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The Effect of FPS Parameters in Seismic Isolation under Nonlinear Time History Analysis: Contribution of Curvature Radius of Isolator to Seismic Performance of Structure

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Abstract: The seismic performance of a medium-rise reinforced concrete building with a 10-story was evaluated using a Single Concave Friction Pendulum System (FPS) base isolation under the impact of the 2023 Kahramanmaraş-Pazarcık earthquake. The structure was designed with three spans in the X direction and two in the Y direction. FPS isolators were installed at the base level for seismic isolation purposes, and two different curvature radii (R = 1.5 m and R = 4 m) were analyzed while keeping the friction coefficient constant (μ = 0.055). The seismic response of the structure was assessed using a nonlinear time history analysis method in a finite element program, considering the ground motion of the February 6, 2023 Kahramanmaraş-Pazarcık earthquake. Four key seismic performance parameters were examined to evaluate the influence of the FPS isolator radius on structural response: base shear force, maximum peak displacement, maximum peak velocity, and maximum peak acceleration. The findings revealed that isolators with smaller curvature radii increased base shear force due to higher stiffness but reduced displacement and acceleration demands to a certain extent. Conversely, isolators with larger curvature radii contributed to lower base shear forces and enabled a more flexible structural response with extended periods, increasing displacement and velocity demands. These results highlight the multifaceted impact of FPS isolator geometry on structural performance and emphasize the need for multi-parameter evaluation in performance-based seismic isolation design.

Keywords: Base Isolation, Earthquake, Friction Pendulum System (FPS), Kahramanmaraş-Pazarcık Earthquake, Seismic Isolation, Seismic Performance, Time History Analysis

Öz: Kahramanmaraş-Pazarcık depremi dikkate alınarak toplam 10 katlı, orta yükseklikteki betonarme bir yapının sismik performansı, Tek Eğrilikli Sürtünmeli Sarkaç Sistemi (FPS) tipi taban izolasyonu kullanılarak değerlendirilmiştir. Yapı, X doğrultusunda 3 açıklıklı, Y doğrultusunda ise 2 açıklıklı olarak tasarlanmıştır. Sismik izolasyon amacıyla temel seviyesinde FPS tipi izolatörler uygulanmış ve bu izolatörlerin yapının sismik performansına olan etkisi, sabit sürtünme katsayısı (μ = 0.055) değerine sahip iki farklı eğrilik yarıçapı (R = 1.5 m ve R = 4 m) dikkate alınarak yapının sismik davranışı, bir sonlu elemanlar programında zaman tanım alanında doğrusal olmayan analiz yöntemi kullanılarak, 6 Şubat 2023 tarihli Kahramanmaraş-Pazarcık depremi yer hareketi etkisi altında değerlendirilmiştir. FPS izolatör yarıçapının yapının sismik tepkisi üzerindeki etkilerini analiz edebilmek amacıyla taban kesme kuvveti, maksimum tepe noktası yer değiştirmesi, maksimum tepe noktası hızı ve maksimum tepe noktası ivmesi olmak üzere dört temel sismik performans parametresi incelenmiştir. Elde edilen bulgulara göre; daha küçük eğrilik yarıçapına sahip izolatörlerin rijitlik etkisiyle taban kesme kuvvetini artırdığı, ancak yer değiştirme ve ivme taleplerini belirli ölçüde azalttığı görülmüştür. Öte yandan, daha büyük yarıçaplı izolatörlerin yapıya aktarılan yatay kuvveti azaltarak daha uzun periyotlu, daha sünek bir davranış oluşturduğu; buna karşılık yer değiştirme ve hız taleplerini artırdığı tespit edilmiştir. Bu kapsamda, FPS izolatör geometrisinin yapısal performans üzerindeki çok yönlü etkileri ortaya konmuş ve performans temelli tasarımda izolatör seçiminin çoklu parametrelerle değerlendirilmesi gerektiği vurgulanmıştır.

Anahtar Kelimeler: Deprem, Kahramanmaraş-Pazarcık Depremi, Sürtünmeli Sarkaç Sistemi (FPS), Sismik İzolasyon, Sismik Performans, Taban İzolasyonu, Zaman Tanım Alanında Analiz

1. Introduction

Earthquakes are among the most devastating disasters for Türkiye and the world [1]. The Kahramanmaraş-Pazarcık earthquakes in 2023 caused serious property and life losses [2–4]. The Myanmar earthquake in 2025 was one of the most crucial ground movements that reminded us again of earthquake-resistant structural design [5, 6]. The essential purpose of earthquake-resistant structural design is to prevent resonance of the structure by differentiating the frequency of the earthquake and the frequency of the structure. The use of isolators is essential to ensure this. Friction Pendulum System (FPS) and Lead Rubber Bearing (LRB) type isolators are widely used worldwide and are more advantageous than other isolator types [7, 8].

