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Seismic Performance of Pile Slab Bridges with Variations in the Number of Lateral Pile Configurations

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Abstract

This study aims to evaluate the seismic performance of pile slab bridge structures in Riau Province as a mitigation measure against the high rate of bridge damage reported by Bina Marga in 2023, totaling 366 bridges with varying levels of deterioration. The analysis was conducted using the nonlinear static pushover method on three pile slab bridge models with five, six, and seven pile configurations to assess the influence of pile quantity on structural capacity. Structural modeling and analysis were performed using finite element–based software to obtain capacity curves, lateral displacements, and performance points in both X and Y directions. The results show that increasing the number of piles from five to seven enhances base shear capacity by up to 12% in the X-direction and 14% in the Y-direction, while lateral displacement and drift ratio increase by 7% and 9%, respectively. However, the five-pile model reached a plastic state at the performance point, with plastic hinges remaining within the Operational–Life Safety limit, indicating safe deformability under seismic loads. This research contributes a comparative evaluation of lateral pile configurations in pile slab bridge seismic performance, which has not previously been analyzed in the case of bridges in Riau Province.

Keywords: Nonlinear Static Pushover; Pile Slab; Performance Point; Plastic Hinge; Capacity Curve.

1. Introduction

Pile slab bridges represent one of Indonesia's most common and practical bridge systems due to their simple structural configuration, rapid construction process, and cost efficiency [1]. Pile slab bridges are lighter than conventional bridges, and the influence of live load in a single span contributes significantly to the overall dynamic response [2]. One of their key advantages lies in their adaptability to water-saturated or soft soils, where deep pile foundations transfer loads to stronger strata. This configuration enhances stability and minimizes differential settlement while ensuring construction quality and efficiency since most components are prefabricated [3, 4].

Structurally, a pile slab bridge consists of spun piles, pile heads, and slabs, which act as an integrated system to distribute superstructure loads into the ground [5]. The effectiveness of this load transfer mechanism depends on several factors, including the number of piles, spacing, and connection stiffness. Variations in these parameters may alter the system's overall stiffness, ductility, and lateral load resistance.

According to data from the Ministry of Public Works and Housing of the Indonesian government [6], approximately 366 bridges in Riau Province were reported to have sustained damage, including 316 in moderate condition, 43 severely damaged, and two critically damaged. For instance, the Cipamingkis Bridge collapse in Jonggol–Cariu resulted from

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severe scouring around shallow foundations, highlighting the vulnerability of conventional bridge systems to environmental and geotechnical factors. Such cases underline the urgency of evaluating bridge systems' seismic and structural performance as part of preventive maintenance and disaster mitigation strategies.

Previous studies have addressed various aspects of bridge performance under seismic loading. Ye [7] investigated bridge collapses triggered by earthquakes and emphasized that inadequate inspection and poor design detailing often contribute to catastrophic failures. Similarly, Novak et al. [8] and Shehu [9] analyzed the nonlinear response of reinforced concrete (RC) and masonry bridge structures, concluding that linear elastic assumptions cannot accurately capture the real seismic behavior of bridges. Htay et al. [10] proposed an incremental dynamic hybrid pushover strategy approach to develop fragility curves for continuous RC bridges, which improved the assessment of near-collapse performance levels.

The pushover analysis method has become widely used to investigate the nonlinear response of a bridge structure. This method applies monotonic lateral loads to capture structural response up to collapse, providing insights into ductility, capacity, and hinge formation [11]. Although effective for estimating displacement and capacity curves, pushover analysis must be interpreted carefully because it is static and does not fully capture the structure's dynamic behavior [10].

Although significant contributions have been made, a significant research gap remains regarding the influence of lateral pile configurations on the seismic performance of bridges, particularly pile-slab bridges on soft soil, such as in Riau Province. Previous studies primarily analyzed single-pile configurations or material improvements without systematically comparing different lateral arrangements. Consequently, the relationship between pile configuration, base shear capacity, and overall performance level under seismic loading remains insufficiently explored.

The present study investigates three pile slab bridge configurations of five, six, and seven piles arranged laterally to address this gap. Using nonlinear static pushover analysis, the research evaluates each configuration's capacity curves, performance points, and structural performance levels to determine the most efficient and resilient design. This approach aims to establish a rational framework for optimizing pile slab bridge configurations in seismic-prone areas, contributing new insights into bridge design, seismic safety, and cost-effectiveness.

The subsequent sections of this article are organized as follows: Section 2 describes the methodological approach, including model configuration, load conditions, and analytical procedures. Section 3 examines the results of the analysis and performance evaluation. Ultimately, Section 4 summarizes the conclusions and provides recommendations for bridge design considerations.

2. Research Methodology

During a severe earthquake, a structure's dynamic response is influenced not only by the behavior of the superstructure but also by the behavior of the surrounding soil [12]. Structure-soil interaction (SSI), a design concept that incorporates soil behavior into structural analysis, ensures that the foundation is no longer treated as a rigid (fixed) base but rather as a flexible and dynamic system [13]. The bridge structure to be analyzed in this study is a pile slab bridge structure with variations in the number of lateral piles of five, six, and seven. In conducting structural analysis, the bridge structure is modeled as a line element, while the plate uses a shell element to provide rigidity to the structural system. Soil is assumed to behave as a series of linear elastic springs, independent in the subgrade reaction approach [14].

The point of stiffness is a well-known concept in the design of piles that must withstand lateral stresses. It gives the piles the stiffness they need to resist these forces and prevent excessive bending. To determine the depth of the point of stiffness, average soil parameters are used and compared with findings from more advanced methods, such as finite element modeling and p-y curve analysis, which account for the special characteristics of each soil layer [15].

