DESIGN AND GEOTECHNICAL STUDIES OF DEEP FOUNDATIONS FOR BRIDGES IN THE PERUVIAN LOWLAND RAINFOREST

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ABSTRACT

This paper summarizes the geotechnical studies carried out in the 1990s by the Centro de Investigaciones Sísmicas y Mitigación de Desastres (CISMID) of the Universidad Nacional de Ingeniería, for the design of deep foundations of five single-span bridges (25–60 m) located in the Amazonian lowlands of Madre de Dios, Peru, as part of the Southern Interoceanic Highway. Standard Penetration Tests (SPT) were performed to define stratigraphy and soil mechanical properties. Based on this data, the axial bearing capacity of steel driven piles was estimated using empirical and analytical methods, incorporating group efficiency and safety factors to define allowable loads. Settlement predictions for single piles and groups confirmed compliance with international displacement criteria. Steel piles were selected due to regional logistical constraints, including difficult access, lack of aggregates, and equipment transport limitations. Additionally, the construction of protective works was proposed to isolate the foundations from the effects of river erosion. To verify the load capacity and settlements of the piles determined in the designs, load tests were suggested in areas with previously known and more unfavorable profiles. The importance of conducting pile driving tests was also emphasized to ensure the success of the design and construction.

Keywords: deep foundations, bridges, geotechnical studies

1. INTRODUCTION

Bridge construction in the Peruvian Amazon presents significant technical challenges due to the region's unique geological, logistical, and environmental conditions. This paper documents the geotechnical studies conducted for the foundation design of five bridges located in the Madre de Dios department, along the Puerto Maldonado–Iberia–Iñapari section of the Southern Interoceanic Highway Corridor which connects Peru with Brazil. All bridges are single-span structures ranging from 25 to 60 meters in length.

The studies were conducted in the 1990s by the Centro de Investigaciones Sísmicas y Mitigación de Desastres (CISMID) of the Universidad Nacional de Ingeniería (UNI), Peru, under the commission of the Proyecto Especial Madre de Dios (PEMD). The field campaigns included detailed investigations at the Yaverija, Primavera, Noaya, María Cristina, and Alerta bridges, all located in the Tahuamanu Province. The primary technical objective was to develop safe and efficient deep foundation solutions tailored to the complex geotechnical conditions of the Amazonian lowlands.

This paper systematizes the methodology applied and the results obtained in the analysis and design of deep foundations using driven piles, based on a detailed geotechnical characterization of the study area. Figure 1 shows the general location of the analyzed bridges, situated in southeastern Peru near the tri-border region with Bolivia and Brazil, underlining their importance for regional road integration. The inset highlights the relative position of the region within the national territory.

Fig. 1. General location of the Yaverija, Primavera, Noaya, María Cristina, and Alerta bridges in the department of Madre de Dios, Peru.

Geology of the Area

The study area is located within a tectonically formed sedimentary basin, situated between the Brazilian Shield and the Sub-Andean Zone. This depression is characterized by gently undulating topography, consisting of Quaternary deposits overlaying older formations, where thick sedimentary sequences with low-intensity folding have accumulated.

Lithologically, the area is dominated by sedimentary rocks of the Capas Rojas Group, composed of red and white sandstones, gray shales, reddish-brown clayey sandstones with clay interbeds, unconsolidated mudstones, and reddish-brown limonites, as well as feldspathic sands of varying grain size.

Additionally, ancient Quaternary sediments have been identified, including beds of whitish-yellow silica sands, gray claystones, and friable sandstones containing paleontological remains, along with more recent deposits of sands, clays, and silts exhibiting pseudostratification.

Although no igneous outcrops have been observed, fragments of volcanic material such as tuffites and volcanic glass have been recorded. This lithological assemblage suggests a complex sedimentary environment with fluvial and possibly lacustrine influences, as evidenced by the textural features and the presence of organic remains.

2. RESEARCH METHODOLOGY

The geotechnical investigation conducted for the five bridges involved a combination of field exploration, laboratory testing, and computational analysis aimed at the design of deep foundations.

The field campaigns included the execution of mechanical borings with Standard Penetration Tests (SPT) performed at 1.0 m depth intervals, as well as test pits and trenches for visual observation and soil classification. Piezometers were installed, and in-situ permeability tests were carried out. These activities enabled the definition of stratigraphic profiles and hydrogeotechnical conditions at each site. The collected samples were tested in the laboratory to determine index properties and strength parameters. Grain size distribution analyses, Atterberg limits, specific gravity, and moisture content were measured. In addition, direct shear tests, one-dimensional consolidation tests, and unconsolidated-undrained (UU) triaxial tests were performed, depending on the nature of the materials. Chemical analyses of the soils were also conducted.

The results were integrated into bearing resistance and settlement models using specialized software, allowing the selection of the most suitable foundation solutions according to ground conditions, structural loads, and logistical constraints of the environment.

