structure. A safety zone, 3–5 m, for barrier work must also be considered.

The degree of reduction in earthquake input motion was considered in terms of the location of seismic barriers from the RSM away from the building. The acceleration reduction at the level of the top point of the building obtained in the RSM barrier located at different distances of 5 m, 10 m, and 15 m from the building is shown in Figure 12.

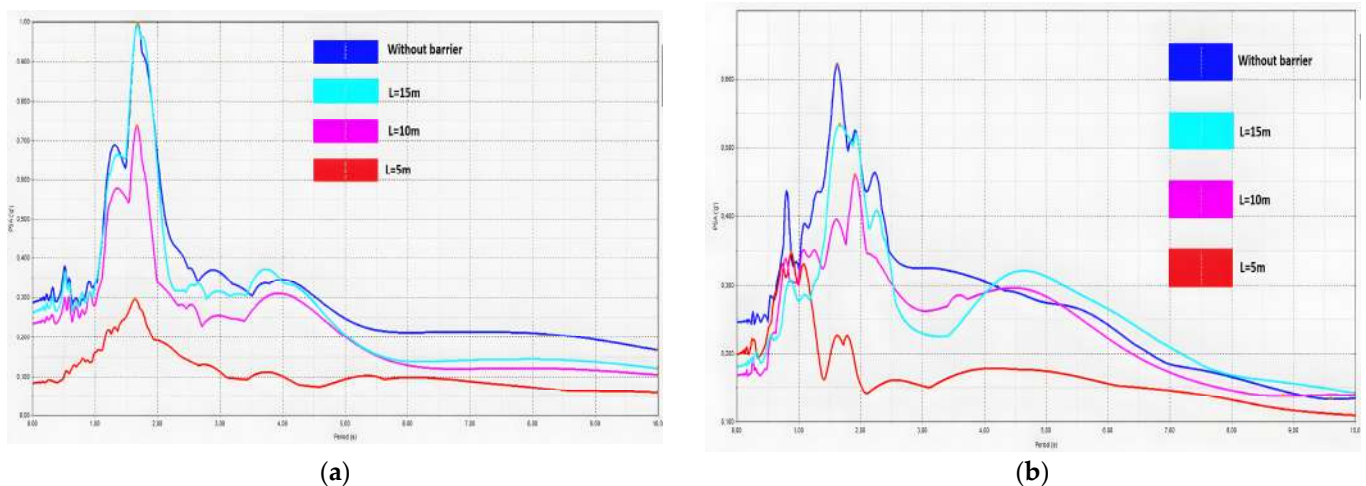


Figure 12. Horizontal acceleration response spectrum of the top point of a building without and with RSM barrier as a function of barrier distance: (a) Kobe earthquake; (b) Northridge earthquake.

The results of the analysis of the horizontal acceleration response spectrum of the top point of the building without and with the RSM barrier show an increase in acceleration at larger barrier locations from the building. As shown in Figure 13a,b, with barrier locations at 5 m spacing, there is an acceleration reduction value of 0.068 g (Kobe) and 0.068 g (Northridge), which corresponds to a reduction efficiency of 60%. Therefore, the smaller the distance from the building, the more acceleration reduction is achieved at the level of the top point of the building.

