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Seismic Response and Pile Foundation Efficiency of an Irregular Hospital Building with Double Friction Pendulum System

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Abstract: Hospital buildings are essential facilities that require adequate seismic performance to maintain post-earthquake functionality. This study evaluates the influence of a Double Friction Pendulum System (FPS) on the seismic response and pile-foundation demand of a nine-story irregular hospital building in Malang, Indonesia, designed in accordance with SNI 1726:2019. Fixed-base and FPS models were analyzed using a 5% damped response spectrum, with structural performance assessed through fundamental period, base shear, lateral displacement, interstory drift, and isolator displacement. Pile-foundation demand was evaluated from the governing support reactions, while the axial resistance of 600 mm prestressed concrete spun piles was determined from subsurface investigation data using the Décourt method. Foundation efficiency was quantified based on the total installed pile length required by each structural alternative. The FPS increased the dominant structural period to 3.063 s in the X direction and 2.580 s in the Y direction and reduced average interstory drift by 73.6–81.7% and 42.8–83.3%, respectively, relative to the fixed-base alternatives. The maximum resultant isolator displacement was 70.64 mm, corresponding to approximately 31.9% of the design displacement capacity of 221.11 mm. The FPS alternative reduced the total installed pile length from 4692 m to 1800 m, indicating a potential foundation-efficiency improvement of 61.63% under the adopted structural and geotechnical assumptions. The main contribution of this study is the integration of seismic-isolation performance with pile-foundation demand for an irregular essential building. Further verification through detailed pile-capacity, settlement, pile-group, and soil–pile–structure interaction analyses is recommended.

Keywords: *base isolation, double friction pendulum system, irregular building, pile foundation, seismic response*

1. Introduction

Hospital buildings are classified as essential facilities because they are expected to remain functional after major earthquakes to support emergency response, evacuation, and medical services. Under SNI 1726:2019, hospitals equipped with surgical and emergency facilities are categorized as Risk Category IV and are therefore designed using a higher seismic importance factor than ordinary buildings [1]. For irregular multi-story structures, nonuniform distributions of mass, stiffness, and geometry may lead to localized deformation and increased force demand. Consequently, seismic design should address not only member strength but also global deformation, interstory drift, acceleration response, and post-earthquake functionality.

Base isolation is widely used as a passive seismic protection strategy to reduce earthquake-induced demand. The system modifies structural dynamic characteristics by lengthening the fundamental period and dissipating seismic energy through flexible isolation devices [2], [3]. Among the available isolation systems, the Friction Pendulum System (FPS) combines frictional energy dissipation with the restoring action generated by a concave sliding surface. A Double Friction Pendulum System employs two concave sliding interfaces, allowing larger displacement capacity within a relatively compact device configuration. Previous studies based on Indonesian seismic provisions have demonstrated that double-concave FPS can improve the seismic performance of reinforced-concrete buildings [4]. A previous study on the same hospital building evaluated the Double FPS primarily in terms of fundamental period, displacement, interstory drift, and base shear [5]. The present study extends that earlier superstructure-focused assessment by explicitly examining pile-foundation demand and total installed pile length.

The broader effectiveness of seismic isolation has also been demonstrated in recent Indonesian studies. Base-isolated reinforced-concrete buildings have shown substantial reductions in base shear, floor acceleration, and interstory drift compared with corresponding fixed-base systems [6]. Similar response modification has been reported for bridge structures using lead-rubber bearings, where isolation increased the structural period and reduced inertia-related demands, including base shear and support reactions [7]. Although these studies adopted isolation systems different from the Double FPS considered in this study, they confirm the general response-control mechanism whereby seismic demand is redistributed through a flexible and energy-dissipating interface. More recently, an HDRB-based study of an 11-story reinforced-concrete lecture building in Jakarta reported substantial period elongation, reductions in seismic base shear, improved interstory-drift control, and more efficient reinforcement demand [8].

Recent research on FPS has progressed from demonstrating basic isolation effectiveness toward addressing more specific design and performance issues. Critical evaluation of FPS design displacement has been reported in [9], while energy-based design procedures for FPS-isolated structures have been proposed in [10]. The influence of parameter uncertainty and the need for robust optimization have also been investigated [11]. In addition, soil–structure interaction has been shown to alter the dynamic response of FPS-isolated systems [12]. Earlier nonlinear time-history research on a high-rise building subjected to Kendeng Fault earthquake simulation also highlighted drift ratio and plastic-hinge development as key indicators of structural performance [13]. This reinforces the need to interpret the response of isolated buildings using deformation-based performance indicators rather than relying only on elastic force demand. These developments indicate that FPS performance should not be evaluated solely from superstructure response, because changes in structural period, displacement, and force transmission can also influence the substructure and foundation system.