FPS isolators have friction surfaces that are resistant to heat and deformation between the surfaces. These friction surfaces absorb seismic energy. In addition, their service life is considerably longer than other isolators. For this reason, although the initial costs are relatively higher, they are pretty economical in the long term when maintenance and repair costs are considered [9–12].

It is critical to model the seismic effect created by an earthquake. As it is known, earthquakes create a nonlinear impact on the building. Therefore, the seismic loads acting on the structure should be determined through dynamic analysis based on nonlinear time history methods [13–16].

FPS isolators can resist this nonlinear ground motion with their very high energy absorption capacity. These low-cost seismic isolators allow period adjustment regardless of building weight. Its simple and compact design enables easy installation without requiring additional space. The isolators offer stable performance due to their durability and consistent characteristics, and maintenance can be easily performed [17–19].

The dynamic behavior of structures equipped with FPS isolators has recently been the subject of many studies. While some studies mainly focused on modeling techniques [20–25], others investigated the effects of structural system parameters, isolator properties, and uncertain seismic effects on the structure response. The seismic response of a single-story shear frame equipped with FPS isolators, characterized by the Coulomb damping model, was investigated. Seismic excitations were represented by either random stochastic processes or near-fault ground motions, and the corresponding analyses were performed [26, 27]. The results indicated that upper-floor accelerations can be minimized within a specific range of friction coefficients (0.05–0.15). The optimal friction value is influenced by factors such as building properties, isolation period, and seismic intensity, and tends to increase with higher earthquake magnitudes [28]. It is seen that the approach of minimizing the maximum accelerations of isolated structures is widely used as a criterion in performance optimization.

This paper analyzes two different FPS isolators consisting of multi-story building frames isolated with FPS bearings using nonlinear time history analysis performed for various values of isolator curvature radius. In this study, where the Kahramanmaraş-Pazarcık earthquake is used, the base shear force, displacement, velocity, and acceleration values are compared with the corresponding predictions obtained using finite element models. This analysis enables the assessment of how isolator curvature radius influences key aspects of the seismic performance of FPS-isolated buildings and offers valuable insights for the design of such isolators.

2. Material and Method

In this paper, a 10-story medium-high-rise reinforced concrete building was designed and analyzed, where each floor is 3.1 meters in height, resulting in an overall building height of 31 meters, as illustrated in Figure 1. It was determined that there would be three spans in the X direction and two in the Y direction, as shown in Figure 2. The spans in the X direction are 4.5 m, while in the Y direction are 4 m. The total floor plan is 108 m^2. Our total construction area was calculated as 1188 m^2. The foundation was assigned as a raft foundation with a thickness of 1 meter. The selected beam dimensions were used as a single type in the entire building, which was 25 x 50 cm. The columns were chosen as the commonly used 30x50 cm and assigned symmetrically.

