Journal of
Advanced Civil and Environmental Engineering
Vol.9, No.1, 2026, pp 55-69
ISSN: 2599-3356
DOI: http://dx.doi.org/10.30659/jacee.9.1.55-69

Technical Evaluation of Bridge Pier Structural Strengthening to Meet Bridge Class Standards Due to Changes in Structural and Traffic Loads

A Didik Setyo Purwantoro[1], Muhammad Nur Fajar[1*], Herlina Arifin[1], and Alfina Maysyurah[1]

[1]*Civil Engineering Study Programme, Faculty of Engineering, University of Muhammadiyah Sorong, Pendidikan Street No. 27, Sorong City, Southwest Papua 98416, Indonesia*

[*]*Corresponding author: muhammad.n.fajar53@gmail.com*

(**Received:** 13th May 2026 ; **Revised:** 3rd June 2026 ; **Accepted:** 8th June 2026)

Abstract: Upgrading bridge specifications from Class B to Class A necessitates a significant increase in structural load capacity. This study evaluates pier P-2, which exhibited capacity discrepancies under new loading standards. The analysis focuses on the stability of existing pile foundations and reinforcement design through modifications to pile-cap dimensions and the addition of piles. The methodology integrates AllPile software with analytical validation via the Chin and Mazurkiewicz methods, alongside axial load tests following ASTM D1143. Structural verification was conducted using the AASHTO LRFD approach to ensure precise load and resistance factors. Static load test results showed a single pile axial capacity of 1,814.23 kN *(SF=2)*. Analysis of the initial 7x3 pile group configuration (21 piles) yielded a total group bearing capacity (Q_{tg}) of 11,995.64 kN. This value is lower than the design axial load (V = 21,228.88 kN), rendering the foundation "unsafe." To achieve stability, reinforcement piles were designed. Utilizing a new static capacity (Q_{static}) of 2,875.85 kN (SF=2), the group capacity increased to 12,012.24 kN. With additional reinforcement valued at 16,040.40 kN, the final total capacity (Q_{tg}) reached 28,052.60 kN. This result satisfies safety requirements (Q_{tg} > V_{total} = 23,152.90 kN), confirming the system as "safe." Reinforcement pile depth is set between 38 m to 42 m based on N-SPT values, referencing the calendaring results at 34 m.

Keywords: Bridge Class Upgrade; Pile stability; Pile-Cap Reinforcement; AllPile Analysis; Static Load Test

1. Introduction

Bridge structural planning often requires adjustments to the bearing capacity of lower components to accommodate specification upgrades from Class B to Class A, driven by increased traffic volume and loading. The Kali Bian Bridge is a strategic infrastructure project located in South Papua Province, Indonesia. The original design featured a Class B steel truss bridge with a total width of 7 meters (0.5 + 6 + 0.5) and a total span of 500 meters, consisting of nine standard spans (50 – 60 – 50 – 50 – 60 – 60 – 60 – 60 – 50 m).

Construction began in 2010 but was suspended, leaving only the substructure completed, specifically the pile foundations at Pier 2 and Pier 3. Following transportation system evaluations, the project resumed in 2023-2024 with a revised design as a Class A bridge, increasing the total width to 8 meters (0.5 + 7 + 0.5). Due to increased loads, the bridge pier's substructure, including the piles and pile cap, needs to be redesigned to accommodate the new superstructure. The existing pile material quality, based on load observations and predictions, is expected to deteriorate due to corrosion, leading to a decrease in the pile group's bearing capacity. In terms of load capacity, Class B bridges are designed to handle 70% to 80% of the BM-100 standard load, whereas Class A bridges are fully designed for 100% of the BM-100 load. Consequently, Class A bridges are significantly stronger and capable of supporting continuous heavy logistics and container traffic. The loading parameters for Class A bridge design refer to SNI 1725:2016, Loading for Bridges, and the Indonesian Bridge Engineering Design Regulations [3]. In accordance with AASHTO standards, the primary loading types for Class A bridge design are further reinforced. Regarding traffic loads (Live Loads - LL), the design refers to the HL-93 vehicle load as per AASHTO LRFD, which consists of a combination of: 1) Design Lane Load ('D' Load), which is a Uniformly Distributed Load (UDL) equivalent to the standard lane load combined with a Knife Edge Load (KEL); 2) Design Truck Load ('T' Load), specifically a three-axle design truck (HS-20-44) with specified wheel loads; and 3) Design Tandem Load, consisting of two heavy axles positioned to produce maximum moment or shear [1], [4].

An investigation into the bearing capacity of the existing piles at Pier 2 was initiated due to concerns regarding their ability to support the design loads, particularly for the bridge class upgrade mentioned above. This investigation includes an assessment of corrosion levels on the bridge pier to evaluate structural capacity degradation, especially for steel/reinforced concrete piles exposed to aggressive corrosive environments (regional factors) that cause material thinning, reduction in cross-sectional area, and loss of structural strength. Subsequently, dynamic load testing on the pile foundations was conducted using a Pile Driving Analyzer (PDA) to rapidly evaluate pile bearing capacity, structural integrity (defects/cracks), hammer efficiency, and pile stress based on mechanical wave principles (ASTM D4945) [4].

This analysis provides a design review for the strengthening of the Kali Bian Bridge pier in South Papua to accommodate changes in bridge classification and structural loading. Furthermore, it develops a design model for additional reinforcement of the pile foundation system, including both the pile elements and the pile cap.

The novelty of this research lies in the design of the pile cap model and the pile foundation configuration, while remaining compliant with stability analysis and pier reinforcement evaluations. This specific reinforcement model for the pile cap has not been previously studied as an integral part of bridge substructures, specifically for pier structures. The design also accounts for regional factors, highlighting the effects of land consolidation on extensive puddle formation in Indonesia, which is associated with land subsidence in lowlands and alluvial soil layers [11].