Despite these advances, the relationship between the seismic response modification produced by FPS and the resulting pile-foundation demand remains less frequently addressed, particularly for irregular essential buildings under Indonesian design conditions. Most previous studies have concentrated on superstructure response parameters such as period elongation, acceleration, displacement, and interstory drift, whereas the consequences for support reactions, pile quantity, pile length, and foundation efficiency have received comparatively limited attention. This issue is important because changes in the force-transfer mechanism introduced by base isolation may affect both structural and geotechnical demands at the foundation level. Therefore, this study evaluates the effect of a Double Friction Pendulum System on the seismic response and pile-foundation demand of a nine-story irregular hospital building in Malang, Indonesia. The assessment focuses on structural period, base shear, lateral displacement, interstory drift, isolator displacement, and pile-foundation requirements.

2. Methods

2.1. Structural Data and Modeling

The research object is a hospital building located in Malang, East Java, Indonesia. The building is modelled as a nine-story reinforced concrete structure, including a basement, with a total height of 42 m. The concrete compressive strength is $f_c{}'$ = 25 MPa for the superstructure and $f_c{}'$ = 30 MPa for the substructure (Figure 1). Deformed reinforcement uses f_y = 400 MPa, while plain reinforcement uses f_y = 240 MPa. Based on its hospital function, the building is classified as risk category IV with an importance factor I_e = 1.50. The soil condition is modelled as site class SD, or medium soil. The isolation system analyzed in this study is the Double Friction Pendulum System type FIP-D M 2200/500 (3100). The main evaluation scope includes comparison of fixed-base and FPS models in terms of structural period, base shear, lateral displacement, interstory drift, isolator displacement control, and pile foundation requirement. The structural configuration and initial FPS modeling framework were developed from the previously reported hospital-building model [5], while the present study extends the assessment to pile-foundation demand and foundation-efficiency indicators.

Table 1. Summary of composite response spectrum data for the FPS system

Parameter	Value
Damping ratio	5%
Sa at T = 0 s	0.269 g
Initial plateau period	T = 0.153 s
Final plateau period	T = 0.767 s
Maximum Sa	0.673 g
Sa at T = 1.834 s	0.164 g
Sa at FPS design T = 2.54 s	0.119 g
Sa at FPS modal Tx = 3.063 s	0.098 g
Sa at FPS modal Ty = 2.580 s	0.117 g
Sa at T = 4.334 s	0.070 g

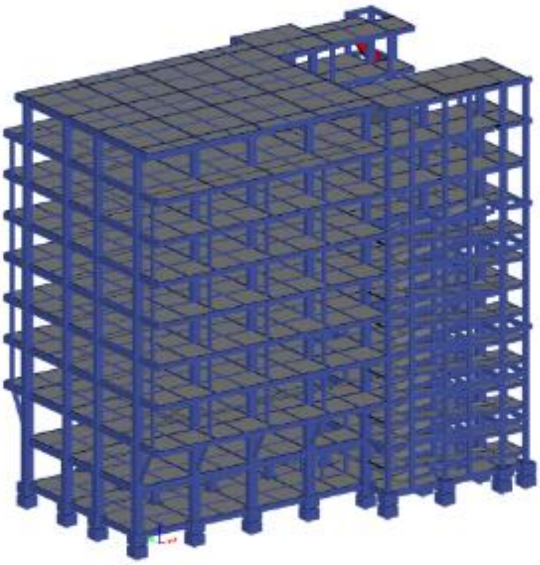

Figure 1. Three-dimensional model of the analyzed building.

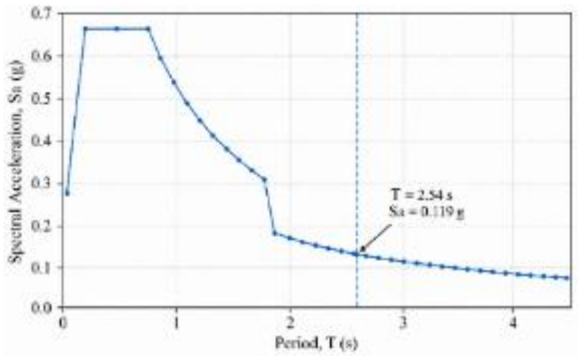

Figure 2. Composite response spectrum used in the FPS analysis.

2.2. Composite Response Spectrum for the FPS System

The composite response spectrum data were used as the response spectrum function for the FPS model. The data have a damping ratio of 5%. The spectrum increases from Sa = 0.269 g at T = 0 s to a plateau of Sa = 0.673 g within T = 0.153-0.767 s and then decreases in the long-period range.

At the FPS design period of 2.54 s, the interpolated Sa value is approximately 0.119 g. A summary of important spectrum values is given in Table 1, and the response spectrum curve is shown in Figure 2.