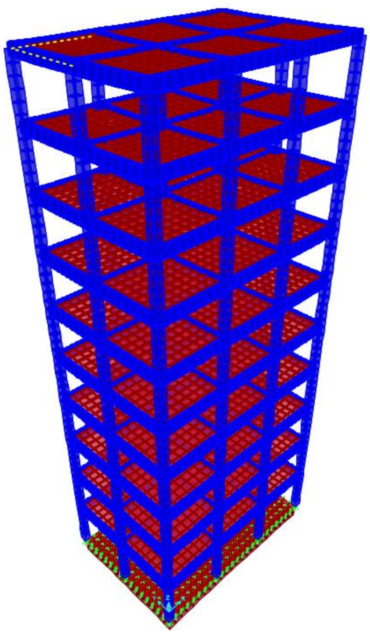

Figure 1. 3D plan of the analyzed building

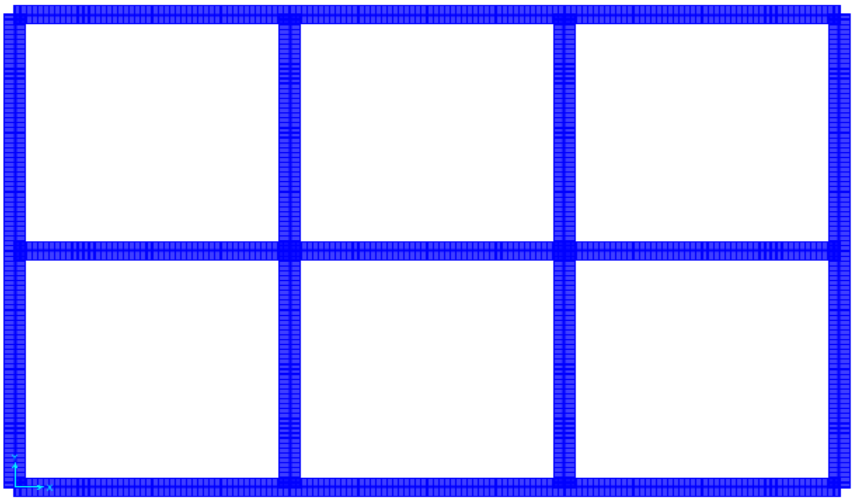

Figure 2. Plan of the designed building

FPS was selected as the seismic isolation system on the foundation. FPS isolators were used in two different values, 1.5 m and 4.0 m in radius, while the friction coefficients were kept constant at 0.055, as selected isolator properties are given in Table 1.

Table 1. Characteristics of assigned FPS isolators

FPS name	Radius of curvature (m)	Coefficient of friction	Displacement of FPS (m)	Effective stiffness (kN/m)	Effective damping	Nonlinear stifness (kN/m)
R4.0	4.0	0.055	0.230	628	0.300	28125
R1.5	1.5	0.055	0.160	1297	0.217	28660

In light of these definitions, isolators' effect on the seismic behavior of the structure was investigated by performing a nonlinear time history analysis in SAP2000 software, as shown in Figure 3, under the impact of the Kahramanmaraş-Pazarcık earthquake.

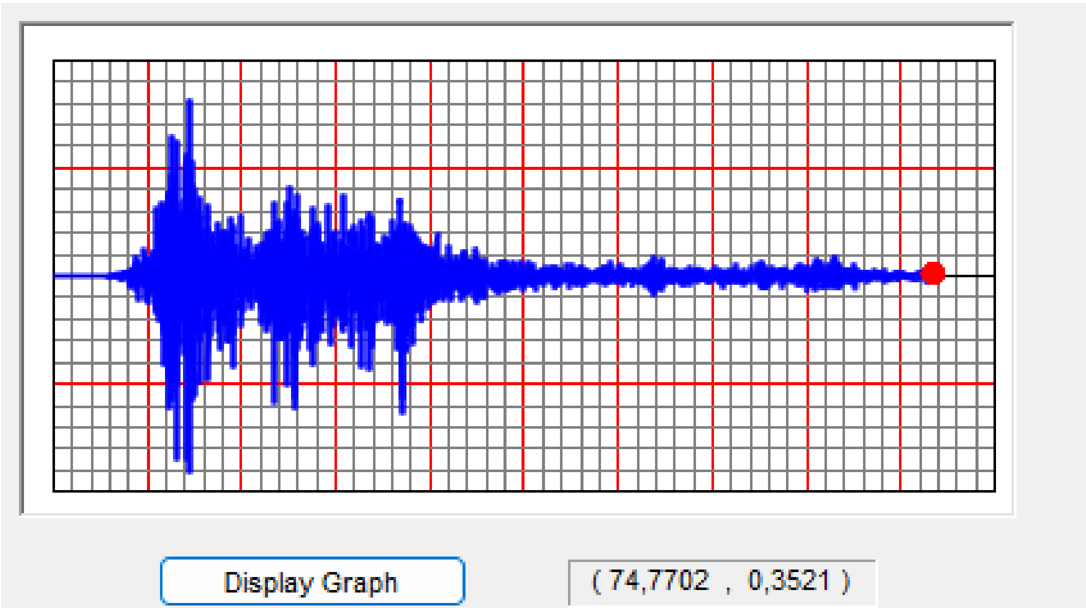

Figure 3. Definition of nonlinear time history analysis in SAP2000 considering the Kahramanmaraş-Pazarcık earthquake

The effects of the isolator radius on the structure performance were examined by comparing the results of base shear force, maximum peak displacement, maximum velocity, and maximum acceleration of the varying isolator radius.