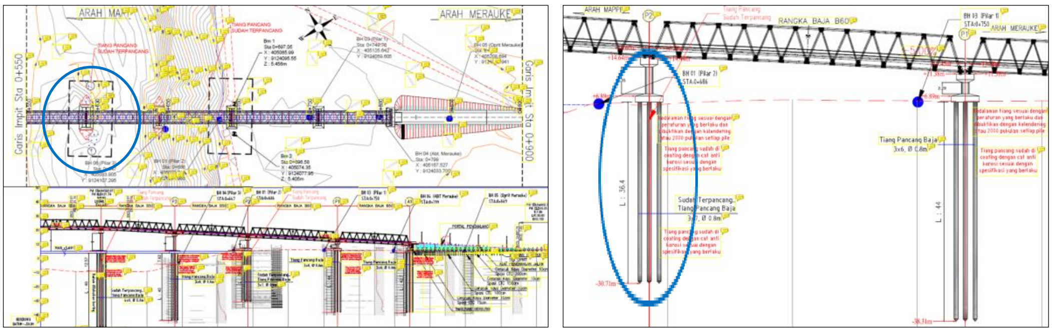

Fig. 1. Layout Illustration Based on The Bian Bridge Design
(Source: Substructure Design, 2022)

2. Research Methods

The following methods are employed for the stability analysis and technical evaluation of the bridge pier reinforcement, resulting from the bridge classification upgrade from Class B to Class A [6]. As a preliminary overview, a layout illustration is provided based on the Kali Bian Bridge design, focusing on the specific spans under review: Abutment-1, Pier-1, and Pier-2 as the primary structures for analysis.

2.1. Evaluate Pile Capacity Using AllPile Software

2.1.1. Soil Investigation Data Collection

Standard Penetration Test (SPT) and Cone Penetration Test (CPT/Sondir) data serve as the primary in-situ investigation methods to determine soil stratigraphy and geotechnical properties, including soil parameters (γ, c, φ, E_s). The SPT provides N-values for cohesionless soils, while the CPT yields real-time tip resistance (q_c) and friction sleeve (f_s) data, offering higher accuracy.

2.1.2. Specifications of the Analyzed Existing Piles

The analysis focuses on the existing steel piles with a diameter (Ø) of 0.80 m, arranged in a 3x7 configuration/pattern, with an embedded depth (length) of 36.40 meters [7]

2.1.3. Data Collection and Model Input Methods

The analysis of pile bearing capacity and deformation is conducted using AllPile software by integrating four primary data components [8]:

2.1.3.1. Soil Stratigraphy and Profile

The soil profile modeling is structured based on the stratigraphic sequence from the ground surface to the pile penetration depth, including:

a. Layer Thickness (H): Defining boundaries between soil layers based on variations in soil types.
b. Soil Classification: Selecting soil models (e.g., sand, soft clay, or stiff clay) to determine the *p-y* and *t-z* curve algorithms for soil-structure interaction simulation.

2.1.3.2. Geotechnical Soil Parameters

Mechanical characteristics are input specifically for each layer to determine end bearing and skin friction resistance, comprising:

a. Unit weight ($\gamma_{sat}/\gamma_{dry}$): Used to calculate effective overburden pressure.
b. Shear strength: Cohesion (c) for undrained analysis in cohesive soils, and internal friction angle (ϕ) for non-cohesive soils.
c. Subgrade reaction modulus (k) and Strain Factor (ε_{50}): Soil stiffness parameters used for lateral pile behavior analysis.

2.1.3.3. Geometric Data and Structural Pile Properties

a. Section Dimensions: Including steel material type and section shape or pile diameter (D).
b. Depth Configuration: Embedded pile length (L) and the portion of the pile extending above the ground surface.
c. Material Properties: Modulus of Elasticity (E) and Moment of Inertia (I) to calculate flexural stiffness (EI).

2.1.3.4. Hydrogeological Conditions

Water Table depth input is performed by establishing the groundwater level relative to the surface. This parameter is crucial for calculating effective soil stress and determining whether to use saturated unit weight or buoyant unit weight.

2.2. Analysis of Static Load Test Results

The analysis of static load test results for deep foundations and bridge structures is based on technical standards to ensure structural safety and bearing capacity [9].

The load is applied incrementally, typically reaching up to 200% of the design working load (WL) for initial verification tests, or 150% for routine tests. Settlement is measured at each loading stage using high-precision dial gauges. In the final phase, loading is terminated upon reaching the specified maximum load or when structural failure occurs. Furthermore, the ultimate capacity is determined through interpretation methods, alongside criteria for total and permanent settlement. Load stabilization regulations typically require that additional load increments may only be applied once the settlement rate falls below 0.25 mm/hour [10].

2.3. Pile Group Capacity Analysis Based on Static Loading Test (SLT) Data

The pile group capacity is determined by first establishing the single pile capacity from test data, then multiplying it by the number of piles and the group efficiency factor. The ultimate group capacity (Q_{ug}) is analyzed using the following eq (1)

$$Q_{ug} = E_g \times n \times Q_u \quad (1)$$

a. Determination of Single Pile Ultimate Capacity (Q_u): Established based on static loading test results
b. Efficiency Calculation (E_g): Efficiency is calculated using eq (2) based on the group configuration, including pile spacing, number of rows, and number of columns:

$$E_g = 1 - \theta \left[\frac{(n-1)m + (m-1)n}{90mn} \right] \quad (2)$$

where: $\theta = arctg(d/s)$, d = pile diameter, s = pile spacing, m = number of rows, and n = number of piles per row

c. Allowable Bearing Capacity Evaluation (Q_{ag}): The ultimate group capacity is divided by a Safety Factor (SF) to obtain the allowable capacity, $Q_{ag} = Q_{ug}$ / SF**.** For static testing, the SF typically ranges from 2.0 to 2.5.
d. Group Settlement Analysis: Data from static loading tests are also used to evaluate whether the pile group settlement remains within permissible tolerance limits [9]

Additionally, testing is conducted to measure the deformation of foundation elements under upward tension to ensure structural safety against uplift forces. This method measures the axial deflection of a single pile or a pile group when subjected to a static axial tensile load [12].

