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STRUCTURAL DESIGN STUDY OF ABUTMENTS USING BORED PILE FOUNDATIONS BRIDGE BESUK BONDOWOSO

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Abstract

This study aims to analyze and plan the abutment structure with bored pile foundations on the Besuk Bridge in Klabang District, Bondowoso Regency, East Java. The analysis was conducted to ensure the bearing capacity of the bored piles against axial and lateral loads in accordance with SNI 1725:2016 and SNI 2833:2016. The data used includes soil data from field investigations, shop drawings, and structural design parameters. The calculation process includes determining load combinations, analyzing axial bearing capacity (end resistance and skin friction), and the lateral capacity of piles against horizontal forces due to wind and earthquakes. The analysis results show that the total axial bearing capacity of the foundation is 10,465.26 kN, with a maximum load occurring on the pile of 1,262.56 kN, which is still below the allowable capacity. Meanwhile, the results of the lateral load control show that all load combinations produce lateral forces (Tx and Ty) that are smaller than the allowable capacity. Based on these results, the bored pile foundation with a diameter of 0.8 m and a depth of 10 m is deemed safe to withstand both axial and lateral loads. Thus, the design of the abutment structure and bored pile foundation for the Besuk Bridge meets the stability and strength criteria in accordance with applicable design standards.

Keywords: Abutment, Bored Pile Foundation, Bridge, Bored Pile Load Capacity

Introduction

This study provides a clear research contribution by presenting an integrated evaluation of axial and lateral performance of bored pile foundations for bridge abutments under site-specific soil conditions in Bondowoso Regency. The analysis demonstrates how local soil characteristics and moderate seismic conditions influence the load transfer mechanism and bearing capacity of bored pile foundations at the design stage. The applied analytical approach is intentionally selected to reflect practical engineering design conditions; however, the study acknowledges limitations related to the use of SPT-based soil parameters and the absence of field load testing and advanced numerical modeling. Despite these limitations, the findings contribute practical design insight for bored pile–abutment systems in similar geotechnical and seismic environments and may serve as a technical reference for bridge foundation planning in comparable regions. Transportation infrastructure development is one of the top priorities in supporting economic growth, equitable development, and improved connectivity between regions (Yasin et al., 2019). One of the vital infrastructures that plays a role in facilitating the flow of goods and community mobility is bridges (Rohadi et al., 2018). Bridges not only serve as connectors between regions, but also as strategic means of supporting the distribution of agricultural products, trade, and the social and economic activities of the surrounding community (Samudin, et al., 2024). Therefore, the planning and implementation of bridge construction must be carried out appropriately, effectively, and in accordance with the technical conditions in the field (Rizky, 2022). The Besuk Bridge was built with the main objective of improving connectivity between regions in Bondowoso Regency, particularly as a link between Klabang District and surrounding districts, as well as connecting Bondowoso and Situbondo Regencies (Yasin et al., 2019). Before the bridge was built, local residents faced transportation limitations because they had to take alternative routes that were longer and took more time, especially during the rainy season when the connecting roads were often flooded or damaged (Alihudien et al., 2025). With the Besuk Bridge, the flow of community mobility has become smoother, both for daily activities such as access to education and health care, as well as for economic activities such as the distribution of agricultural products, local trade, and the transportation of basic necessities (Latumahina et al., 2025). In addition, this bridge is also a vital piece of infrastructure that strengthens the inter-village road network, shortens travel distances, and improves travel efficiency between regions (Wisnu et al., 2025). The Besuk Bridge is expected to have a long-term positive impact on regional economic growth, equitable development, and improved welfare for the people of Bondowoso (Suwana, 2022).