Structural analysis was performed using a linear dynamic analysis approach based on the response spectrum method, followed by nonlinear static analysis (pushover analysis) [16–18]. This procedure served as the basis for evaluating how variations in lateral column configurations affect the seismic resistance of slab-on-column bridge structures. The nonlinear pushover method is described in ASCE 41-17 and NCHRP-440, which relate base shear-displacement capacity to the demand spectrum. This concept enables performance-based evaluation by identifying the performance point at which the capacity satisfies the load.

The pile slab structure model to be analyzed is divided into three models: pile slab bridges with seven-pile, six-pile, and five-pile configurations, as in Figures 1 to 3.

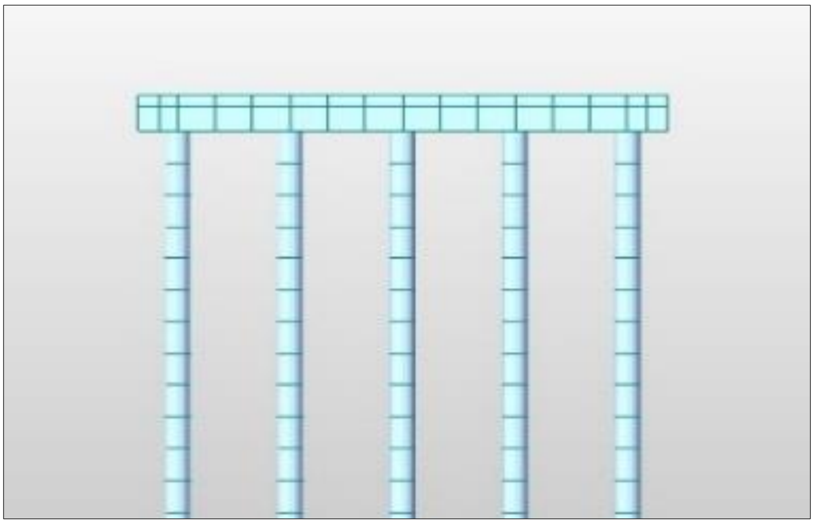


Figure 1. Pile Slab with Five-Pile Configuration

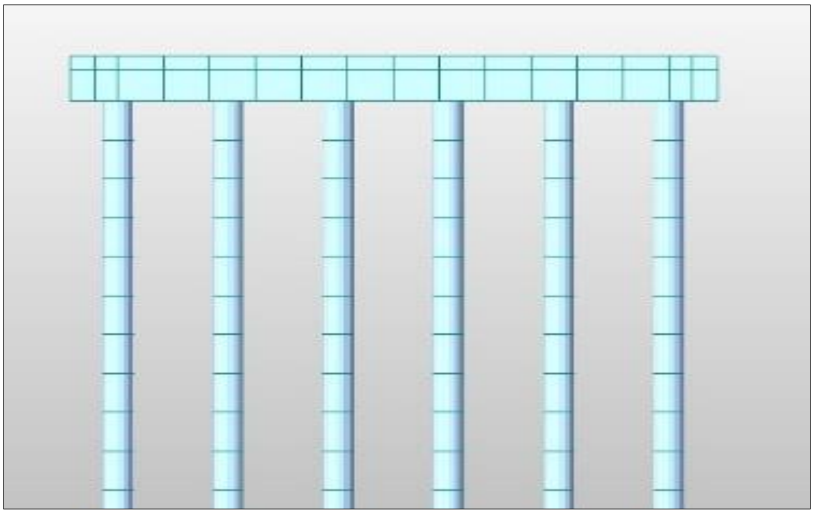


Figure 2. Pile Slab with Six-Pile Configuration

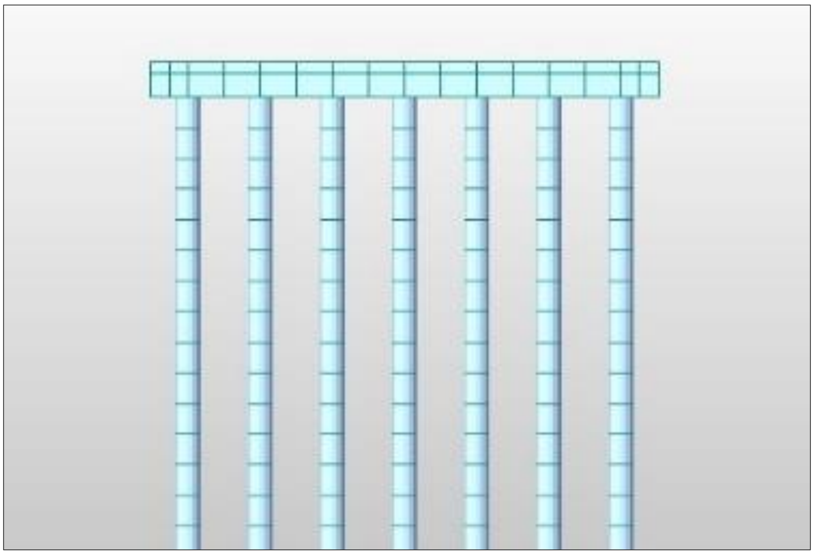


Figure 3. Pile Slab with Seven-Pile Configuration

The research flowchart of this study can be seen in Figure 4.