3. FOUNDATION ANALYSIS

The analysis of deep foundations was carried out considering the characteristics of the stratigraphic profile and the loads transmitted by the proposed structures, using both empirical and analytical methods. Since SPT testing is the most widely used geotechnical investigation method in Peru, empirical formulas based on N-SPT values were applied to estimate the bearing resistance of piles. Specifically, the methods of Aoki-Velloso (1975), Decourt-Quaresma (1978), P.P. Velloso (1982), and Meyerhof (1976) were used, with and without N-SPT value corrections. These calculations were processed using the FEPC software developed by Bertolucci et al. (1988) and modified by Guillén (1993).

In parallel, analytical methods were applied using the SPTSP software (based on Schmertmann, 1967) for the Yaverija, Primavera, and María Cristina bridges, and the SPILE program (which incorporates the methodologies of Nordlund (1963), Tomlinson (1980, 1985), and FHWA (1993)) for the Noaya and Alerta bridges.

Settlement calculations included the evaluation of single piles using both the semi-empirical (Vesic, 1977) and the empirical (Vesic, 1970) methods, as well as group pile analysis based on the approaches of Vesic (1977) and Skempton (1951). Additionally, group efficiency was assessed in accordance with the AASHTO Bridge Design Specifications using the Converse-Labarre equation.

The selection of driven open-ended steel piles as the foundation solution was based on their construction practicality under remote site conditions, supported by the results of bearing resistance and settlement performance analyses.

4. EVALUATED BRIDGES

The following sections detail the investigations conducted for each of the analyzed bridges. In all cases, the use of open-ended steel piles with a diameter of 0.30 m was recommended.

Yaverija Bridge

Located over the Yaverija River in the district of Iñapari, Tahuamanu Province, the Yaverija Bridge spans 60 m. The fieldwork was carried out in 1998 and included two boreholes reaching depths of up to 30.45 m, with Standard Penetration Tests (SPT) conducted at 1.0 m intervals, one test pit, permeability tests performed within the boreholes, and the installation of piezometers. The stratigraphy revealed high- and low-plasticity clay soils interbedded with sandy layers, as shown in Fig. 2.

The recommended foundation solution consisted of driven steel piles, 10 m long and 0.30 m in diameter, with allowable capacities of 350 kN and a group efficiency factor of approximately 0.90. Settlement calculations were conducted for both individual piles and pile groups, yielding values of 5.0 mm for individual piles and 21.4 mm and 35.0 mm for the group. It was recommended that at least one pile load test be conducted at each abutment of the bridge foundation.

In 2003, static load tests were conducted on both abutments, following the guidelines established in ASTM D 1143 Standard. The results yielded allowable capacities of 637 kN for the right abutment and 701.18 kN for the left abutment, values that exceeded those considered in the initial design. The corresponding pile lengths were 11.60 m and 8.90 m, respectively. The ENR (Engineering News Record) driving formula was used during pile driving to determine the refusal. To determine the ultimate capacity in the load tests, Davisson's (1972) graphical method was applied.

As an additional measure against scour, in 2005, riverbank protection works were implemented using geocells filled with concrete over geotextile layers.