A bridge basically consists of two main parts, namely the upper structure and the substructure (Susanto et al., 2020). The upper structure is the part that directly receives traffic loads, both vehicles and pedestrians, and then transfers them to the substructure (Jawat et al., 2020). This section includes girders that support the vehicle deck, a deck slab as the main roadway, and is equipped with sidewalks, safety railings, and expansion joints to accommodate movement due to temperature changes or dynamic loads (Yus et al., 2021). The superstructure is designed to efficiently withstand loads while providing comfort and safety for bridge users. Meanwhile, the substructure functions as a support and transfers the load from the superstructure to the ground (Wei et al., 2025). This section includes abutments at both ends of the bridge, pillars as additional supports for longer spans, foundations that transfer the load to the hard soil layer, and retaining walls around the abutments to maintain the stability of the embankment (Liao et al., 2025). In addition, there are also bearings that connect the girders and abutments, allowing horizontal and vertical movement without damaging the structure (Jiang & Billah, 2025). With this combination of upper structure and substructure, the bridge can function optimally, safely, and sustainably in supporting community mobility (Zhao et al., 2023). Of the various substructure elements, the foundation plays a crucial role as it is the main conduit for transferring the bridge's load to the ground (Rohmawati et al., 2022).

One type of foundation that is widely used in bridge construction is bored pile foundations (Rizqi et al., 2022). Bored pile foundations are deep foundations made by drilling into the ground until reaching a layer of hard soil or soil with adequate bearing capacity (Candra, 2018). The implementation of bored pile foundations requires a systematic, planned method that complies with applicable technical standards (Sudjani & Putra, 2025). The implementation process includes the preparation stage, drilling work, casing installation, hole base cleaning, reinforcement installation, concrete casting, and quality control stage (Ramdhany & Permana, 2021). Each stage has potential technical obstacles, such as the collapse of the borehole wall, the entry of groundwater, and concrete segregation during casting (Kartikasari & Sanhadi, 2019). This confirms that the abutment and bored pile foundation structures are important factors in building structures (Rumahlaiselan & Siahaya, 2024). Considering the complexity of soil conditions, technical requirements, as well as safety and environmental aspects, the development of a bored pile foundation construction method is very important (Rachman & Hendrayana, 2019). This method not only serves as a technical guideline for contractors in carrying out the work, but also as a reference to ensure that the foundation construction can function optimally, safely, and in accordance with the design plan (Pormes et al., 2025). Therefore, a discussion of the planning of the abutment structure using bored pile foundations in the Besuk Bridge construction project in Bondowoso Regency is highly relevant (Pranata & Priyono, 2022). This study is expected to provide a comprehensive overview of the planning stages using bored pile foundations, the challenges faced, and the quality control measures implemented (Halawa et al., 2023). An abutment is a retaining structure at the end of a bridge that receives loads from girders and embankments (Putri, 2022). These loads are then transferred to the foundation (Hariyanto, et al., 2024). The bored pile foundation functions to transfer the abutment load to hard soil at depth so that the abutment remains stable (Fataruba et al., 2025). The relationship between the two: the abutment as a load distributor, the bored pile as a load receiver and supporter to the ground, so that the bridge is safe from subsidence or displacement. Therefore, this analysis needs to be carried out to improve structural safety (Mukhlisin et al., 2019). The contribution of this research lies in the comprehensive assessment of multidirectional loading effects, including vertical loads, seismic forces, earth pressure, braking forces, and wind loads, using actual project data and current Indonesian bridge design standards (SNI 1725:2016 and SNI 2833:2016). In terms of novelty, this study provides the latest assessment of the performance of bored piles for bridge abutments located in moderate seismic zones such as Bondowoso Regency. Unlike previous studies that focused on axial capacity, this study combines axial and lateral load analysis with real project data and evaluates compliance with the latest Indonesian bridge design regulations (SNI 1725:2016 and SNI 2833:2016).