2.4. Reinforcement Alternatives

Determining reinforcement models or alternatives for the stability of existing piles and bridge pier structures due to the bridge classification upgrade, as well as evaluating the reinforcement design for the pile cap.

3. Result and Discussion

3.1. Review of Pile Capacity Using AllPile Software

The parameters for the AllPile software analysis [8] were determined as follows:

3.1.1. Pile Type Selection: The analysis uses a driven steel pipe pile with a closed end.
3.1.2. Pile Length and Top Elevation: The total pile length (L) is set to 34 meters, with the pile top established at the ground surface level.
3.1.3. Pile Dimension Input: The pile dimensions are based on the design data, specifically a diameter of 80 cm.

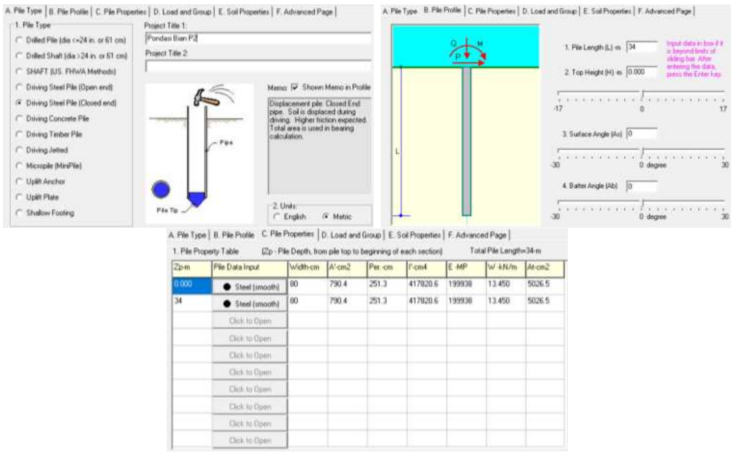

Fig. 2. Input Data for Sections 3.1.1, 3.1.2, and 3.1.3

Data regarding existing pile depths and initial design calking/calendaring records are presented in Table 1, while the planned configuration and pile codes are shown in Fig. 3. Both datasets were designed in 2011 for Class B bridges.

Table 1. Existing Pile Depths Based on Calendaring Data

Pile code	Depth (m)	Pile code	Depth (m)	Pile code	Depth (m)
A1	40.0	B1	40.0	C1	40.0
A2	40.0	B2	40.0	C2	40.0
A3	40.0	B3	40.0	C3	40.0
A4	40.0	B4	39.5	C4	42.5
A5	40.0	B5	38.0	C5	38.5
A6	38.5	B6	34.0	C6	34.0
A7	34.0	B7	34.0	C7	34.0

Source: Record of the calendaring results of existing Pier-2 piles (2011)

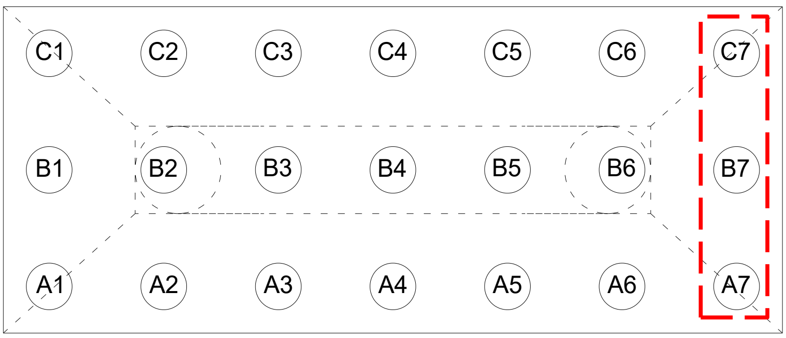

Fig. 3. Pile Configuration and Pile Codes

Axial loads (15,217.3 kN), lateral loads (1,125 kN), and moments (16,167.75 kN) were obtained from the design consultant's foundation analysis. The analysis utilizes a pile group consisting of a 3x7 driven steel pipe pile configuration, as shown in Fig. 4.

The service load distribution analysis at Pier-2 is transferred to the foundation in the form of axial force (V), shear force (H), and moment (M). This analysis is crucial for determining the number and dimensions of the piles to ensure that the resulting stresses do not exceed the allowable soil bearing capacity (q_{all}), as presented in Table 1. These loads are transmitted from the superstructure through the pier to the foundation [3].

Table 1. Design Service Loads

Service Load 1		Maximum	
Column axial force due to Service Load 1,	P_{uk-1} =	15,217.30	kN
x-direction moment due to Service Load 1 combination,	M_{ux-1} =	448.44	kN.m
y-direction moment due to Service Load 1 combination,	M_{uy-1} =	16,167.75	kN.m
Maximum lateral force due to Service Load 1,	P_{h-1} =	112.50	kN

Source: Bian Bridge Design Notes (2022 Planning)

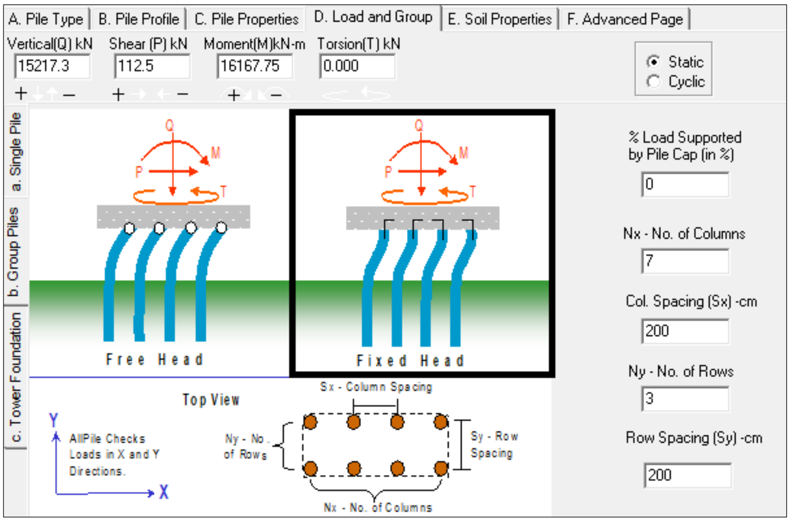

Fig. 4. Axial, Lateral, and Moment Load Inputs

3.1.4. Soil Data Input

Soil data was obtained from the Bian Bridge soil investigation report, as shown in Fig. 5. Technical drilling data—including soil layer profiles, depths, soil types, consistency, and groundwater levels from Borehole log BH-01—are presented in Table 2 and Table 3. The analysis further defines the Safety Factor (SF) and involves a Vertical Analysis Run to calculate the bearing capacity results.