Table 2. FPS device specification

Parameter	Value
Type	FIP-D M 2200/500 (3100)
Isolator mark	Q1
NED	9300 kN
Dimension D	870 mm
Dimension Y	1110 mm
Dimension Z	1010 mm
Height H	220 mm
Number of dowels	8
Device weight	820 kg
Design displacement, DM	221.11 mm

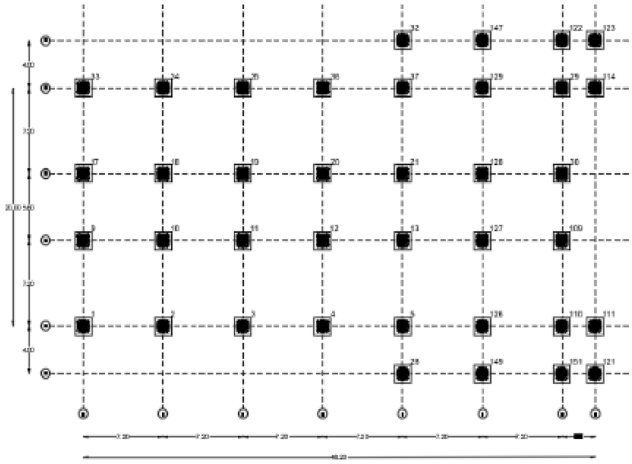

Figure 3. Layout of isolator joints in the FPS model.

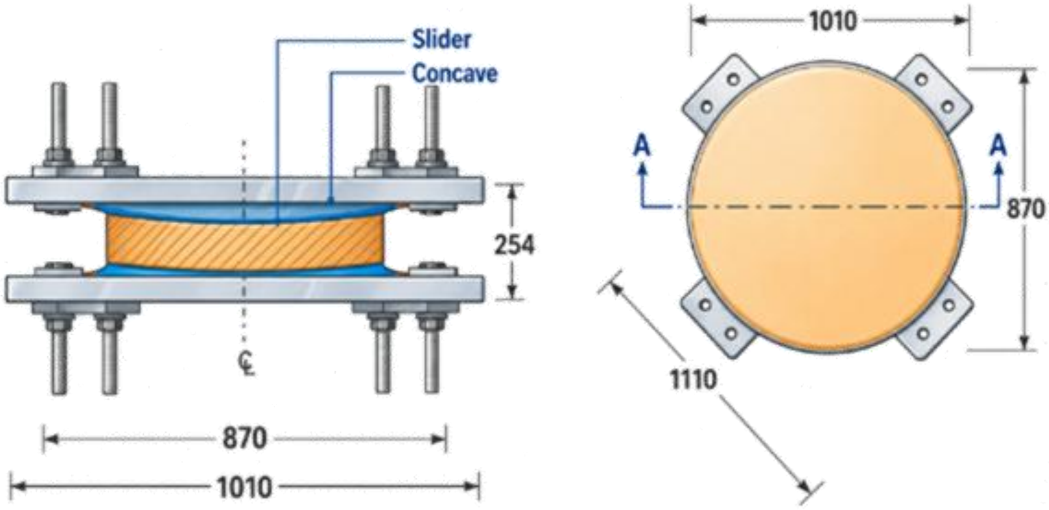

Figure 4. Cross-section of FIP-D type FPS device

2.3. Fixed-Base and FPS Models

The analysis compares fixed-base and FPS models. The fixed-base alternatives include an ordinary moment-resisting frame (OMF), special moment-resisting frame (SMF), ordinary shear wall system, and special shear wall system. In the FPS model, the base support is replaced by Double FPS devices so that the main horizontal deformation is expected to be concentrated at the isolation layer. The evaluation procedure includes checking the modal period, base shear, floor displacement, interstory drift, isolator displacement (Figure 3), and pile foundation requirement.

2.4. FPS Parameters and Performance Indicators

The FPS device selected in this study is FIP-D M 2200/500 (3100). The isolator type was selected through an iterative process until the actual displacement was lower than the design displacement. The main device parameters are presented in Table 2, while the device cross-section is illustrated in Figure 4.

The structural performance level is evaluated using the drift ratio and interpreted in terms of Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), as commonly used in performance-based design documents [14]. Because the building functions as a hospital, the result interpretation is directed toward the IO performance level.

Accordingly, the present study treats drift-based performance as a system-level indicator rather than an isolated member check. This approach is consistent with performance-based structural assessment in which deformation demand, nonlinear response, and support flexibility are evaluated together. For pile-supported systems, explicit soil-structure interaction modelling has been shown to materially change seismic displacement, demand-capacity ratios, and performance-point response [15]. Although the present work uses a response-spectrum-based building model rather than a nonlinear wharf model, this evidence is relevant when interpreting foundation demand and motivates the geotechnical verification discussed later.

2.5. Pile Foundation Evaluation

The pile-foundation requirements for the fixed-base and FPS models were evaluated using support reactions obtained from the corresponding structural analyses. Foundation design was performed for each support or pile-cap location using the governing vertical reaction together with the associated horizontal forces and overturning moments from the controlling load combinations. The same pile type, geotechnical design approach, and acceptance criteria were applied to both structural systems to ensure a consistent basis for comparison.