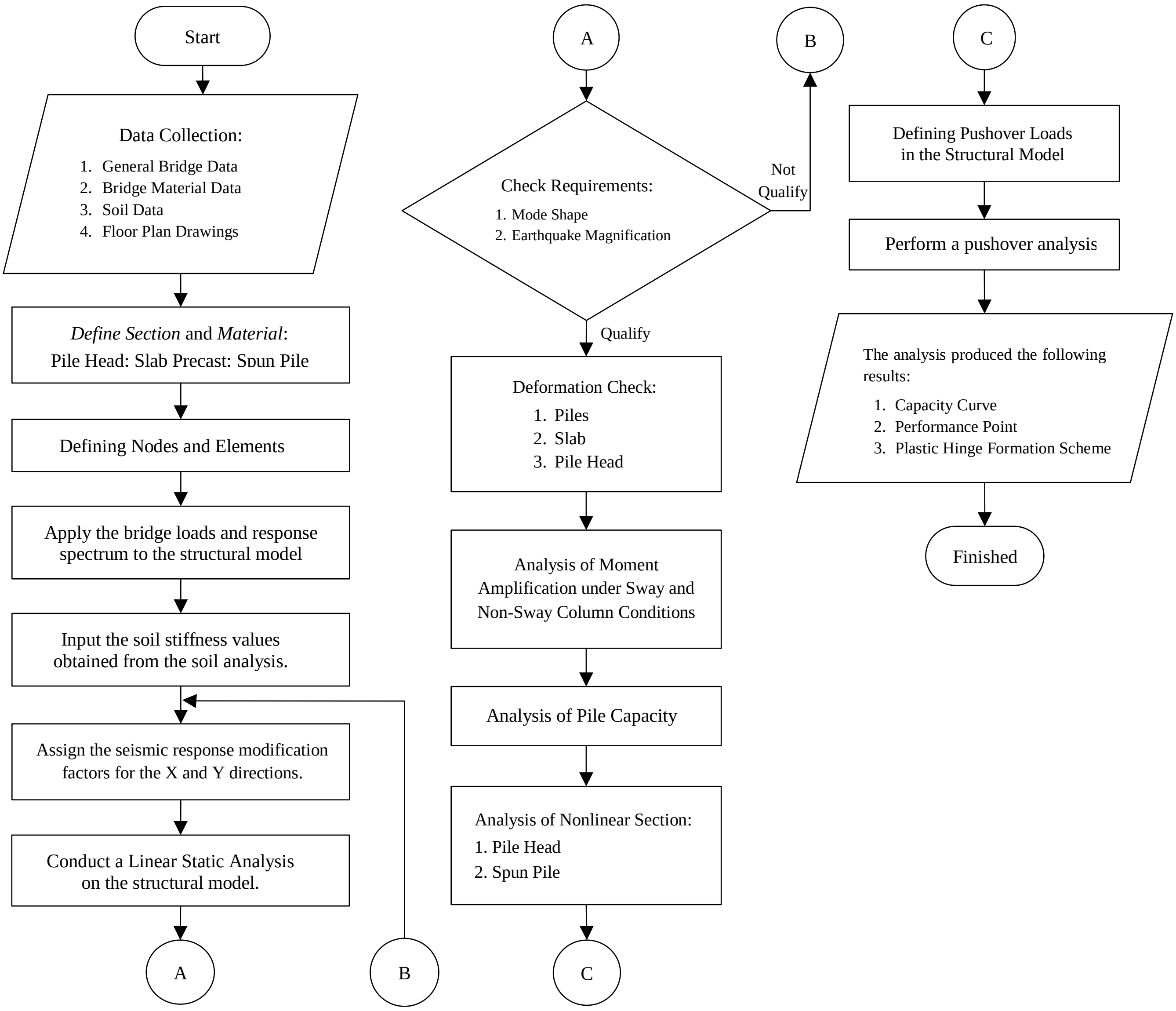


Figure 4. Research Flowchart

2.1. Design Load

The loading on the pile slab bridge structure is carried out in accordance with SNI 1725:2016 [19]. Table 1 illustrates the masses that must be entered into the pile slab model analysis.

Table 1. Pile Slab Design Load

Design Load		Load Size	Units
Barrier		19,200	kN/m²
Asphalt		1,120	
Uniform Distributed Load (UDL)	Traffic 1 (7 m)	9	
	Traffic 2 (14 m)	9	
	Traffic 3 (70 m)	6,429	
Knife Edge Load (KEL)		68,600	kN/m
Brake Load (TB)		8,836	
Temperature Load	T+	40	°C
	T-	15	

2.2. Nonlinear Static Pushover

Nonlinear static analysis is a structural analysis method in which loads are applied incrementally, and the structural response is calculated by taking into account that the relationship between force and deformation is no longer linear, whether due to material behavior or changes in the structure's geometry. This method is used to describe the actual conditions of a structure once it has exceeded its elastic limit that is, when elements begin to crack, yield, or approach failure. [11]. This analysis evaluates the structure's seismic behavior against the planned earthquake load based on the capacity curve formed. Additionally, this analysis can provide information on critical parts of the structure. In the context of pile slab bridges, the nonlinear pushover method provides insight into how pile configurations influence the lateral stiffness, ductility, and overall seismic performance of the structure. Since pile slab systems combine substructure–superstructure interaction, this approach captures nonlinear material behavior and the progressive formation of plastic hinges at critical locations such as pile heads and pile tips.

2.3. Moment Curvature Relation

The moment-curvature of a concrete reinforcement section is typically determined for both the confined and unconfined sections, using various compressive strains associated with the following points: the moment of cracking, the initiation of concrete nonlinearity, the yield point of the longitudinal reinforcement, the first phase of strain hardening, the detachment of the concrete cover, and the maximum capacity [20]. Curvature moment analysis is a necessary stage in determining the ductility of a structural element that is closely related to moment redistribution, where a statically indeterminate structure will not collapse when one of the cross-sections reaches its maximum capacity, but will distribute the moment to the cross-section area that has not reached its maximum capacity.

The nonlinear properties of the material and plastic hinges of each pile slab element are determined through the cross-section analysis in the form of moment curvature of the cross-section. According to Park & Paulay [21], the moment-curvature curve is shown in Figure 5.