Table 2. Soil data

Depth m	Gamma kN/m^3	Phi	C kN/m^2	K MN/m^3	E50 or Dr %	N spt
0	4.6	0.0	0.6	0.4	5.38	0
4	6.0	0.0	7.8	4.9	3.01	1
6	7.6	0.0	19.0	11.3	1.81	3
10	6.9	0.0	13.2	8.3	2.19	2
12	8.1	0.0	22.1	13.9	1.60	4
18	7.8	0.0	19.8	12.4	1.71	3
26	9.9	0.0	44.9	54.5	1.04	8
30	10.5	0.0	60.4	86.2	0.87	10
34	11.5	0.0	180.1	372.6	0.45	30
36	12.1	0.0	243.6	534.0	0.37	41

Table 3. Pile Foundation Properties

Depth m	Width cm	Area cm^2	Per. cm	I cm^4	E MP	Weight kN/m
0.0	80	790.4	251.3	417820.6	199938	13.45
34.0	80	790.4	251.3	417820.6	199938	13.45

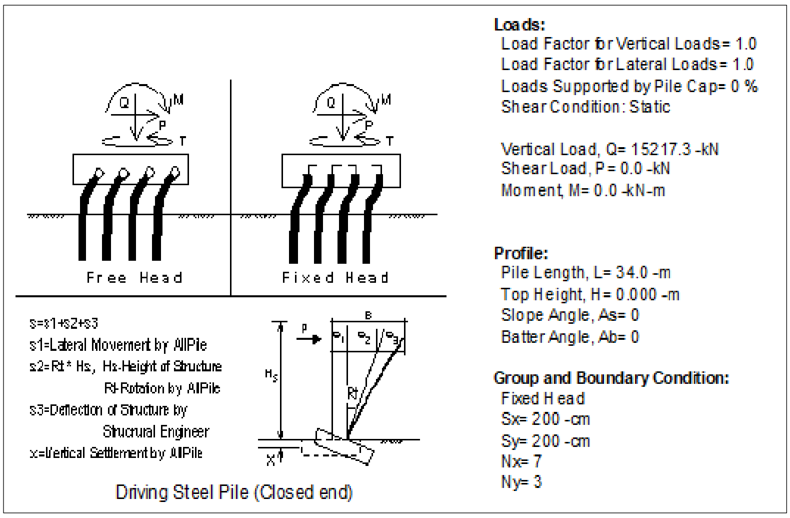

Fig. 5. Vertical Load Analysis

The foundation evaluation shows that the pile group exhibits a total downward ultimate capacity of 65226 kN and an upward ultimate capacity of 35162 kN, yielding total allowable downward and upward capacities of 21742 kN and 20624 kN, respectively. The design is structurally adequate since the allowable capacity exceeds the working load ($Q_{allow} > Q$). Furthermore, the settlement analysis indicates high serviceability; under the maximum permissible settlement (X_{allow}) of 2.50 cm, the allowable capacity reaches 64951 kN, whereas the actual working load of Q = 15217 kN only generates a minor immediate settlement of 0.13018 cm, which is well within the safe limits.

3.2. Pile Capacity Results using AllPile Software

3.2.1. The single pile bearing capacity is 1,035.34 kN, with an applied axial load of 724.63 kN and a recorded settlement of 0.104 cm.

3.2.2. For the pile group, the bearing capacity is 21,742.04 kN against a working load of 15,217.30 kN, with a total group settlement of 0.13018 cm.

3.2.3. Based on Section 3.2.1, the working load of 724.63 kN is less than the single pile capacity of 1,035.34 kN.

3.2.4. Based on Section 3.2.2, the total working load of 15,217.30 kN is less than the group bearing capacity of 21,742.04 kN.

3.2.5. Lateral Analysis (y-direction):
   a. Lateral cap movement (y_t): 0.015 cm (within the allowable deflection of 2.500 cm).
   b. Maximum settlement/deflection (x_{max}): 0.207 cm (within the allowable deflection of 2.500 cm).

3.2.6. Lateral Analysis (x-direction):
   a. Lateral cap movement, y_t: 0.015 cm (within the allowable deflection of 2.500 cm).
   b. Maximum capacity settlement, x_{max}= 0.161 cm (within the allowable deflection of 2.500 cm).

3.3. Static Loading Test (SLT) Analysis Results

The vertical bearing capacity and settlement behavior of the structural elements, specifically the pile foundations, were determined by applying incremental compressive loads [9].

3.3.1. Axial Test 1, Pier 2

Pile Testing Data:

Type : Steel pipe pile
Pile Number : TP No.1 Pier-2
Pile dimension : ϕ 80 cm
Pile Length : (Not recorded/Unknown)
Ultimate Load : 320 Tons (200% of design load)

Axial testing was conducted to evaluate settlement values at load increments of 150%, 175% (asumsi perbaikan dari 275%), and up to 200%, with the following parameters:

a. Test/Design Load: The maximum test load during the pile loading test was 200% of the 160-ton design load, as shown in Table 4. Total and residual movement values are derived from the loading test data records.
b. Deformation Limits: At 200% of the design load, the maximum allowable deformation is 25 mm for an 80 cm diameter pile, in accordance with SNI 8460:2017 (page 189) [10].