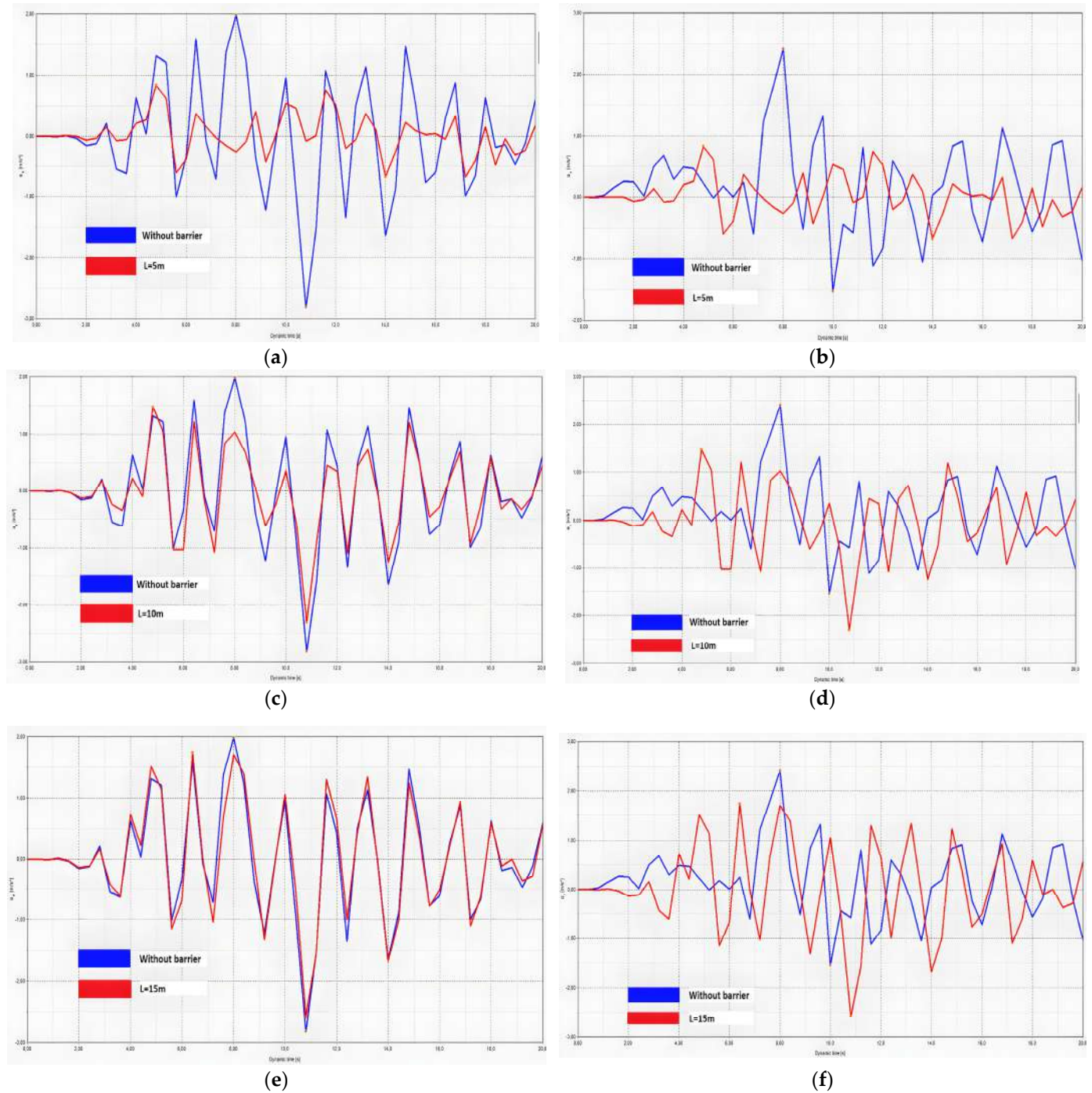


Figure 13. Normalized time histories of the horizontal accelerations of the top point of the building obtained from the parametric study as a function of the RSM distance of the barrier: (a) barrier distance 5 m, Kobe earthquake; (b) barrier distance 5 m, Northridge earthquake; (c) barrier distance 10 m, Kobe earthquake; (d) barrier distance 10 m, Northridge earthquake; (e) barrier distance 15 m, Kobe earthquake; (f) barrier depth 15 m, Northridge earthquake.

When the barrier is located 10 m away from the building, a reduction effect of 40% is observed (Figure 13b,c) and 15 m away from the building, a reduction effect of 30% is observed (Figure 13e,f).

From the graph of the dynamics of the horizontal accelerations' dependence on the distance of the barrier from the building (Figure 14), we also see the difference in the indicators when using different accelerograms. The Kobe earthquake, with higher magnitude (6.9–7.2)

compared to Northridge (6.7) with high amplitude, shows rapid oscillation damping for all barrier design parameters.