Prestressed concrete spun piles with an outside diameter of 600 mm were adopted for both foundation alternatives. The axial pile capacity was evaluated from the available subsurface investigation data using the Décourt method [16]. The subsurface profile consists predominantly of a clay layer within the upper 5 m, with an average SPT N-value of approximately 16, underlain by sandy soils extending to a depth of approximately 30 m with an average SPT N-value of about 40. The groundwater table was identified at approximately 3 m below ground level. The pile-tip elevation for each foundation alternative was selected based on the depth required to provide sufficient geotechnical resistance. Based on the adopted pile-capacity analysis, the design axial resistance of a single pile was 2940 kN at a pile length of 10 m and 3620 kN at a pile length of 12 m.

Foundation efficiency was evaluated using total installed pile length rather than pile number alone because the fixed-base and FPS alternatives resulted in different pile quantities and penetration depths. The total pile length for each structural system was calculated as

$$L_{\text{tot}} = \sum_{i=1}^{m} n_i \, L_i \quad (1)$$

where n_i is the number of piles in the i-th pile cap and L_i is the corresponding pile length. The relative reduction in total pile length due to FPS was then calculated as

$$\eta_L = \frac{L_{\text{FB}} - L_{\text{FPS}}}{L_{\text{FB}}} \times 100\% \quad (2)$$

where L_{FB} and L_{FPS} are the total installed pile lengths of the fixed-base and FPS alternatives, respectively. This procedure was used as a comparative foundation-efficiency indicator; final foundation acceptance additionally requires verification of axial and lateral pile resistance, uplift, pile-group effects, settlement, and pile-cap capacity.

3. Results and Discussion

3.1. Structural Period and Response Spectrum Implication

The period comparison shows that the FPS model has a longer dominant period than the fixed-base models (Table 3). The modal period of the FPS model is 3.063 s in the X direction and 2.580 s in the Y direction, while the design period used in the response spectrum evaluation is 2.54 s. This period is located on the descending branch of the response spectrum, with Sa of approximately 0.119 g at T = 2.54 s. This condition is consistent with the basic principle of seismic isolation, which shifts the structural period to a longer range to reduce the acceleration demand on the superstructure.

3.2. Base Shear

The FPS model produces base shear values of 20,006.87 kN in the X direction and 20,046.87 kN in the Y direction (Table 4 and Figure 5), which are higher than those obtained for the fixed-base alternatives. The corresponding base shear values for the OMF, SMF, ordinary shear-wall, and special shear-wall systems are 13,854.59, 4,586.20, 10,385.41, and 8,901.78 kN in the X direction, respectively. A similar trend is observed in the Y direction. Therefore, although the FPS system lengthens the structural period and shifts the response toward a lower-acceleration region of the response spectrum, the resulting design base shear does not necessarily decrease.

This behavior is primarily associated with the seismic design parameters adopted for the isolated structure. Under the applicable seismic design provisions, the response modification factor used for the FPS-isolated system is lower than that assigned to several conventional fixed-base lateral-force-resisting systems. Consequently, the reduction in elastic seismic demand due to period elongation is partly offset by the lower force-reduction factor applied in the design procedure. In other words, the increased base shear obtained for the FPS model does not indicate inferior seismic performance, but rather reflects the different force-reduction assumptions applied to the isolated and fixed-base structural systems.

The effectiveness of the FPS system should therefore not be assessed solely on the basis of global base shear. For an isolated structure, seismic performance should be interpreted together with period elongation, interstory drift, floor displacement, isolator displacement, and the distribution of support reactions. In the present study, despite the higher design base shear, the FPS model produces substantially lower interstory drift than the fixed-base alternatives and maintains the isolator displacement well below its design capacity. This indicates that the primary benefit of the FPS system is the redistribution of seismic deformation and force demand rather than a direct reduction in the global design base shear (Table 5).

Table 3. Comparison of structural periods from the models

Structural system	Tx (s)	Ty (s)	Tx used (s)	Ty used (s)
FPS base isolation	3.063	2.580	2.54	2.54
OMF	2.750	2.290	1.89	1.88
SMF	2.750	2.290	1.89	1.88
Ordinary shear wall	1.930	1.480	1.89	1.48
Special shear wall	1.930	1.480	1.89	1.48

3.3. Lateral Displacement, Interstory Drift, and Performance Level

Compared with the fixed-base alternatives, the FPS model produces a substantial reduction in interstory drift (Figure 6). The average reduction ranges from 73.6% to 81.7% in the X direction and from 42.8% to 83.3% in the Y direction (Figure 7). This response is consistent with the fundamental behavior of base-isolated structures, in which a significant portion of the horizontal deformation is concentrated at the isolation interface (Table 6), thereby reducing deformation demand in the superstructure [4], [17].