Table 4. Loading Test Results

	Parameter	Value	Unit
a.	Design load /test load (100%)	160.00	Ton
	Total movement	4.80	mm
	Elastic movement	3.79	mm
	Residual movement	1.01	mm
b.	Design load /test load (175%)	280.00	Ton
	Total movement	28.51	mm
	Elastic movement	-	mm
	Residual movement	-	mm
c.	Pile capacity		
	Chin Method	225.00	Ton
	Mazurkiwiewich Method	220.00	Ton
	Davission	-	Ton

c. Using the Chin Method [15] with design load of 160 ton and ultimate load of 320 ton, as shown in Table 5 and Fig. 6, the settlement at 150% loading (240 Tons) remained within the allowable limit at 11.83 mm. However, at 175% loading (280 Tons), the settlement failed to meet the requirements, reaching 28.51 mm, which exceeds the 25 mm threshold.

Table 5. Data record of Axial Test 1 Results for Pier-2

Percentage (%)	Load P (ton)	Movement	
		S (mm)	S/P
0	0	0.0000	0.00000
25	40	0.2675	0.00669
50	80	1.3775	0.01722
75	120	3.0025	0.02502
100	160	4.7975	0.02998
125	200	7.0100	0.03505
150	240	11.8250	0.04927
175	280	28.5100	0.10182

Source: Bian Bridge Site, Axial Test 1 Results for Pier-2

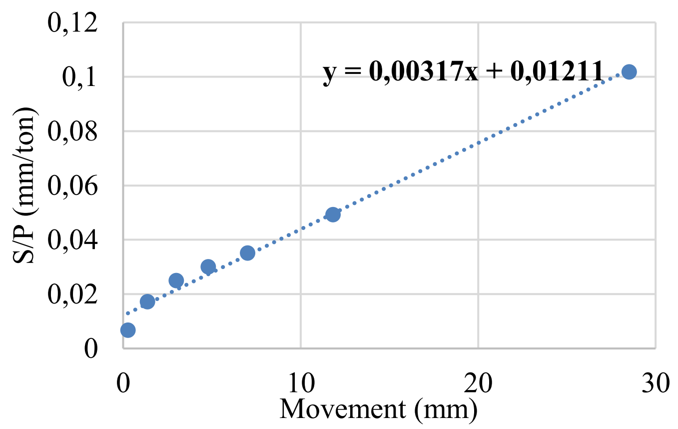

Fig. 6. Chin Method of Axial Test 1 Results for Pier-2
(**Source:** Bian Bridge Site, Axial Test 1 Results for Pier-2)

From Table 5, and Fig. 6. Above, we can calculate ultimate load as follows:

$$P_{ult} = \frac{1}{c_1} \times \text{correction factor}$$

$$P_{ult} = \frac{1}{0.00317} \times 1.4$$

$$P_{ult} = 225 \text{ ton}$$

Using Equations (3) and (4), the maximum and minimum values of the axial load can be calculated. The results of the load capacity analysis, alongside the extreme loads in both the X and Y directions, are presented in Table 6,

$$P_{u_{max}} = \frac{P_u}{n} + \frac{M_{ux} \times y_{max}}{\sum y^2} + \frac{M_{uy} \times x_{max}}{\sum x^2} \quad \text{......} \quad (3)$$

$$P_{u_{min}} = \frac{P_u}{n} + \frac{M_{ux} \times y_{min}}{\sum y^2} + \frac{M_{uy} \times x_{min}}{\sum x^2} \quad \text{......} \quad (4)$$

Table 6. Maximum and minimum axial load values

Load Parameter	Maximum Axial Load	Minimum Axial Load
Load capacity 1	1109.57	406.78
Extreme loads x	1007.37	377.86
Extreme loads y	1066.94	318.29

Source: Bian Bridge Design Notes (2022 Planning)

d. Based on the results in Section (c) above, it can be concluded that the soil bearing capacity is sufficient to support a structural load of 240 Tons.
e. Using the Mazurkiewicz Method [15] with design load of 160 ton and ultimate load of 320 ton, as shown in Table 7 and Fig. 7, the settlement at 150% loading (240 Tons) remains within the allowable limit at 11.83 mm. However, at 175% loading (280 Tons), the settlement fails to meet the criteria, reaching 28.51 mm, which exceeds the 25 mm threshold.

Table 7. Data record of Axial Test 1 Results for Pier-2

Percentage (%)	Load P (ton)	Movement (mm)	
0	0	0.00	0.00
25	40	0.27	-0.27
50	80	1.38	-1.38
75	120	3.00	-3.00
100	160	4.80	-4.80
125	200	7.01	-7.01
150	240	11.83	-11.83
175	280	28.51	-28.51

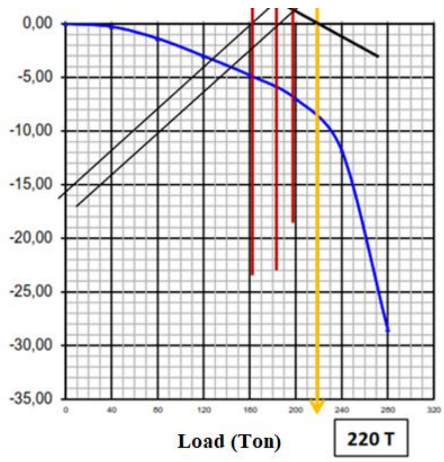

Fig. 7. Mazurkiewicz method of Axial Test 1 Results for Pier-2
Source: Bian Bridge Site, Axial Test 1 Results for Pier-2

Based on the Mazurkiewicz Method, the soil bearing capacity is sufficient to support a structural load of 240 Tons. This exceeds the initial design load of 110 Tons. Even if the design load is increased to 200% (220 Tons), it remains below the calculated bearing capacity of 240 Tons.