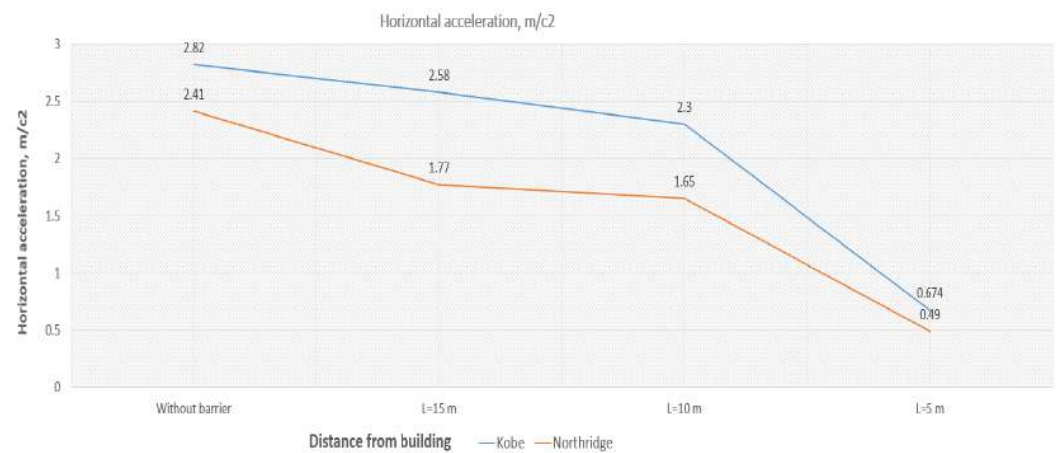


Figure 14. Graph of the dynamics of horizontal accelerations as a function of the distance of the barrier from the building.

Figure 14 shows that a significant reduction in acceleration reaches approximately 60% at a distance of 5 m from the building, 40% at a distance of 10 m, and 30% at a distance of 15 m from the building.

The location of the barrier away from the building has a significant effect on reducing horizontal accelerations at the top point of the building. The distance of 5 m from the building, established by the experiments, showed the effectiveness of the GSI system as seismic isolation. When the distance increases up to 15 m, the seismic isolation efficiency decreases due to the possible penetration of seismic waves from below the barrier.

The method of geotechnical seismic isolation in the form of vertical barriers made of RSM is based on the existing soil piling technology. The depth of the barrier is achieved by drilling a borehole to the design grade and packing the RSM to the required density. The width of the barrier is created by installing several rows of rubber–soil piles to a specified thickness. The use of industrial waste greatly reduces the cost of geotechnical seismic isolation technology.

If the barrier is located too far from the building, its ability to protect the structure may be reduced because some of the seismic energy may not be fully absorbed before reaching the building. This can reduce the overall effectiveness of the protection and increase the risk of seismic waves impacting the building.

A promising direction for further research is to evaluate the effectiveness of seismic barriers and their design solutions in different seismic parameters of ground conditions. Also, we consider the possibilities of using industrial wastes in GSI system additives as seismic isolation geomaterials.

4. Conclusions

1. The analysis of theoretical and experimental studies allows us to justify the system of geotechnical seismic isolation as an alternative method in reducing the intensity of seismic loads.
2. Geotechnical seismic isolation in the form of vertical barriers, characterized by new principles of action and better modified properties of geomaterial, to reduce inertial seismic loads on buildings is proposed.
3. The results of the study highlight the favorable effect of using RSM as a geomaterial for vertical barriers for the response of structures under dynamic loads.
4. As a result of numerical studies, it was found that the thickness, height, and distance between the barrier and the building are the main factors determining the damping performance and the degree of reduction in earthquake input motion.

5. Vertical seismic barriers made of geomaterials with 75% rubber content reduces horizontal accelerations by 60% at selected optimum thickness, height, and spacing of RSM around the building.
6. The effectiveness of geotechnical seismic isolation on the degree of reduction in earthquake input motion is observed by the depth or height of vertical seismic barriers. With increasing barrier depth, a reduction in input acceleration of up to 60% is observed.
7. The results of the study recorded a significant decrease in acceleration depending on the location of the barrier from the building: 60% at a distance of 5 m from the building, 40% at a distance of 10 m, and 30% at a distance of 15 m from the building.
8. Structural and technical solutions of vertical seismic barriers on RSM are characterized by reliability in providing seismic isolation of objects of existing buildings from the impact of seismic forces and the technological efficiency of their construction during construction and operational periods.
9. The results of this study contribute to the substantiation of methodology and scientific and technical efficiency of geotechnical seismic isolation as a simple and reliable system, an economically favorable design alternative to the traditional seismic isolation system, and greatly reduces the financial and time costs of providing seismic resistance.
10. The developed system of geotechnical seismic isolation and the results of computational and experimental modeling will become a research, analytical, and design basis for the development of new ways of ensuring seismic resistance of construction objects.
11. A promising direction for further research, in our opinion, is the development of a comprehensive theory of calculation, which allows calculating and selecting the structure and geometry of the geotechnical seismic isolation system.

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