3. Results and Discussion

In this part of the research, the seismic response results derived through non-linear time history analyses are presented in detail. The primary objective is to evaluate how the variation in the curvature radius of FPS isolators affects the dynamic performance of a medium-high-rise reinforced concrete building under strong ground motion. For this purpose, two different curvature radius were considered, and critical seismic parameters such as base shear force, maximum peak velocity, maximum peak displacement, and maximum peak acceleration were comparatively analyzed. The selected parameters are essential for assessing the effectiveness and suitability of FPS isolators in minimizing seismic demands on structures. The numerical results are graphically illustrated and interpreted to highlight the influence of isolator geometry on structural response characteristics. The findings are expected to contribute to a better understanding of isolator performance under varying design conditions and support decision-making in isolation system selection.

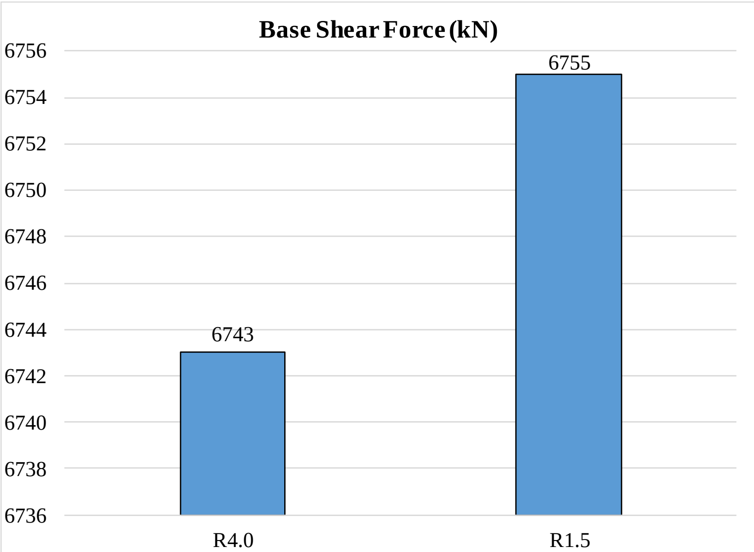

Figure 4. Base shear force according to the radius of FPS isolators

Figure 4 shows the effect of FPS isolators' radius of curvature (R) on the base shear force. When an isolator with a radius of curvature of 4 m was used, the maximum base shear force in the structure was recorded as 6743 kN, and when the radius of curvature was 1.5 m, it was recorded as 6755 kN. This result reveals that isolators with a smaller radius of curvature transfer higher horizontal forces to the structural system. This increase shows that as the radius of curvature decreases, the period of the system decreases, and therefore, the structure becomes more rigid. The increase in rigidity prevents the weakening of the bond between the structure and the ground movement, which can cause higher force transfer during an earthquake. Therefore, it is clear that not only ductility and displacement demands but also structural demands, such as base shear force, should be taken into consideration when selecting an isolator. Especially in high-mass or medium-long period structures, choosing isolators with a larger radius of curvature can provide advantages reducing structural demands and increasing energy absorption capacity.