3.3.2. Axial Test 2, Pier 2

The analysis for Axial Test 2 is subsequently substituted with ultimate loads of P_{ult} = 191.00 Tons and P_{ult} = 185 Tons, as detailed below:

1) Test/Design Load: The pile loading test was conducted at 200% of the 140-ton design load, as presented in Table 8 and Fig. 8.

Table 8. Axial Test 2 Results for Pier-2

Percentage (%)	Load P (ton)	Movement	
		S (mm)	S/P
0	0	0.0000	0.0000
25	35	0.4425	0.0126
50	70	1.1600	0.0166
75	105	2.6200	0.0250
100	140	4.8400	0.0346
125	175	10.8750	0.0621
150	210	18.6625	0.0889
175	245	27.4175	0.1119

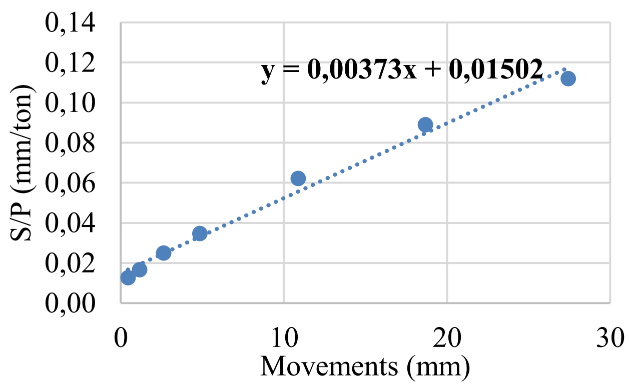

Fig. 8. Chin Method of Axial Test 2 Results for Pier-2
Source: Bian Bridge Site, Axial Test 2 Results for Pier-2

From Table 8, and Fig. 8. Above, we can calculate ultimate load as follows:

$$P_{ult} = \frac{1}{c_1} \times \text{correction factor}$$

$$P_{ult} = \frac{1}{0.00373} \times 1.4$$

$$P_{ult} = 191.43 \text{ ton}$$

2) Deformation Limits: At 200% of the design load, the maximum allowable deformation is 25 mm for an 80 cm diameter pile, in accordance with SNI 8460:2017 (page 189) [10].
3) Chin Method Analysis [15]: As shown in Table 8, at 150% loading (210 Tons), the settlement remained within the allowable limit at 18.66 mm. However, at 175% loading (245 Tons), the settlement failed to meet the criteria, reaching 27.42 mm, which exceeds the 25 mm threshold.
4) Conclusion from Chin Method: Based on the results in Section 3, it is concluded that the soil bearing capacity is sufficient to support a structural load of 240 Tons.
5) Mazurkiewicz Method Analysis [15]: As shown in Table 9, the soil bearing capacity is determined to be 210 Tons, which exceeds the initial design load of 110 Tons. However, if the load is increased to 200% (220 Tons), the resulting structural load exceeds the calculated capacity (220 Tons > 210 Tons).

The equations and the maximum/minimum axial load values (load capacity 1, extreme loads x-axis, and extreme loads y-axis) are consistent with those provided in Table 6.

Table 9. Data record of Axial Test 2 Results for Pier-2

Percentage (%)	Load P (ton)	Movement (mm)	
0	0	0.00	0.00
25	35	0.44	-0.44
50	70	1.16	-1.16
75	105	2.62	-2.62
100	140	4.84	-4.84
125	175	10.88	-10.88
150	210	18.66	-18.66
175	245	27.42	-27.42
150	210	27.30	-27.30
100	140	26.27	-26.27
50	70	25.13	-25.13
0	0	23.83	-23.83

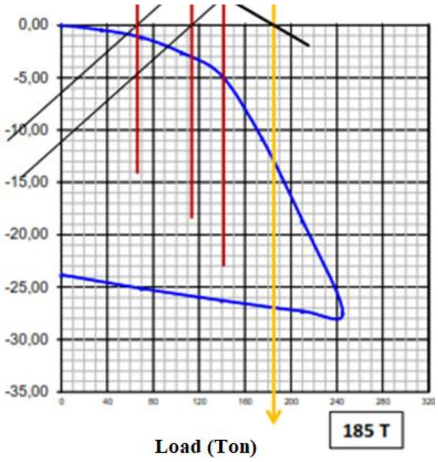

Fig. 9. Mazurkiewicz method of Axial Test 2 Results for Pier-2
Source: Bian Bridge Site, Axial Test 2 Results for Pier-2

3.4. Pile Group Capacity Analysis Based on Static Loading Test Data

3.4.1 Static Test Results for 185-Ton Bearing Capacity

Table 10. Total Factored Axial Force

Total factored axial force,	**$P_u = P_{uk} + 1.0\ (Q_w + Q_c)$**		**Maximum**	**Unit**
Load capacity 1 (Service load)	P_{u1}	=	21,228.88	kN
Extreme loads x-axis	P_{ux}	=	19,393.13	kN
Extreme loads y-axis	P_{uy}	=	19,393.13	kN

Source: Bian Bridge Design Notes (2022 Planning)

Analysis of existing pile group capacity calculation
It is known,

V	=	21,228.88	kN	Design load (class A bridge)
$Q_{static\ test}$	=	1,813.40	kN	Based on the results of static testing

The required number of piles (N_p) can be calculated by dividing the applied vertical load, *V*, by the individual pile capacity, Q_p, which yields a theoretical requirement of 11.71 piles. For the actual design implementation, a configuration of 21 piles with a diameter of 0.8 m was analyzed. Adopting a minimum spacing criteria of 2.5D, the center-to-center spacing, *S*, between the piles is determined to be 2.0 m.

We can calculate Pile Group Efficiency, E_g, using equation 5 below.

$$E_g = 1 - \frac{\theta}{90} \times \left(\frac{(n-1)m + (m-1)n}{mn} \right) \quad \text{(5)}$$

To determine the efficiency of the foundation configuration, the geometry angle, *θ, w*as first calculated as arctan(0.40), yielding a value of 21.80^0. The existing foundation layout consists of a pile group arrangement with m = 7 rows and n = 3 piles per row. By substituting these spatial parameters into Equation (5), the pile group efficiency (E_g) is mathematically determined to be 0.63.