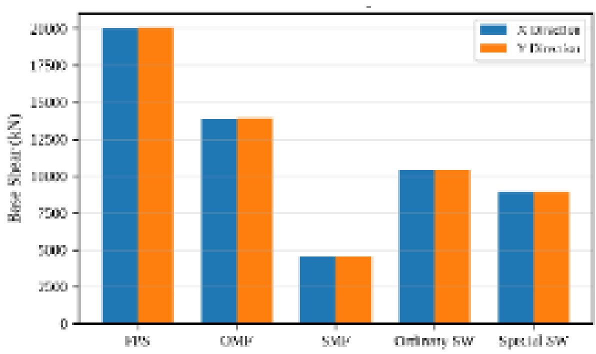

Figure 5. Base shear comparison in the X and Y directions.

Table 4. Base shear comparison.

System	X direction (kN)	Y direction (kN)
FPS base isolation	20,006.87	20,046.87
OMF	13,854.59	13,886.41
SMF	4,586.20	4,583.52
Ordinary shear wall	10,385.41	10,389.56
Special shear wall	8,901.78	8,905.32

Table 5. Summary of displacement and performance level of the FPS model.

Parameter	X direction	Y direction
Top-floor displacement	84.052 mm	129.29 mm
Global drift ratio	0.20%	0.31%
Maximum interstory drift	12.92 mm	31.84 mm
Story height at maximum drift	5000 mm	5000 mm
Maximum interstory drift ratio	0.258%	0.637%
Performance level	Immediate Occupancy	Immediate Occupancy

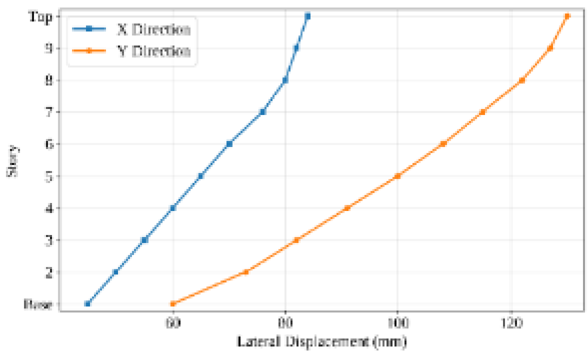

Figure 6. Lateral displacement profile of the FPS model

The observed drift reduction is also consistent with recent studies on isolated reinforced-concrete structures (Figure 7 and Table 6). Significant decreases in interstory drift have been reported for base-isolated buildings [6], while studies on bridge structures equipped with lead-rubber bearings have shown that period elongation and isolation-induced flexibility can reduce inertia-related demands and improve the response of primary structural components [7]. Although different isolation devices were adopted in those studies, the underlying response-control mechanism is comparable to that of the FPS system considered herein. A recent HDRB-isolated reinforced-concrete building study likewise reported improved drift control following period elongation [8].

Table 6. Average interstory drift reduction of the FPS model relative to fixed-base alternatives.

Fixed-base alternative	X direction	Y direction
OMF	81.7%	83.3%
SMF	73.6%	75.7%
Ordinary shear wall	80.6%	46.1%
Special shear wall	79.4%	42.8%

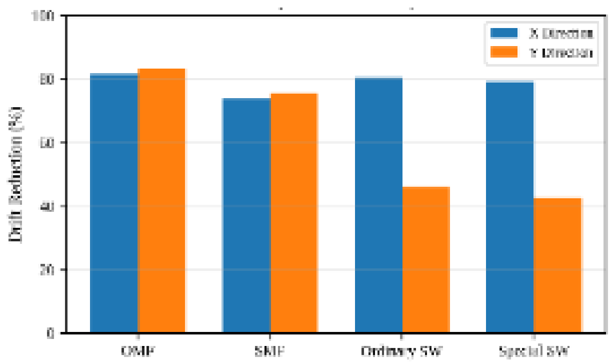

Figure 7. Average interstory drift reduction caused by FPS.

Table 7. Summary of FPS isolator displacement demand and design capacity

Component	UX (mm)	UY (mm)	Resultant
Minimum actual	40.559	30.240	-
Maximum actual	44.467	57.648	70.64
DM	221.11	221.11	221.11
Maximum ratio to DM	20.1%	26.1%	31.9%

From a performance-based perspective, interstory drift remains a key indicator for evaluating seismic response. Nonlinear seismic assessment has shown that drift ratio, together with member response and plastic-hinge development, can govern the assigned structural performance level under strong ground motion [13]. Accordingly, the principal benefit of the FPS in the present study is not merely a reduction in global force demand, but the redistribution of lateral deformation away from the superstructure toward the isolation layer, resulting in lower interstory drift and improved overall seismic performance.