Research Methods

This study is unique in that it integrates the analysis of the axial and lateral bearing capacity of bored pile foundations in bridge abutment structures based on actual project data and specific soil conditions in Bondowoso Regency, which is dominated by fine to medium-grained soils with moderate density and is located in an area with moderate seismicity. Unlike previous studies, which generally focused only on axial bearing capacity analysis, this study evaluates the influence of a combination of vertical and horizontal loads, including earthquake loads, active soil pressure, vehicle braking forces, and wind loads, with reference to the latest regulations SNI 1725:2016 and SNI 2833:2016. The analytical method was chosen because it is suitable for the structural planning stage, consistent with national regulations, and practical to apply to bridge projects with limited field data availability. However, this study has limitations because the soil parameters used mainly come from Standard Penetration Test (SPT) results and the analysis was carried out using an analytical-empirical approach without field load testing or advanced numerical modeling. Therefore, the results of this study are intended as a planning evaluation and are recommended for further validation through load testing and numerical analysis in subsequent studies. In this study, the data used consists of primary and secondary data, including: SNI 1725-2016 Regulation on Bridge Loads, SNI 2833-2016 Guidelines for Earthquake-Resistant Bridge Design. Software applications for structural modeling: Microsoft Excel 2021 (Badan Standarisasi Nasional, 2016). And general data: 2D drawings (working drawings) of the project for modeling, as well as soil investigations to understand the soil characteristics at the project site (Saputra, 2023). Soil data was used to understand the soil characteristics at the project site, which is very important in planning abutment structures using bored pile foundations (Warouw et al., 2022). This data includes soil density, bearing capacity, shear strength, as well as soil elasticity and plasticity parameters, bored pile foundation bearing capacity calculations (ultimate and allowable bearing capacity), and the design of abutment dimensions and reinforcement requirements to withstand loads from the superstructure and foundation (Wahyuddin et al., 2020). Shop Drawings are used to ensure that the modeling is consistent with the existing drawings, so that the analysis remains consistent with the established design (Sadad, et al 2024). All modeled structural elements must refer to the Shop Drawings, while non-structural elements are not included in the model as they do not affect the research results. The location of this study is at the Besuk Subdistrict Bridge Construction Project on Jl. Raya Sitobondo KM BWS 18+300, Besuk Village, Klabang Subdistrict, Bondowoso Regency, East Java, as shown in Figure 1.