The bearing capacity of the pile group, Q_{tg}, was evaluated by incorporating the group efficiency of 0.63, a total configuration of 21 piles, and an individual pile capacity of 1813.40 kN, which yields a total capacity of 24024.63 kN. To verify the structural compliance of the design, this value was subsequently compared against the applied vertical load, *V*, of 21228.88 kN. Because the total bearing capacity of the pile group structurally exceeds the designated design load, the proposed foundation arrangement is confirmed to be entirely safe and adequate to sustain the vertical loading conditions.

3.4.2 Analysis of 185-Ton Bearing Capacity with a Safety Factor (SF) of 2

In this study, a 185-ton bearing capacity analysis was conducted using a safety factor (SF) of 2.0, which yields an allowable bearing capacity of 906.7 kN. Consequently, utilizing a configuration of 21 piles with a diameter of 0.8 m results in a structurally inadequate design under vertical loading, as the ultimate bearing capacity of the pile group (Q_{tg} = 11995 kN) is lower than the applied vertical load (V = 21229 kN).

3.4.3 Required Follow-up Actions (Existing Reinforcement Alternatives)

To increase the bearing capacity and structural stability of Pier-2 in response to the bridge classification upgrade (from Class B to Class A), the design incorporates additional piles and an expanded pile cap. Table 11 presents the actual ultimate capacity of the existing piles. The most critical value obtained was 185 tons with an SF of 3. However, to analyze the effective bearing capacity, SNI 8460:2017 recommends a Safety Factor (SF) of 2 for static testing [10]. A review of the results indicates that an ultimate capacity of 185 tons for a 42m pile is insufficient. Furthermore, it is unlikely that the actual pile length reached 42m, given that calendaring records show a length of only 34m. Re-analysis of an 80 cm diameter pile with a 34m length, incorporating N-SPT correction factors, yields an ultimate bearing capacity of 105 tons.

Table 11. Single Pile Bearing Capacity Summary

N-SPT	Cu (kPa)	Φ^0	γ (kN/m³)	Q_b (kN)	Q_s (kN)	Q_u (kN)	$Q_{a\ static}$ (kN)	$Q_{a\ earthquake}$ (KN)
0	0	-	6	0	0	0	0	0
1	8	-	6	27.1296	30.1714	57.301	19.1003	34.312
3	18	-	6	81.3888	120.686	202.075	67.3582	121.003
8	48	-	6	217.037	362.057	579.094	193.031	346.763
2	12	-	6	54.2592	442.4	476.659	158.886	285.425
4	24	-	6	108.518	543.086	651.604	217.201	390.182
5	30	-	6	135.648	693.943	829.591	276.53	496.761
7	42	-	6	189.907	905.143	1095.05	365.017	655.719
3	18	-	6	81.3888	995.657	1077.05	359.015	644.938
6	36	-	6	162.778	1176.69	1339.46	446.488	802.074
4	24	-	6	108.518	1297.37	1405.89	468.63	841.85
6	36	-	6	162.758	1478.4	1641.18	547.059	982.741
8	48	-	6	217.037	1719.77	1936.46	645.603	1159.77
9	54	-	6	244.166	1991.31	2235.48	745.16	1338.61
10	60	-	6	271.296	2293.03	2564.32	854.775	1535.52
25	150	-	6	678.24	3047.31	3725.55	1241.85	2230.87
30	180	-	6	813.888	3952.46	4766.8	1588.78	2854.1
41	246	-	6	1112.31	5189.49	6301.8	2100.6	3773.53
60	360	-	6	1627.78	6999.77	8627.55	2875.85	5166.2
60	360	-	6	1627.78	8810.06	10437.8	3479.28	6250.2
60	360	-	6	1627.78	10620.3	12248.1	4082.71	7334.2

In the alternative reinforcement analysis, maintaining the methodology from the preceding subsection, an additional configuration consisting of 8 piles with a diameter of 0.8 m is utilized. This revised foundation arrangement yields an individual allowable bearing capacity of 2876 kN and a reinforcement pile group capacity of 16036 kN. Consequently, the total bearing capacity of the combined pile group, $Q_{tk\ total}$, is determined as follows:

$Q_{tk\ existing}$ = 11995.64 kN, Load-bearing capacity of existing pile (as constructed on site)
$Q_{tk\ reinforcement}$ = 16035.74 kN, For additional reinforcement or stability
$Q_{tk\ total}$ = 28031.38 kN

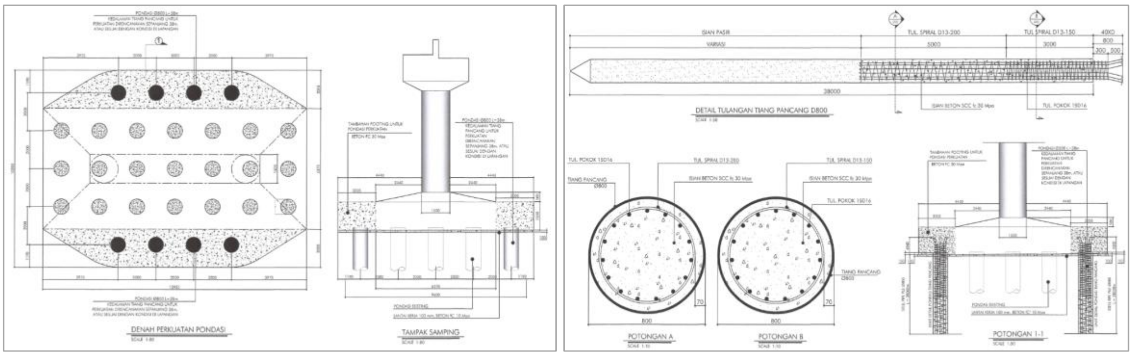

Fig. 10. Final Substructure Reinforcement Design

With a total bearing capacity of 28031 kN, which exceeds the applied vertical load of V = 23152 kN, this reinforcement pile group configuration is structurally adequate to sustain the vertical loading. The final design of the substructure reinforcement model is presented in Fig. 10. The planned depth for the reinforcement piles is determined based on achieving three times the required N-SPT value, with a maximum depth of 42 m or a minimum efficient depth of 38 m (while reconsidering the previous calendaring results at 34 m). Additionally, in accordance with the AASHTO LRFD Bridge Design Specifications, the minimum pile embedment length into the pile cap is 6 inches or 150 mm [1].