3.4. *FPS Isolator* Displacement *Control*

Isolator displacement is a critical design parameter for Friction Pendulum Systems because excessive movement may lead to insufficient clearance, interaction with shear keys, or impact with adjacent structural and nonstructural components. Previous studies have shown that collision between an FPS device and a shear key can significantly alter the displacement response [18]. Accurate estimation of the peak isolator displacement is therefore essential for ensuring adequate displacement capacity and maintaining the intended isolation performance [9], [19].

In the present analysis, the maximum envelope displacements of the isolators are 44.467 mm in the X direction and 57.648 mm in the Y direction (Table 7). Because these directional maxima may occur at different isolator locations or analysis conditions, they should not be directly combined to obtain the maximum resultant displacement. Instead, the resultant displacement is determined from the simultaneous orthogonal displacement components at the same isolator location and analysis condition as

$$D_R = \sqrt{{U_X}^2 + {U_Y}^2} \quad (3)$$

where U_X and U_Y are the simultaneous isolator displacements in the two horizontal directions. Based on the analysis results, the maximum resultant displacement is 70.64 mm, corresponding to approximately 31.9% of the design displacement capacity, $D_M = 221.11$mm. The displacement demand therefore remains well below the adopted design capacity, indicating an adequate displacement margin for the response-spectrum loading considered in this study.

Although the calculated displacement demand satisfies the adopted design criterion, FPS behavior is inherently nonlinear and may be influenced by variations in friction coefficient, effective stiffness, vertical load, temperature, aging, and earthquake input characteristics. Robust optimization studies have demonstrated that uncertainty in FPS mechanical parameters can affect the seismic response of isolated structures [11]. Consequently, nonlinear time-history analysis using representative ground-motion records, together with sensitivity analyses of the principal FPS parameters, is recommended for further verification of the isolation-system performance.

3.5. Effect of FPS on Pile Foundation Requirement

The pile-foundation requirements obtained from the fixed-base and FPS models are summarized in Table 8. The fixed-base configuration requires 391 prestressed concrete spun piles with an outside diameter of 600 mm and a pile length of 12 m, corresponding to a total installed pile length of 4692 m (Figure 8). Based on the adopted geotechnical analysis using the Décourt method, the design axial resistance of a single 12 m pile is 3620 kN. In comparison, the FPS configuration requires 180 piles of the same diameter with a pile length of 10 m, for which the design axial resistance is 2940 kN per pile. The corresponding total installed pile length is 1800 m.

The relative reduction in total installed pile length is therefore calculated as

$$\eta_L = \frac{4692-1800}{4692} \times 100\% = 61.63\% \quad (4)$$

The result indicates a potential foundation efficiency of 61.63% in terms of total installed pile length under the adopted structural and geotechnical assumptions. This reduction reflects the combined effects of modified support-reaction distribution due to the FPS and the higher design axial resistance of the 10 m piles used in the FPS alternative compared with the 12 m piles in the fixed-base model. Therefore, the reduction in pile demand should not be attributed solely to changes in global seismic response, particularly because the FPS model produces a higher design base shear than several fixed-base alternatives. Instead, foundation demand is governed by the local combination of vertical reaction, horizontal force, overturning moment, and available pile resistance at each support location.

The foundation result should also be interpreted in the context of soil–structure interaction. Previous studies have shown that replacing simplified fixity assumptions with distributed SSI representation can significantly alter seismic displacement and demand-capacity ratios in pile-supported structures [15], while pile–soil interaction and soil conditions have also been shown to influence the seismic and long-term response of marine foundation systems [20]. Accordingly, the reported reduction in pile number and total length should be regarded as a design-stage efficiency indicator and should be confirmed through local support-reaction evaluation, pile-capacity checks, settlement analysis, pile-group effects, and soil–pile–structure interaction assessment.

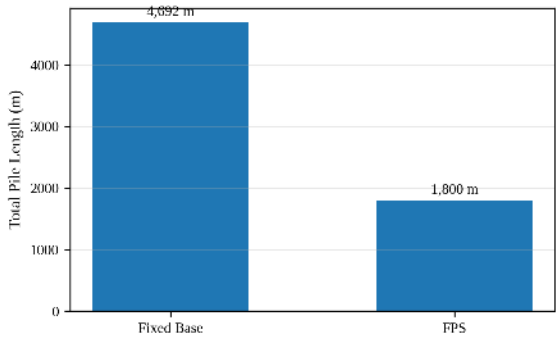

Figure 8. Total length comparison of 60 cm spun piles.

Table 8. Comparison of pile foundation requirement

Model	Pile Type	No. of Points	Depth	Total Length
Fixed base	CSP Ø60 cm	391	12 m	4692 m
FPS	CSP Ø60 cm	180	10 m	1800 m

3.6. Discussion of Previous Research and Limitations

The drift reduction and period lengthening obtained in this study agree with [4] and [17], who showed that friction pendulum bearings can improve the seismic performance of reinforced concrete buildings. However, the present study adds a substructure perspective by presenting the comparison of pile foundation requirements. This perspective is important because recent studies indicate that the response of isolated buildings is governed not only by the isolator but also by soil interaction, substructure behavior, and ground-motion characteristics [12], [21]–[23]. The response trends are also consistent with the earlier FPS assessment of the same hospital building [5] and with recent HDRB-based building results [8]. Importantly, the present work extends the earlier hospital study by linking the isolation-induced response modification to pile-foundation demand and total installed pile length.