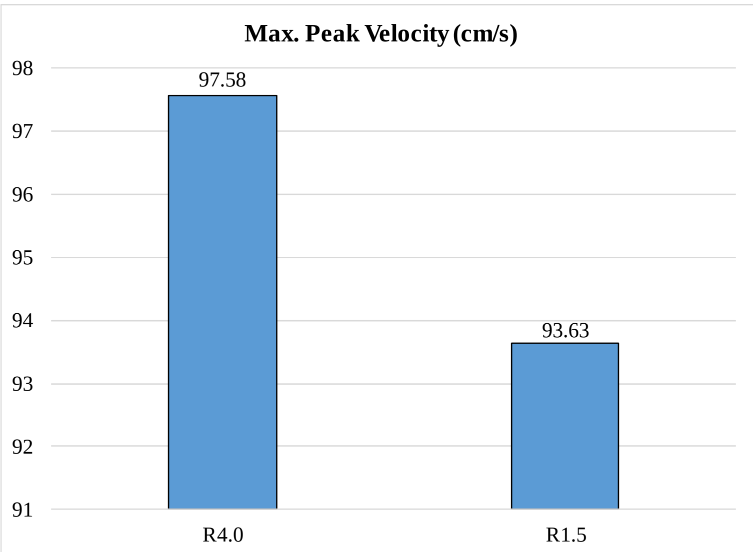

Figure 5. Maximum peak velocity according to the radius of FPS isolators

Figure 5 reveals the effect of the size of the radius of curvature on the maximum velocity demand of the structural system. As the radius of curvature increases it is observed that the maximum peak velocity increases (97.58 cm/s). In contrast, the maximum velocity value was measured as 93.63 cm/s in the system equipped with an isolator with a smaller radius of curvature. This stuation indicates that an increase in the isolator's curvature radius leads to a corresponding increase in the effective period of the structure. Therefore, the velocity component rises due to the increase in the displacement capacity. Isolators with larger radii cause the base of the structure to move for a longer time; this leads to an increase in the maximum displacement and, therefore, the velocity component.

On the other hand, in isolators with small radii, the system behaves more rigidly, and this rigidity contributes to the peak velocity remaining at a lower level. However, since this situation may also cause an increase in the base shear force, it is understood that velocity and force demands should be optimized together in the isolator design.

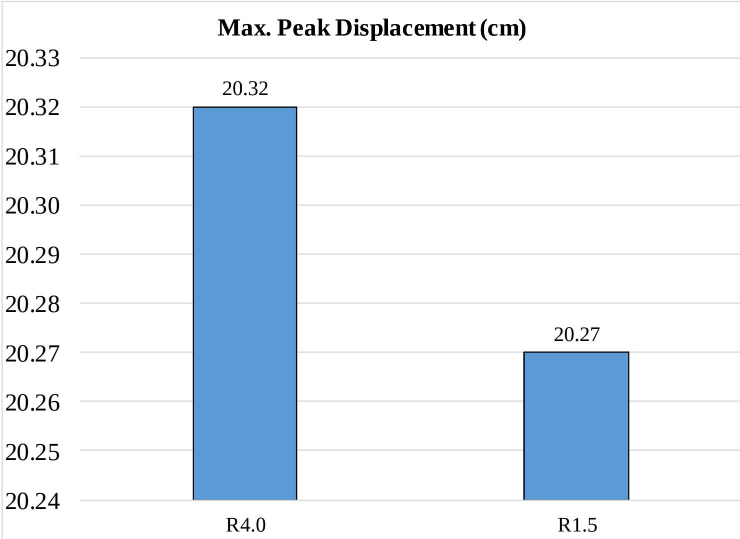

Figure 6. Maximum peak displacement according to the radius of FPS isolators

Figure 6 shows a direct relationship between the size of the isolator radius of curvature and the displacement capacity of the structural system. It is observed that the maximum peak displacement is 20.32 cm in the isolator with a radius of curvature of 4 m, and this value decreases to 20.27 cm in the isolator with a radius of curvature of 1.5 m. This slight difference means larger radius isolators produce longer adequate periods, allowing the system to displace more. Since the radius of curvature in FPS isolators is a parameter that directly affects the period of the system, the resonance risk of the system decreases as the radius increases, but in return, the displacement demand increases. This result shows that FPS isolators with larger radii can be preferred in structures where the displacement capacity needs to be increased. Still, this situation should be evaluated in detail and optimized with other performance parameters such as base shear force and velocity. In addition, the limited difference in maximum displacement seen in the analysis reveals that the system operates under similar loading, but the isolator characteristics affect the structure at different levels.