4. Conclusion

Static loading test results to determine the actual capacity of existing piles yielded a critical value of 185 tons with a Safety Factor (SF) of 3; however, according to SNI 8460:2017, an SF of 2 is recommended for static testing. Based on the pile group analysis, structural reinforcement is recommended by adding four piles on each side, with a spacing of 200 cm from the outermost row, a diameter of 80 cm, and a depth of 38 m. Considering the previous calendering results at a depth of 34 m, the proposed number and depth of piles satisfy the required capacity for the bridge design load. Regarding the design review, it is suggested to adjust the pile embedment length into the pile cap from 30 cm (as shown in the design drawings) to 15 cm. This adjustment aligns with the structural assumption of a pinned support (hinge) and ensures that the tension reinforcement remains continuous without buckling or excessive bending.

Acknowledgments

The authors would like to express their sincere gratitude to everyone who contributed to the writing and preparation of this article, with special thanks to Prof. Dr. Ir. H. S. Imam Wahyudi, DEA., Prof. Ir. H. Pratikso, MST., Ph.D., Ir. H. Rachmat Mudiyono, M.T., Ph.D., and Prof. Dr. Ir. Antonius, M.T. We also extend our appreciation to the academic community of the Doctoral Program in Civil Engineering at Sultan Agung Islamic University (UNISSULA), Semarang.

Furthermore, our gratitude is extended to the National Road Planning and Supervision Working Unit of Papua (Merauke), the Merauke National Road Construction Agency (BPJN), and the Directorate General of Highways under the Ministry of Public Works, as well as the technical supervision team from PT. Yodya Karya (Persero) for their support and collaboration.

References

[1] American Association of State Highway and Transportation Officials. (2020). The AASHTO LRFD Bridge Design Specifications, 9th Edition, Washington, D.C.
[2] American Association of State Highway and Transportation Officials. (2018). Guide Specifications for Analysis and Identification of Fracture Critical Members and System Redundant Members (GSFCM-1).
[3] Badan Standardisasi Nasional. (2016) SNI 1725:2016: *Pembebanan untuk jembatan* [Load for Bridges]. Standar Nasional Indonesia,.
[4] Texas Department of Transportation. (2024). Bridge Inspection Manual: Policy and Procedures. Statewide Bridge Inspection Program, Bridge Division.
[5] Kementerian Pekerjaan Umum dan Perumahan Rakyat. (2019). *Panduan Teknik Pelaksanaan Jembatan* [Bridge Construction Engineering Guide]. Direktorat Jenderal Bina Marga.
[6] American Society for Testing and Materials International. (2017). Standard Test Method for High-Strain Dynamic Testing of Deep Foundations. West Conshohocken, PA.
[7] Direktorat Jenderal Bina Marga. (2017). *Ketentuan Praktis Uji Pondasi Tiang Jembatan* [Practical Provisions for Bridge Pile Foundation Testing]. Available: pu.go.id,
[8] CivilTech Software. (2020). User's Manual Volume 1 and 2: AllPile Software Version 7. CivilTech Corporation, Bellevue, Washington (WA).
[9] ASTM International. (2020). ASTM D1143/D1143M: Standard Test Methods for Deep Foundations Under Static Axial Compressive Load," West Conshohocken, PA, United States.
[10] Badan Standardisasi Nasional. (2017). *SNI 8460:2017 Persyaratan Perancangan Geoteknik* [Geotechnical Design Requirements]. Standar Nasional Indonesia.
[11] Pratikso and Soedarsono. (2015). The Effect of Land Subsidence to Changes in The Most Extensive Puddle in Semarang-Indonesia. International Journal of Applied Engineering Research Sultan Agung Islamic University Indonesia, pp. 1-11.
[12] ASTM International (2022). ASTM D3689/D3689M: Standard Test Methods for Deep Foundations Under Static Axial Tensile Load," West Conshohocken, PA, 19428-2959 USA.
[13] Banjad Pečur, I., et al. (2021). Assessment and Strengthening of Bridge Piers: A Case Study. *Materials*, 14(10), 2568.
[14] Brown, D. A., & Thompson, W. R. (2018). Design and Construction of Deep Foundations. Federal Highway Administration (FHWA).
[15] Fellenius, B. H. (2021). Basics of Foundation Design, Red Book Scientific Engineering.
[16] Han, J. (2015). Principles and Practice of Ground Improvement. John Wiley & Sons.
[17] Luo, Y., et al. (2019). Numerical and Experimental Study on the Bearing Capacity of Large-Diameter Steel Pipe Piles. Journal of Marine Science and Engineering, 7(12), 435.
[18] Poulos, H. G. (2017). Tall Building Foundation Design. CRC Press.
[19] Tomlinson, M., & Woodward, J. (2014). Pile Design and Construction Practice. 6th Edition, CRC Press.
[20] Chin, F. K. (1970). Estimation of the Ultimate Load of Piles not Carried to Failure. Proceedings of the 2nd Southeast Asian Conference on Soil Engineering.
[21] Mazurkiewicz, B. K. (1972). Test Loading of Piles according to Polish Regulations. Royal Swedish Academy of Engineering Sciences.
[22] Wang, S. T., & Reese, L. C. (1993). Design of Pile Foundations in Liquefiable Soils. Geotechnical Special Publication.