From the methodological perspective, response spectrum analysis is suitable for initial evaluation and design comparison. Nevertheless, recent literature shows that FPS response can be affected by friction coefficient uncertainty, peak displacement demand, three-dimensional effects, long-period ground motion, and near-fault characteristics [9], [19], [24]. Therefore, the results should be viewed as an initial design stage that should be complemented by nonlinear time-history analysis, FPS parameter variation, and detailed geotechnical verification before being used as a final design basis (Figure 9).

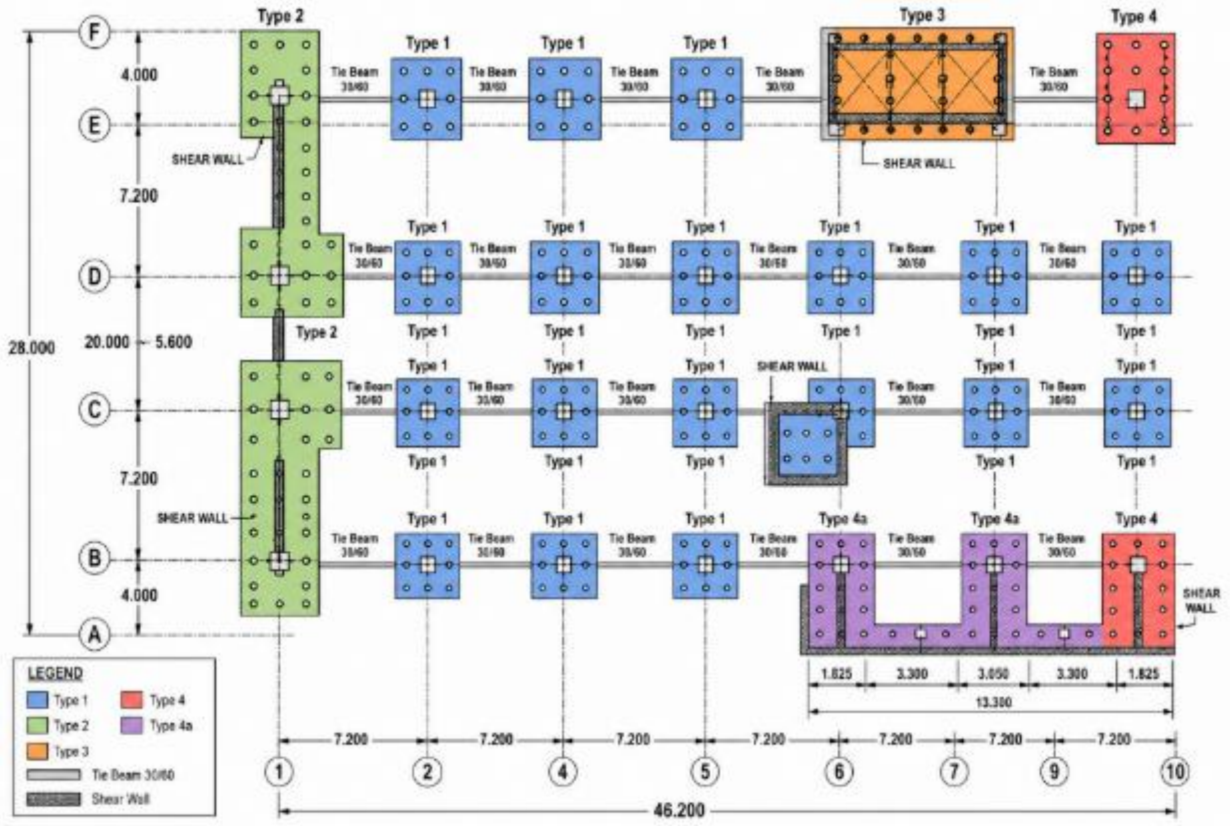

Figure 9. Foundation plan of the fixed-base model.