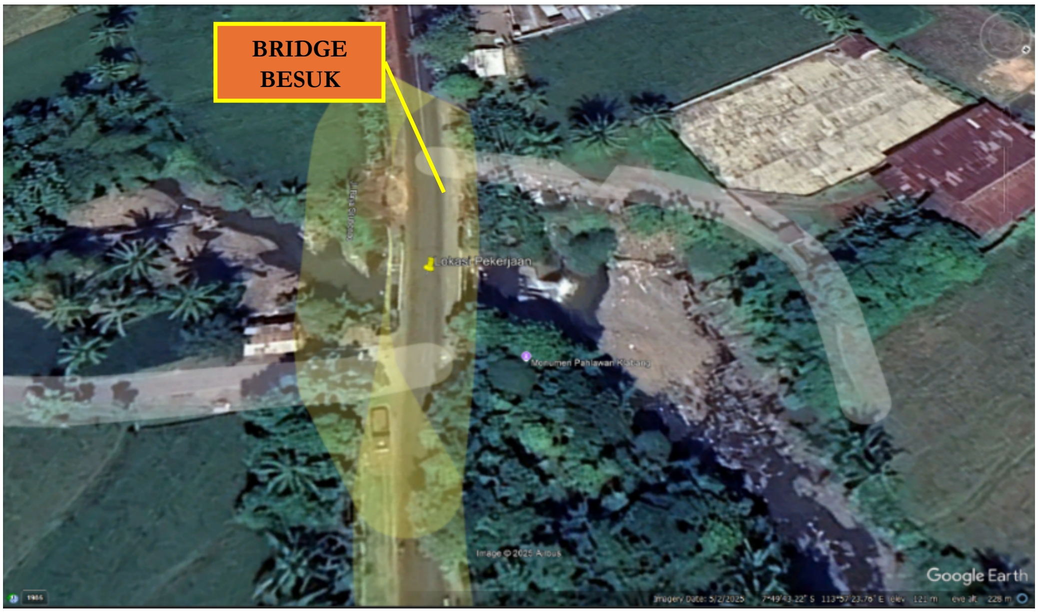

Figure 1. Research Location

This research was conducted in several stages. The initial stage was a literature study to strengthen the theoretical basis regarding soil bearing capacity and bridge standardization in accordance with SNI (Sartika et al., 2019). The second stage was a field survey, which included collecting soil data through Standard Penetration Tests (SPT) and shop drawings to determine the specifications according to the planned design. The third stage was the analysis of girder and abutment loads to calculate the loads occurring on the bridge (Hermawan, 2024). The fourth stage was the calculation of the axial and lateral bearing capacities acting on the bored pile foundations (Tampubolon et al., 2024). The final stage was to check whether the bridge met safety requirements (Hakim, 2021). The data collected through field surveys was systematically compiled and analyzed. The data collection and presentation procedures are carried out with attention to accuracy and consistency, so that the information produced can be a strong basis for the planning process (Nahla et al., 2022).

Research Results and Discussion

Calculating Load Combinations

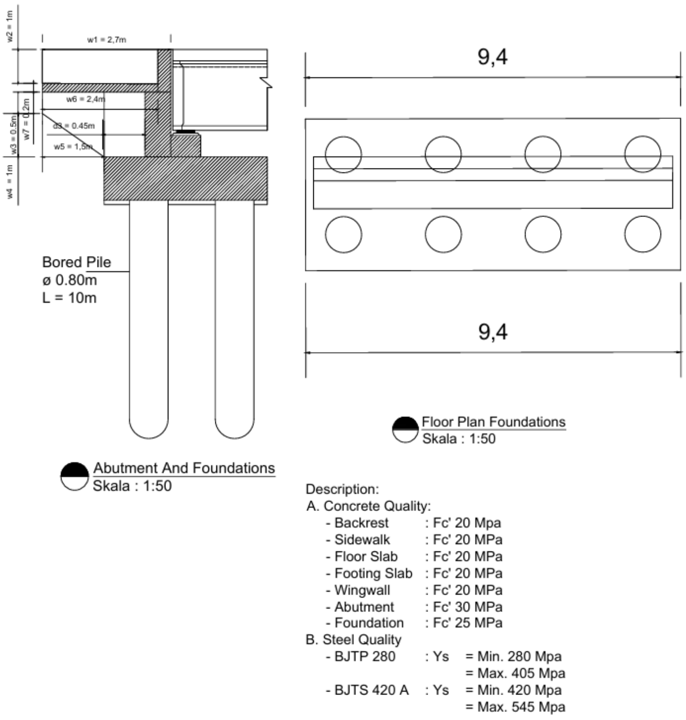

Figure 2. Abutment & Floor Plan

The Besuk Bridge analyzed in this study consists of a superstructure and substructure. The superstructure includes the main girders, vehicle floor slabs, sidewalks, and a bearing system that transfers traffic loads to the substructure. The substructure consists of two abutments located at both ends of the bridge, each equipped with wing walls, footing slabs, and a bored pile foundation system as load-transferring elements to the subgrade. The abutments designed and analyzed in this manuscript are inverted T-type abutments, as shown in Figure 2, with the same geometric configuration, dimensions, material quality, and foundation layout for both sides of the bridge. Each abutment is supported by a group of bored pile foundations with a diameter of 0.80 m and a depth of 10 m, arranged symmetrically according to the foundation plan along a length of 9.4 m. Since both abutments have relatively uniform structural conditions, loading systems, and soil characteristics, the analysis focuses on one abutment unit as a representative model. This approach was chosen to simplify the presentation of the analysis without reducing the accuracy of the results, so that the evaluation results of the axial and lateral bearing capacity of the bored pile foundations could be applied to all bridge abutments.