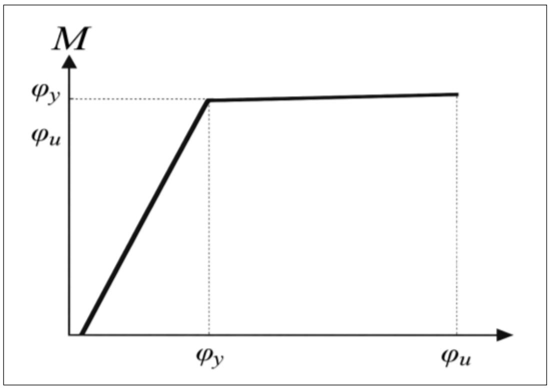


Figure 5. Concrete Moment–Curvature Curve [21]

In Figure 5, there are two conditions: the yield curvature condition and the ultimate curvature. The moment-curvature curve is then used to estimate the backbone curve's rotation value by multiplying the plastic hinge length (Lp) on each pile slab bridge structure element.

2.4. Plastic Hinge Length

Plastic hinges are areas defined at a distance equal to twice the depth of the component from the face of the column or beam where yielding of reinforcement can occur as a result of lateral displacement [22]. In the AASHTO guidelines (2011), a formulation is established for calculating the plastic hinge length [23]. The equation for the length of the plastic hinge (L_p) of columns on pile slab bridges can be seen in Equation 1:

$$L_p = 0.1H + D^* \leq 1.5D^* \tag{1}$$

where H is the length of the shaft from the ground level to the point of inflection (in.), D^* is the shaft diameter in the direction currently being considered for the oval-shaped shaft (in.). The equation for the length of the plastic joint in the beam can be seen in Equation 2:

$$L_p = \frac{H}{2} \tag{2}$$

Where H denotes the cross-sectional dimension orthogonal to the bending axis (in.), the application of seismic loading to a reinforced concrete structure results in the development of discontinuities as the moment capabilities of the members are obtained. Plastic hinges develop, and the response of the structure becomes inelastic [23, 24].

2.5. Moment Rotation Relation (Backbone Curve)

The correlation between load and displacement is linear at the initial stages of loading. As the load displacement at the endpoint of beam increases, the cross-sectional reaction force exhibits a brief, linear increase before transitioning into a curved phase, indicating the structure's transition into the plastic stage [25].

Nonlinear static pushover analysis requires a structural model that can capture the central damage state of structural elements during seismic response, which is also known as a hysteresis model. The hysteresis model estimates the deviation from the backbone curve due to the load on the structural element. The backbone curve illustrates the force and deformation characteristics, serving as a fundamental basis for assessing the overall capacity of the structure [15]. Figure 6 illustrates the moment–rotation curve (backbone curve):

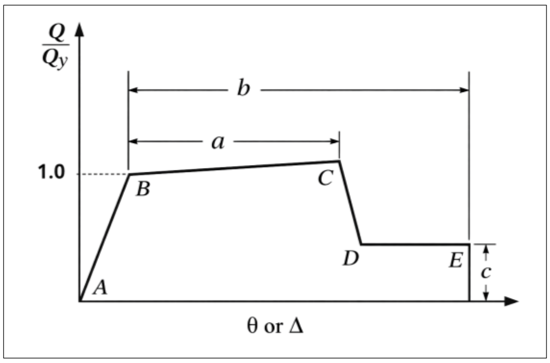


Figure 6. Moment Rotation Curve [26]

According to ASCE 41-17 [26], the rotation value is obtained through Equations 3 and 4 as follows:

$$\theta_y = \phi_y \times L_p \tag{3}$$

$$\theta_u = \phi_u \times L_p \tag{4}$$

where θ_y is yield rotation (in rad), θ_u is ultimate rotation (in rad.), ϕ_y is yield curvature (in 1/m), ϕ_u is ultimate curvature (in 1/m), and L_D is plastic hinge length (in m). With the acceptance criteria boundary condition value of the structure based on ASCE 41-17 is determined according to Equations 5 to 7 as follows:

$$CP = \theta_{\text{point}E} \tag{5}$$

$$LS = 0.75 \cdot CP \tag{6}$$

$$IO = 0.67 \cdot LS \tag{7}$$

where *CP* is Collapse Prevention, *LS* is Life Safety, *IO* is Immediate Occupancy, and $\theta_{point\ E}$ is the rotation that occurs on the curvature moment curve at point E, Figure 6.

2.6. Performance Level

Based on the nonlinear static pushover analysis results, the structural performance level can be determined using NCHRP on "Performance Based Bridge Design," as shown in Table 2:

Table 2. Bridge Performance/Design Parameters [27]

Level	Description	Drift %	Ductility
I	Fully Operational	<1.0	<1.0
II	Operational	1.0	1.0
III	Life Safety	3.0	2.0
IV	Near Collapse	5.0	6.0
V	Collapse	8.7	8.0

To determine the drift ratio, Equation 8 is used as follows:

$$Drift = \frac{D}{H} \times 100\% \tag{8}$$

where *D* is the lateral displacement (m), and *H* is the free-standing pile height (m).