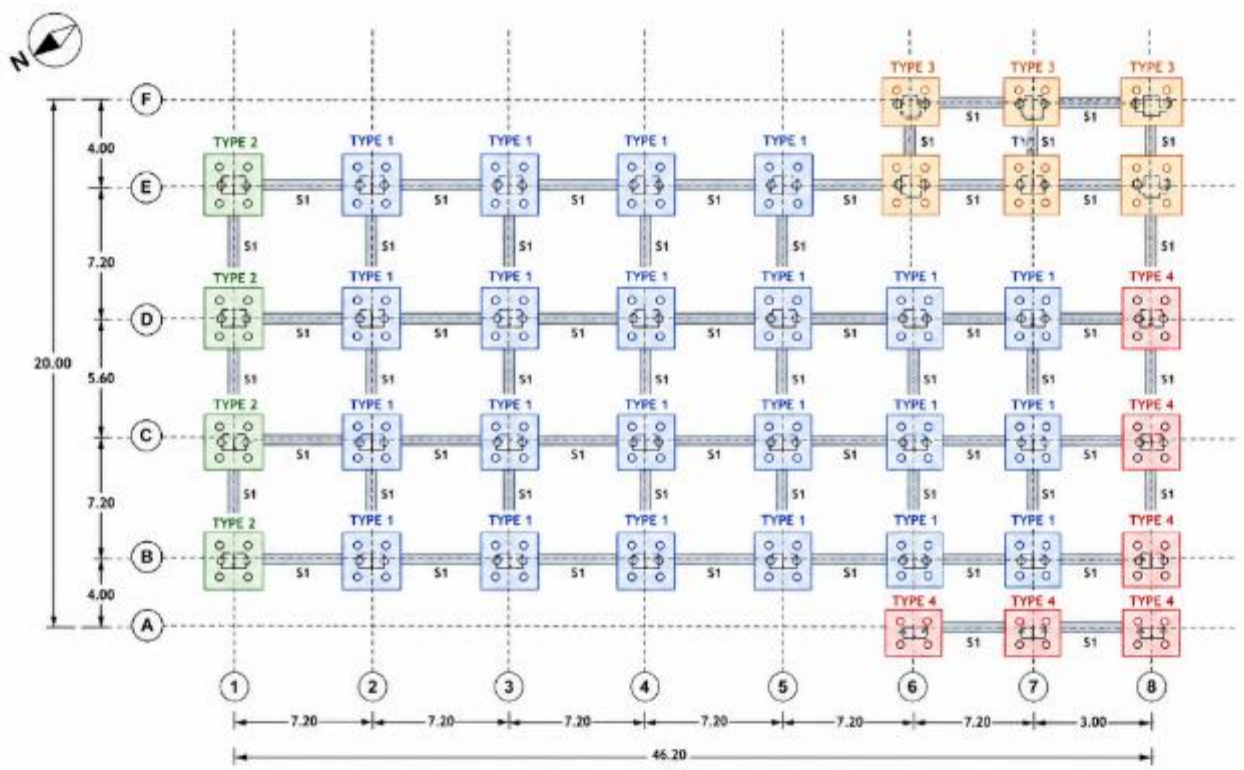

Figure 10. Foundation plan of the FPS model.

Taken together, these prior studies indicate that isolation-device behavior, nonlinear structural response, and soil-structure interaction should be considered as coupled contributors to foundation demand. The present response-spectrum comparison therefore provides evidence of potential pile-foundation efficiency, but not a complete SSI-based proof of pile reduction. A subsequent stage should incorporate nonlinear time-history analysis, distributed soil springs or p-y/t-z/q-z representation, reaction-envelope comparison, and pile-group settlement verification (Figure 10).

4. Conclusion

The application of a Double Friction Pendulum System (FPS) significantly modifies the seismic response of the investigated nine-story irregular hospital building. The FPS lengthens the dominant structural period to 3.063 s in the X direction and 2.580 s in the Y direction, shifting the structural response toward a lower spectral-acceleration range. This period elongation is accompanied by substantial reductions in interstory drift, ranging from 73.6% to 81.7% in the X direction and from 42.8% to 83.3% in the Y direction relative to the fixed-base alternatives.

The maximum isolator displacement remains within the adopted design capacity. The maximum resultant isolator displacement is 70.64 mm, corresponding to approximately 31.9% of the design displacement, $D_M = 221.11$mm. Although the FPS model produces higher global base shear than several fixed-base alternatives, the seismic performance should be interpreted through the combined response of structural period, interstory drift, isolator displacement, and local foundation demand rather than through base shear alone.

From the foundation perspective, the FPS alternative reduces the total installed pile length from 4692 m to 1800 m, corresponding to a potential reduction of 61.63% under the adopted structural and geotechnical design assumptions. This result reflects the combined effects of modified support-reaction distribution and the adopted axial resistance of the selected piles. Therefore, the reported reduction should be interpreted as a design-stage foundation-efficiency indicator rather than as an unconditional foundation-saving factor.

The main contribution of this study is the integration of seismic isolation performance with pile-foundation demand for an irregular essential building under Indonesian design conditions. Nevertheless, the foundation-efficiency result should be further verified through detailed support-reaction envelopes, axial and lateral pile-capacity checks, uplift, settlement, pile-group effects, pile-cap structural capacity, and soil–pile–structure interaction. Future studies should also incorporate nonlinear time-history analysis and sensitivity assessment of FPS parameters to provide a more comprehensive evaluation of the isolated structural system.

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