Dead load (D) – comes from the weight of the abutment structure, slabs, and bridge components above it. Live load (L) – includes vehicle traffic loads that are transferred from the floor slabs to the abutment. Soil pressure (E_h) – in the form of active soil pressure against the abutment wall. Earthquake load (E) – calculated according to the seismic category of the bridge location. Brake load (BR) and forces resulting from vehicle braking on the bridge deck. Wind load and pedestrian load. The load combination is analyzed for Ultimate Limit State (ULS) and Serviceability Limit State (SLS) conditions to obtain the maximum internal forces in the structure, which are then used for reinforcement design and borepile foundation bearing capacity verification. From the results of all loads that occur, a summary of the combined loads is obtained as listed in Table 1.

Table 1. Load Combination Summary

No	Combination	Excessive voltage	P (kN)	Tx (kN)	Ty (kN)	Mx (kN-m)	My (kN-m)
1	Combination -1	0%	4491.35	547.56	0.00	1336.14	0.00
2	Combination -2	25%	4491.37	308.16	1959.39	665.76	4800.30
3	Combination -3	40%	4491.37	672.56	1959.39	1773.64	4800.30
4	Combination -4	40%	4491.37	689.86	1959.39	1540.35	4800.30
5	Combination -5	50%	3378.06	1400.72	313.75	4122.12	1114.54

Calculating Carrying Capacity

Axial Load Capacity,

This section calculates the axial bearing capacity of bored pile foundations, which consists of two main components, namely skin friction and end resistance (end bearing resistance). The second component plays a role in supporting the vertical load from the superstructure.

Skin Friction :

Blowout resistance is the friction between the surface of the pile and the surrounding soil, which contributes significantly to the total bearing capacity. Its value can be calculated using the following equation:

$$Qs = \pi . Ds . (1 - Sin\varphi) . \sigma . tan\delta . dz = 162.99\ kN \ldots (1)$$

Description :

Qs	: Skin Friction
π	: Phi Constant (3.14)
Ds	: Pole Diameter
Φ	: Angle of Internal Friction
σ	: Effective Overburden Stress
δ	: Tan Of Interface Friction Angle
Dz	: Thickness calculated from soil layer elements,

End Bearing Resistance :

End bearing is the compressive force received by the bottom end of the pile when it reaches the hard soil layer. Its value is calculated using the following equation:

$$Qp = Ap . [q' . (Nq - 1) . Fqs\ Fqd\ Fqc] = 808347.700\ kN \ldots (2)$$

Description :

Qp	: End Bearing Resistance
Ap	: Base Area
q’	: Effective Overburden Pressure
Nq	: Bearing Capacity Factor
Fqs	: Shape Factor
Fqd	: Depth Factor

Fqc : Load Inclination Factor,

Allowable Net Load :

After calculating the blanket bearing capacity and end bearing capacity, both are added together to obtain the total bearing capacity. This value is then divided by the safety factor (SF = 2.5) to obtain the allowable bearing capacity:

$$Qall(net) = \frac{Qp(net) + Qs}{FS} = 323404.277\ kN \ldots (3)$$

Description :

Qp (net) : Net End Bearing Resistance

Qs : Skin Friction Resistance

FS : Factor of Safety (2,5)

Lateral Load Capacity,

Pile Lateral Capacity

In addition to vertical loads, bored piles must also be able to withstand horizontal forces caused by earthquakes, wind, and vehicle brakes. Therefore, lateral bearing capacity analysis is performed using the following formula:

$$Qc = 1{,}57.Ds^2.(Ep.R1)\left(\frac{\gamma.Ds.\varphi'.Kp}{Ep.R1}\right)^{0{,}57} = 15013.66\ kPa\ldots(4)$$

Description :