2.7. Performance Point

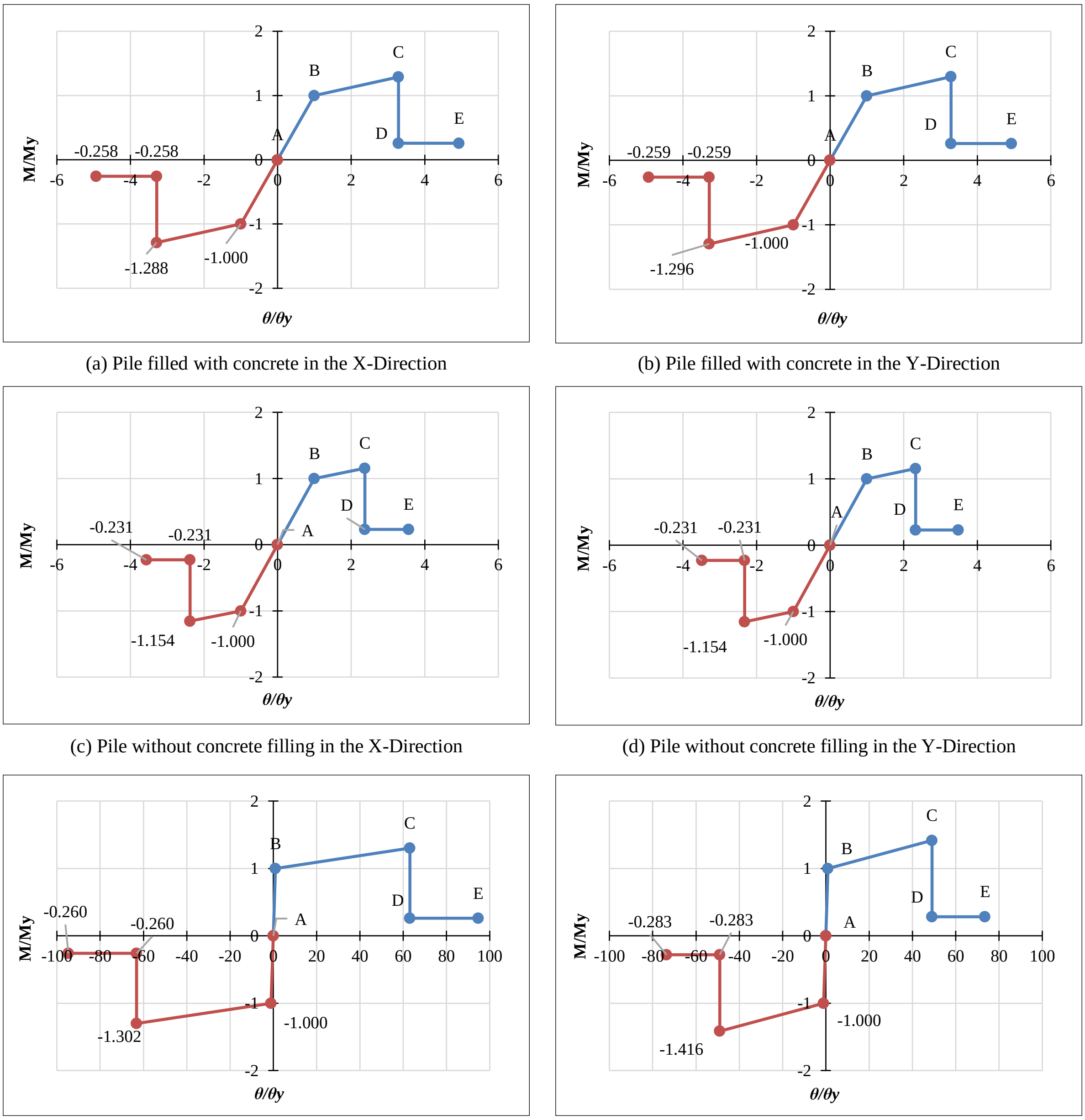
The performance point represents an estimate of the structural capacity to resist the applied seismic demand. The resulting performance point curve consists of two spectra: the capacity and the demand spectrum. At this point, information such as the building's period and the effective damping resulting from changes in structural stiffness due to the formation of plastic hinges can be obtained. Based on this information, other structural responses, such as inter-story drift and the location of plastic hinges, can also be determined.

3. Results and Discussion

Through nonlinear static pushover analysis, capacity curves, performance points, and structural performance levels on pile slab bridges will be obtained.

3.1. Backbone Curve

Through the results of the plastic joint length and the moment-curvature curve obtained through nonlinear analysis on each cross-section, the moment-curvature curve and plastic joint length are then used in estimating the rotation value for the backbone curve on each element. The top 1-meter section of the column was reinforced with concrete and modeled with a different backbone curve compared to the section of the column that was not reinforced with concrete. The remaining lower section of the pile was not reinforced with concrete. The backbone curves of each element are shown in Figure 7.