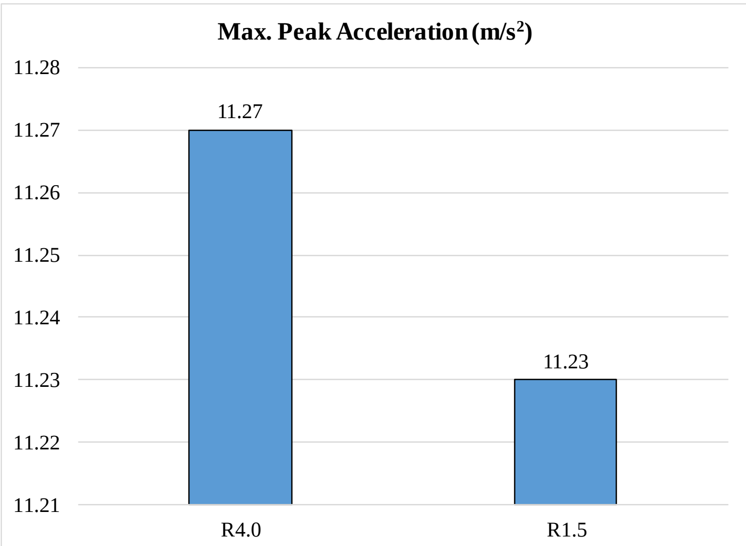

Figure 7. Maximum peak acceleration according to the radius of FPS isolators

The results shown in the Figure 7 the effect of the radius of curvature on the acceleration demands transferred to the structural system in FPS isolators. The isolator with a large radius of curvature transferred a higher level of acceleration to the structure (11.27 m/s²). In contrast, this value remained at the level of 11.23 m/s² with the isolator with a smaller radius of curvature. Although the difference is quite limited in this graph, it is seen that the acceleration level slightly decreases with the R1.5 configuration. This situation shows that isolators with a smaller radius of curvature may provide advantages, especially in structures where high acceleration demands are critical. However, as shown in the previous graphs, since such isolators may cause higher base shear forces, optimizing acceleration, velocity, displacement and shear forces together during the design process is mandatory.

4. Conclusion

This study analyzed the effects of FPS isolators with different radii of curvature on seismic performance. The analyses were performed in the nonlinear time history, and the responses of the structures were investigated based on four basic seismic parameters including base shear force, maximum peak velocity, maximum peak displacement, and maximum peak acceleration. The findings are discussed in detail below.

- As the radius of curvature of the FPS isolator decreases, the effective period of the system decreases, and therefore, the structure exhibits more rigid behavior. This situation causes an increase in the horizontal forces transferred to the base. In the analyses performed, the base shear force for the R1.5 isolators was 6755 kN, and the base shear force for the R4.0 isolator was 6743 kN. An increase of approximately 0.18% was observed in the base shear force in the R1.5 configurations. This difference shows that small-radius isolators transfer the earthquake force more effectively to the superstructure due to their high rigidity. Therefore, it is recommended that larger-radius isolators be preferred in designs that require limiting the base shear force.
- The peak velocity of the system is a parameter that directly reflects the structure's response to dynamic energy. Since a larger radius of curvature results in a more extended oscillation period and a wider range of motion, an increase in peak velocity is expected in this case. As a result of the analyses performed, the maximum velocity for R4.0 is obtained 97.58 cm/s while maximum velocity for R1.5 is 93.63 cm/s. This approximately 4.2% increase is associated with the more significant displacement and damping capacity of the R4.0 isolator, revealing that the structural system absorbs energy by making slower but wider oscillations. This situation shows that small radius isolators may be advantageous in systems where velocity demands are critical.
- In FPS isolators, the radius of curvature is one of the main parameters that determine the period of the system and, therefore, the displacement capacity. In the analyses performed, the maximum displacement for R4.0 is obtained 20.32 cm. Maximum displacement of 20.27 cm is measured for R1.5. Although the difference obtained is low, there is an increase of approximately 0.25% in the R4.0 configuration. This result confirms that the system tries to dissipate energy with a more extended period by creating more displacements. More miniature radius isolators, such as R1.5, may be more appropriate in structures where displacement demands must be limited.
- Acceleration is a critical parameter that determines the effect of the structure on sensitive components, especially non-structural elements and interior equipment. The analysis results are as follows: Maximum peak acceleration for R4.0 is 11.27 m/s², and maksimum peak acceleration for R1.5 is 11.23 m/s². A decrease of approximately 0.36% between these values indicates that more miniature radius isolators have acceleration damping potential. This result case supports the preference for isolators such as R1.5, especially in structures with interior comfort or sensitive equipment.
- As a result of the analysis, the radius of curvature of FPS isolators directly affects the seismic behavior of structures. In this context, R4.0 isolators increase the displacement and velocity capacity by producing extended periods but decrease acceleration and shear force. R1.5 isolators reduce acceleration and displacement demands by providing a more rigid system behavior; conversely, they increase the base shear force. Therefore, isolator selection should be made not according to a single performance criterion but by considering the purpose of use of the structure, the number of floors, the center of gravity, the ground profile, and the target performance level. A performance-based engineering approach should be adopted in seismic isolation design, and multi-parameter optimization should be used as a basis.

Conflict of Interest

The authors declare that they have no competing interests.

Ethics Committee Approval

Ethics committee approval is not required.

Author Contribution

The authors have read and agreed to the published version of manuscript.

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