Qc : Ultimate Lateral Load Capacity

Ds : Pile Diameter

Ep : Modulus Of Elasticity Of Pile Material

R1 : Relative Stiffness Ratio

γ : Unit Weight Of Soil

Φ' : Effective Internal Friction Angle

Kp : Coefficient Of Passive Earth Pressure,

Calculating Resistance to Axial and Lateral Loads,

Axial load control analysis is performed to check whether the bearing capacity of the bored pile foundation is capable of withstanding the combination of vertical loads and bending moments acting on the abutment structure. This calculation is important to ensure that the forces received by each pile do not exceed the allowable bearing capacity. Prior to the calculation, all load combinations (1–5) were obtained from the structural analysis results in accordance with SNI 1725:2016 and SNI 2833:2016. These loads include dead loads, live loads, soil loads, as well as loads due to earthquakes and wind.

Control of Axial :

Table 2. Axial Load and Moment Combinations on Bored Pile Foundation

Combination	Q	My	Mx	n1	åx^2	åy^2	x	y
Combination -1	4491.35	0.00	1136.14	8	8	62.5	1	3.75
Combination -2	4491.37	4800.30	665.76	8	8	62.5	1	3.75
Combination -3	4491.37	4800.30	1773.64	8	8	62.5	1	3.75
Combination -4	4491.37	4800.30	1540.35	8	8	62.5	1	3.75
Combination -5	3378.06	1114.54	4112.12	8	8	62.5	1	3.75

Table 3. Axial Load Safety Check of Bored Pile Foundation

Combination	Q/n1	My x/åx^2	Mx y/åy^2	P_{o1}		$P_{allowable}$	Check
Combination -1	561.4188	0	80.1683	641.5871	<	10465.26	**SAFE**
Combination -2	561.4211	600.0371	39.9457	1201.404	<	10465.26	**SAFE**
Combination -3	561.4211	600.0371	106.4183	1267.877	<	10465.26	**SAFE**
Combination -4	561.4211	600.0371	92.4207	1253.879	<	10465.26	**SAFE**
Combination -5	422.2578	139.3181	247.3271	808.903	<	10465.26	**SAFE**

Description :

Q : Axial force (kN)
My : Moment about the Y-axis (kN-m)
Mx : Moment about the X-axis (kN-m)
n1 : Number of control points / dividing elements
Σx^2 : Sum of squares of distances in the X-direction
∑y2 : Sum of squared distances in the Y direction
X : Coordinate or distance of the center relative to the X axis (m)
y : Coordinate or distance of the center relative to the Y axis (m)
P_{o1} : Maximum pressure occurring (kN)
$P_{allowable}$: Permissible soil pressure (kN/m²)

above shows the results of axial load resistance control of piles against various load combinations (Combination 1–5). This analysis aims to evaluate the ability of piles to withstand combined loads between axial loads and bending moments resulting from a combination of vertical forces and lateral forces on the upper structure. From the results of axial load resistance control of the pile group, it can be concluded that:

All load combinations (Combination 1–5) produce maximum force values on a single pile that are smaller than the allowable capacity ($P_{allowable}$). The condition of the pile foundation structure is declared SAFE against axial loads and combined moments. These calculations prove that the foundation design has met the stability and strength requirements of the foundation structure in withstanding vertical forces and bending moments.

After ensuring safety against axial loads, the next step is to control lateral loads to verify the foundation's ability to withstand horizontal forces caused by earthquakes, wind, and active soil pressure. These lateral loads can also arise due to soil collapse behind the abutment or vehicle braking forces on the bridge. The main parameters examined are Tx and Ty, which are the horizontal forces in the X and Y directions for each load combination. These values are compared with H_allowable, which is the allowable lateral capacity of the foundation calculated from the ultimate lateral capacity (Qc) multiplied by the number of piles in the group (n).