(a) Pile filled with concrete in the X-Direction

(b) Pile filled with concrete in the Y-Direction

(c) Pile without concrete filling in the X-Direction

(d) Pile without concrete filling in the Y-Direction

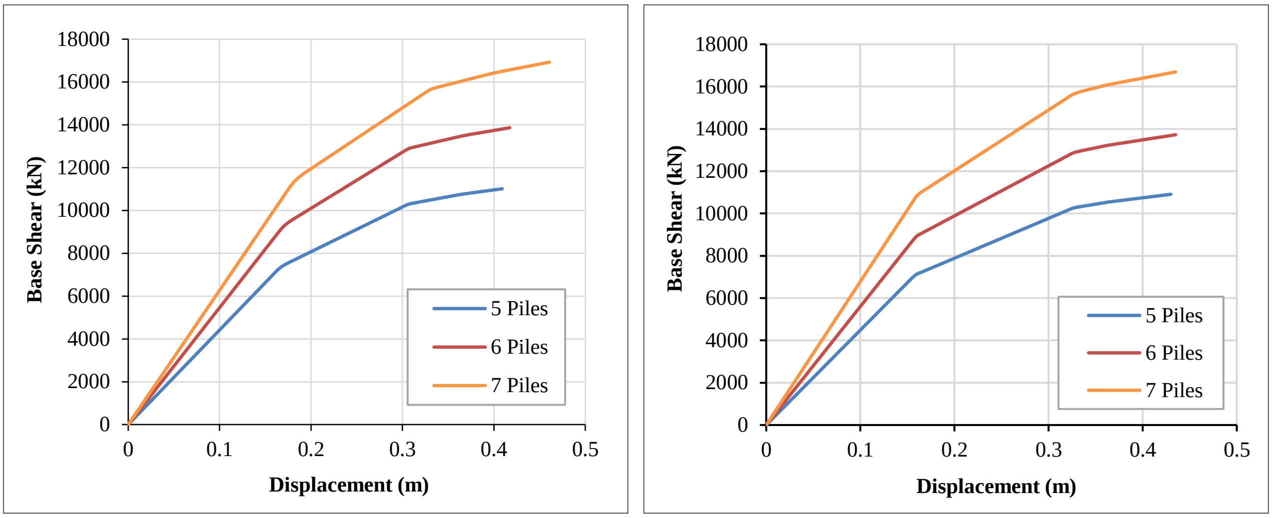
(e) Pile Head in the X-Direction

(f) Pile Head in the Y-Direction

Figure 7. Backbone Curve for Each Element

3.2. Capacity Curve

The capacity curve is the relationship between displacement (D) and the base shear force (V) in a structure that shows a linear condition before reaching a yield condition and then behaves nonlinearly. The results of comparing the capacity curve analysis on the pile slab bridge model with five, six, and seven pile configurations can be seen in Figure 8.



(a) X-Direction (b) Y-Direction

Figure 8. Capacity Curve in X and Y Directions

Based on the capacity curve obtained from the three pile slab models, the ultimate of displacement and base shear can be seen in Table 3:

Table 3. Ultimate condition capacity curve results

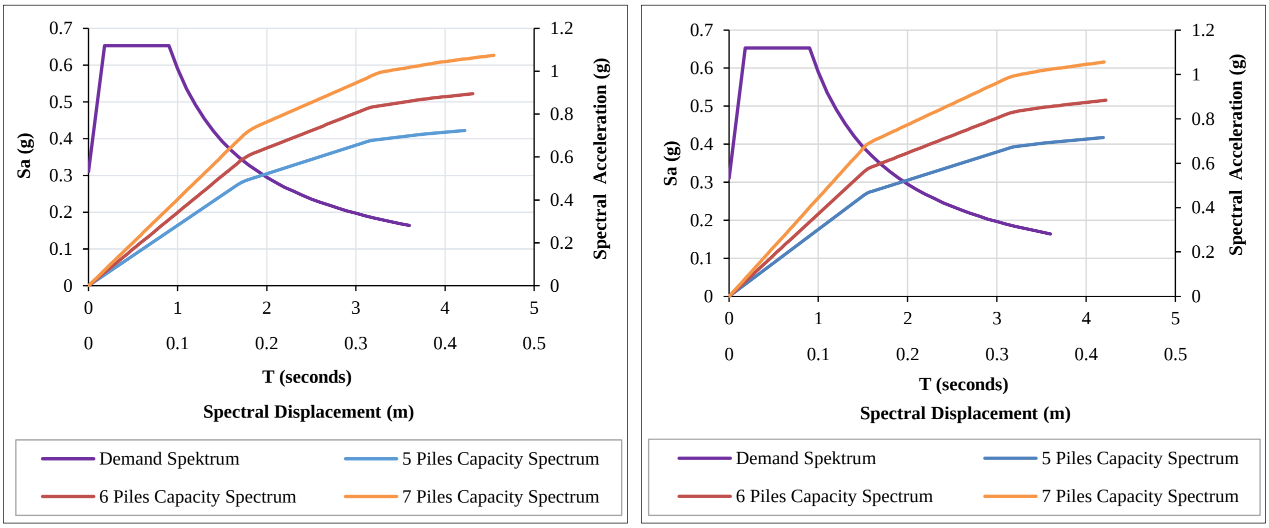
Model		Displacement (m)	Base Shear (kN)
5 Piles	X	0.409	11013
	Y	0.430	10909
6 Piles	X	0.417	13864
	Y	0.435	13724
7 Piles	X	0.461	16925
	Y	0.435	16694

The base shear capacity in the X-direction increased by 12% in the seven-pile configuration compared to the five-pile model. This improvement results from increased lateral stiffness and a more uniform redistribution of seismic forces among the pile group. As a result, the bridge experiences reduced local stress concentrations and higher resistance to lateral deformation.

3.3. Performance Point

A performance point is an estimate of the structure's capacity to withstand the load (demand) given. At the performance point, information can be obtained regarding the structure period and effective damping resulting from changes in structural stiffness following the occurrence of plastic hinge mechanisms, so that other structural responses, such as inter-story drift and plastic hinge positions, can be determined. The following are the performance point results of three pile slab models, as seen in Figure 9.

In the X and Y direction performance point graphs of the five-pile configuration pile slab model, it is found that the structure at the time of the performance point is already inelastic (plastic), while through the performance point results on the six and seven-pile configuration pile slab models, it is found that both structural models are still elastic at the time of the plan earthquake in the X and Y directions.



(a) X-Direction (b) Y-Direction

Figure 9. Performance Point Results in X and Y Directions

The values obtained through the performance point results on the pile slab bridge structure model can be seen in Table 4. Where *V* is the maximum base shear inelastic condition at the performance point (kN), *D* is the maximum displacement inelastic condition at the performance point (m), S_a is the spectral acceleration at the performance point (g), and S_d is the spectral displacement at the performance point (m).

Table 4. Pile Slab Bridge Performance Point Results

Model		*V* (kN)	*D* (m)	S_a (g)	S_d (m)
5 Piles	X	7318	0.166	0.481	0.172
	Y	7317	0.170	0.480	0.166
6 Piles	X	8233	0.151	0.531	0.156
	Y	8610	0.154	0.555	0.149
7 Piles	X	9102	0.145	0.578	0.143
	Y	9581	0.141	0.606	0.137

Figure 9 shows the capacity curves of the three-pile models. The five-pile configuration model exhibits a steep initial slope but reaches its yield point earlier, indicating lower ductility. In contrast, the seven-pile configuration maintains a higher post-yield slope, which implies greater energy dissipation capacity and improved seismic performance.

3.4. Performance Level and Plastic Hinge Distributed

The structural behavior is examined when the load acting on the structure continues to increase linearly, and when the load on the structure is relatively small, the magnitude of the moment at each cross-section is still in the elastic region. Then, if the load is increased, it will cause the magnitude of the moment at one of the cross-sections to reach the plastic moment condition, which will form the first, second, and third plastic joints, and so on, until a sufficient number of plastic joints are formed to cause the structure to collapse.

The plastic hinge scheme in the pile slab bridge structure model with five, six, and seven pile configurations yields first at the end of the pile (under the pile head) and then at the pile part below the ground. The drift ratio results can be used to determine the structural performance level of the three-pile slab bridge structure models (see Table 5).

Table 5. Drift Ratio of Pile Slab Bridge Structure

Model		Drift Ratio (%)	Performance Level
5 Piles	X	2,078	Operational–Life Safety
	Y	2,123	Operational–Life Safety
6 Piles	X	1,884	Operational–Life Safety
	Y	1,921	Operational–Life Safety
7 Piles	X	1,814	Operational–Life Safety
	Y	1,766	Operational–Life Safety

The scheme of plastic joints that occur in pile slab bridges under conditions of exceeding the maximum limit of structural capacity or collapse state can be seen as follows:

- ***Five-pile configuration model***

As shown in Figures 10 and 11, in the five-column configuration—both in the X and Y directions—it can be seen that the structure collapses first at the ends of the columns, specifically at the column heads.

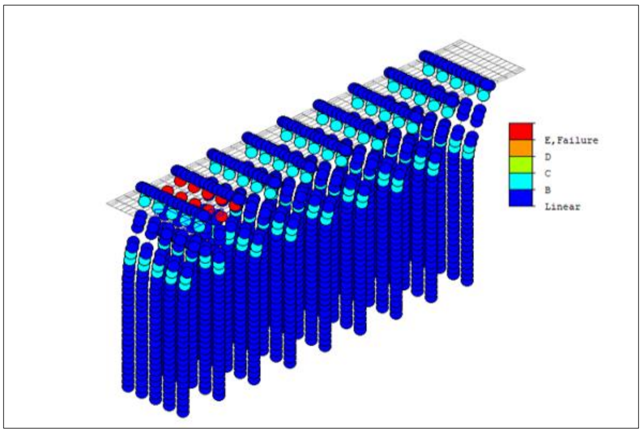


Figure 10. Yield Status of Pile Slab with Five-Pile Configuration in the X-Direction

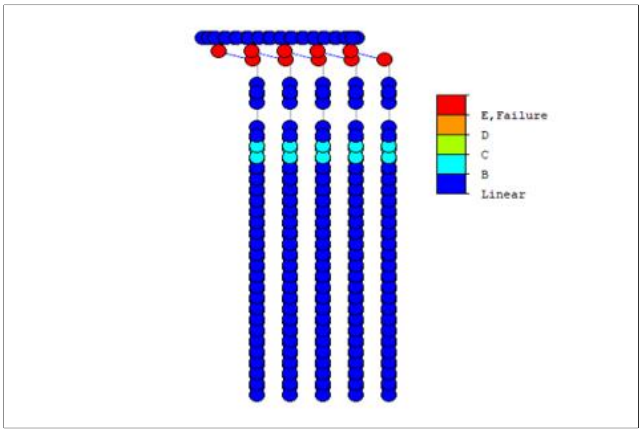


Figure 11. Yield Status of Pile Slab with Five-Pile Configuration in the Y-Direction

- ***Six-pile configuration model***

Figures 12 and 13 illustrate that in the six-column configuration, both in the X and Y directions, structural failure initially occurs at the column ends, particularly at the lower section of the column heads.

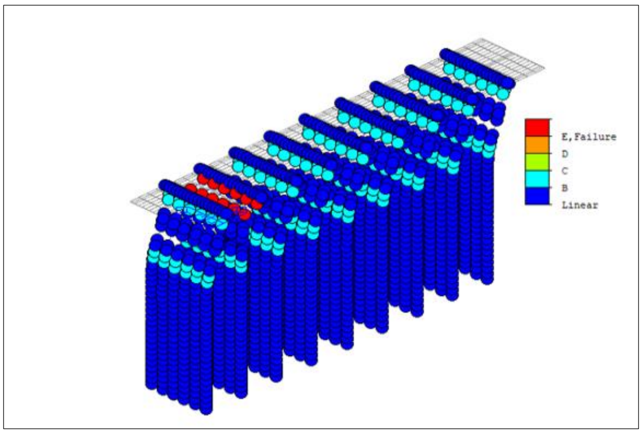


Figure 12. Yield Status of Pile Slab with Six-Pile Configuration in the X-Direction

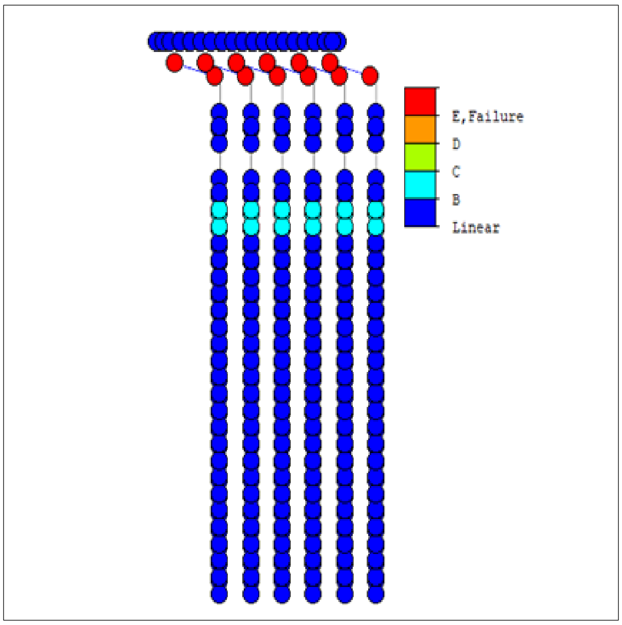


Figure 13. Yield Status of Pile Slab with Six-Pile Configuration in the Y-Direction

- ***Seven-pile configuration model***

In the seven-pile configuration in both the X and Y directions, it is explained that the structure collapses at the pile tip (below the pile head) first, as shown in Figures 14 and 15.