Control Of Lateral :

Table 4. Lateral Load Safety Check of Bored Pile Foundation

Combination	Ty	Tx				$H_{\text{allowable}}$	Check
Combination -1	0.00	547.56	<	Qc.n	=	120.109	**SAFE**
Combination -2	1959.39	308.16	<	Qc.n	=	120.109	**SAFE**
Combination -3	1959.39	672.56	<	Qc.n	=	120.109	**SAFE**
Combination -4	1959.39	689.86	<	Qc.n	=	120.109	**SAFE**
Combination -5	313.75	313.75	<	Qc.n	=	120.109	**SAFE**

where :

Ty : Lateral force in the y-direction (kN)
Tx : Lateral force in the X-direction (kN)
Qc.n : Total allowable lateral capacity (kN)
H_{ijin} : Allowable horizontal force (kN)

The table above shows the results of the control of lateral load resistance on the pile group for five load combination conditions. This analysis aims to evaluate the ability of the piles to withstand horizontal forces (Tx and Ty) due to the lateral load effects from the upper structure, such as wind loads, earthquakes, or load eccentricity. From the results of the lateral load resistance check, it can be concluded that: All load combinations produce lateral forces that are smaller than the allowable capacity. (Tx, Ty < Qc.n). The pile foundation is safe against lateral loads, both due to static horizontal loads (wind) and dynamic loads (earthquakes). The foundation design applied meets the lateral stability criteria in accordance with foundation design standards (e.g., SNI 2833:2016 and SNI 1725:2016).

The validation of the analysis results in this study was carried out by comparing them with the results of similar case studies that had been published previously. The total axial bearing capacity value of the bored pile obtained was 10,465.26 kN, which showed a similar trend to the studies by Halawa et al. (2023) and Fataruba et al. (2025), who reported that bored pile foundations in abutment structures with fine to medium granular soil conditions are capable of providing adequate bearing capacity for bridge axial loads. Additionally, the lateral load control results in this study indicate that all load combinations produce lateral forces smaller than the allowable capacity, consistent with the findings of Susanto et al. (2020) and Wahyuddin et al. (2020), who stated that bored pile foundations with appropriate embedment depths and group configurations perform well under horizontal loads. The consistency of these results indicates that the analytical approach used in this study provides realistic and technically acceptable results. However, this study has not been supplemented with static or dynamic pile load tests, so direct validation in the field has not yet been carried out and is recommended as a further development of the research.

This integrated approach offers practical references for engineers in similar regional contexts. The implications of these findings emphasize the importance of considering soil-structure interaction and multi-directional loading in foundation design. The results show that bored pile foundations not only ensure structural safety but also minimize the risk of differential settlement and long-term deformation. Therefore, the design adopted in this project can serve as a reference model for future bridge construction in areas with comparable geotechnical conditions. For further research, it is recommended to conduct field validation using the Pile Load Test (PLT) or PDA test to verify the analysis results and develop numerical modeling (e.g., finite element simulation) to gain a more comprehensive understanding of pile behavior under combined dynamic and static loads.

Conclusion

Based on the results of the combined load analysis, all loading conditions produce a maximum force on the single column that is smaller than the allowable foundation capacity (P allowable = 10,465.26 kN), so the foundation is declared safe against axial loads and combined moments. The lateral load control results show that the horizontal forces in the X and Y directions are still far below the allowable lateral capacity (H allowable = 120,109 kN), so the foundation is also stable against horizontal forces due to wind and earthquake loads. The bored pile foundation design with a diameter of 0.8 m and a depth of 10 m is capable of providing adequate bearing capacity and meeting the stability and safety requirements of the abutment structure in accordance with SNI 1725:2016 and SNI 2833:2016. The analysis also shows that the soil-structure interaction in the soil layers at the project site is good, with balanced skin friction and end resistance values, so that the load distribution between piles in the foundation group is even without showing the potential for differential settlement. Overall, the results of this study indicate that the application of bored pile foundations on the Besuk Bridge is effective in withstanding a combination of vertical and horizontal loads and is suitable for use as the main foundation system for local soil conditions.

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