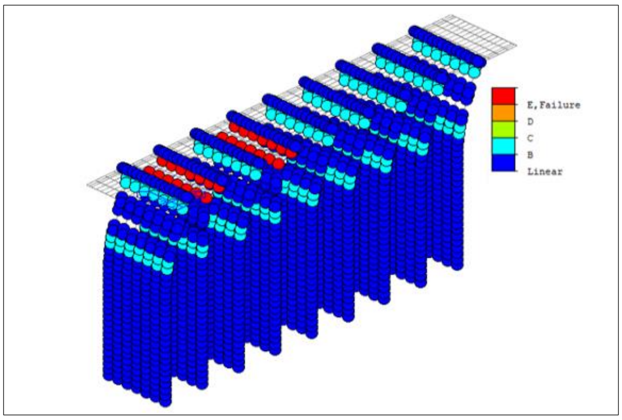


Figure 14. Yield Status of Pile Slab with Seven-Pile Configuration in the X-Direction

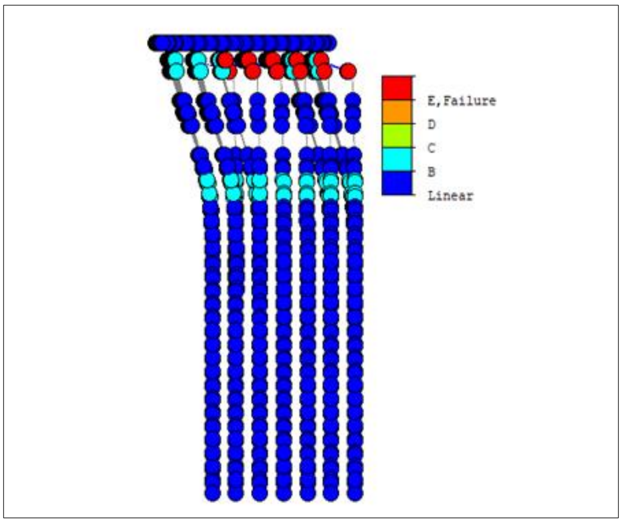


Figure 15. Yield Status of Pile Slab with Seven-Pile Configuration in the Y-Direction

As the number of piles increases, the total lateral stiffness also increases, leading to higher base shear capacity. However, this also results in reduced ductility, as indicated by the smaller curvature after yielding. Therefore, while additional piles enhance strength, they may slightly reduce the energy absorption capacity of the system. These findings suggest that optimizing the number of lateral piles is crucial to achieving an effective balance between strength and ductility. The five-pile configuration offers a good compromise, providing sufficient lateral resistance without excessive material use, which is beneficial for cost-efficient bridge design in seismic regions.

The study by Setiawan et al. [1] determined that incorporating soil-pile structure interaction (SPSI) results in the development of predominant plastic hinges in the upper piles, leading to a distributed curvature pattern in the embedded pile region and yielding a moderate curvature intensity in the upper piles relative to models that ignore the SPSI effects.

Similarly, the present study also reveals that the analysis incorporating soil structure interaction indicates the formation of plastic hinges at the pile head region (immediately below the pile cap), suggesting that the maximum bending moment occurs at this location. Therefore, it is recommended to provide additional reinforced concrete infill at the pile head to reduce the bending moment and enhance the overall structural performance.

4. Conclusion

The nonlinear pushover analysis of the pile slab bridge models with different lateral pile configurations revealed notable variations in structural performance under seismic loading. Among the three configurations analyzed, the seven-pile model demonstrated the highest lateral load capacity and stiffness, indicating superior resistance to seismic forces. The capacity curve showed that the increased number of piles effectively enhanced the overall lateral strength and reduced displacement demand. Furthermore, the performance point analysis indicated that all three models exhibited performance levels within the Operational to Life Safety (LS) range according to ASCE 41-17. At this level, minor cracking was observed in the structural elements without significant damage or loss of structural integrity, suggesting that all configurations can maintain functionality during design-level earthquake events.

The formation of plastic hinges was observed to occur earlier and in greater numbers in the five-pile configuration, reflecting higher stress concentrations due to reduced lateral stiffness. However, despite these conditions, the five-pile model still exhibited adequate structural strength and demonstrated efficient material utilization compared to other configurations. In contrast, the seven-pile bridge model showed greater resilience during the development of plastic hinges, maintaining its capacity and stability under increased lateral demands. The six-pile configuration provided a balanced performance between strength, ductility, and economy. Overall, the analysis results indicate that increasing the number of lateral piles enhances strength and displacement control but may reduce efficiency in material use. Therefore, an optimal pile configuration, such as the six-pile model, can be recommended to achieve a practical balance between seismic performance, cost-effectiveness, and ease of maintenance for pile slab bridge structures in seismic-prone regions.

5. Declarations

5.1. Author Contributions

Conceptualization, A.K. and F.R.S.; methodology, A.K.; software, A.K. and F.R.S.; validation, A.K., F.R.S., and I.; formal analysis, F.R.S.; investigation, A.K.; resources, F.R.; data curation, F.R.; writing—original draft preparation, A.K.; writing—review and editing, A.K., F.R.S., and I.; visualization, F.R.S.; supervision, A.K. and I. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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