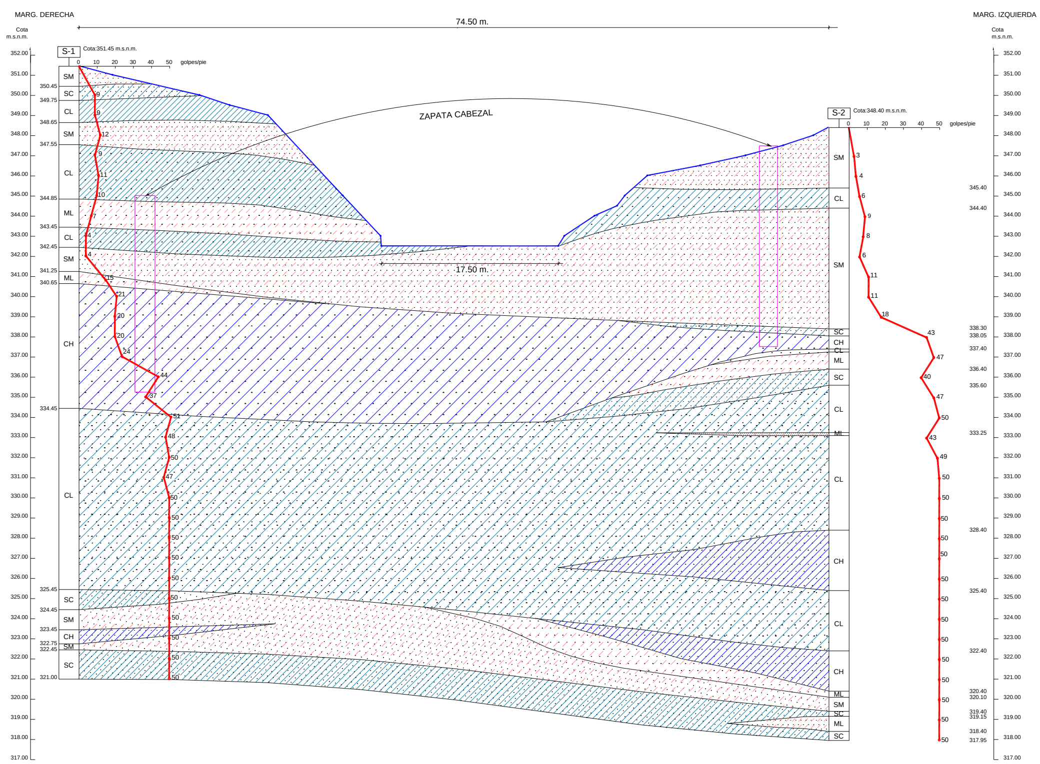

Fig. 2. Stratigraphic profile of the area where the Yaverija Bridge is located

Primavera Bridge

Located over the Primavera River, approximately 10 km from the city of Iñapari, this bridge has a length of 55 m. Field investigations were conducted in July 1999 and included two boreholes reaching depths of 20.45 m, with SPTs performed at 1.0 m intervals, one test pit, one trench, in situ permeability tests within the boreholes, and piezometer installation. The stratigraphic profile revealed predominantly clayey soils with interbedded silty sands, as shown in Fig. 3. The proposed foundation consisted of steel piles with a diameter of 0.30 m and lengths ranging from 8 to 10 m. The allowable load capacity was determined to be

350 kN, with a group efficiency of 0.85. The calculated settlements were approximately 5.3 mm for individual piles and between 20.1 mm and 22.3 mm for the pile group.

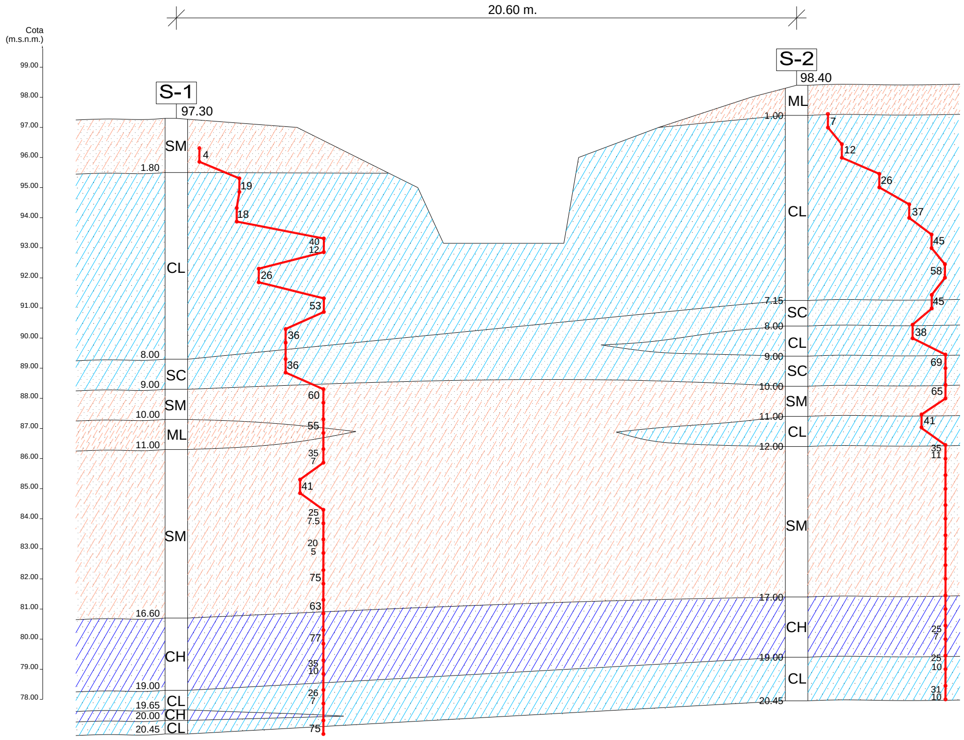

Fig. 3. Stratigraphic profile of the area where the Primavera Bridge is located

Noaya Bridge

Situated over the Noaya River, approximately 30 km from Iñapari, this bridge has a length of 35.0 m. Fieldwork was carried out in August 1999 and consisted of two boreholes up to 25.45 m deep, with SPTs performed every meter, one test pit, one trench, permeability tests within the boreholes, and piezometer installation. The stratigraphy showed high- and low-plasticity clays in the upper layers, followed by sandy soils, as illustrated in Fig. 4. The recommended foundation system comprised driven steel piles 9 m in length and 0.30 m in diameter. The allowable capacity was 300 kN, with a group efficiency of 0.85. Settlements ranged from 5.3 to 5.6 mm for individual piles and up to 23.1 mm for the group. Drainage works were recommended to protect the wall edges from erosion and scour caused by rainwater runoff and river flow.

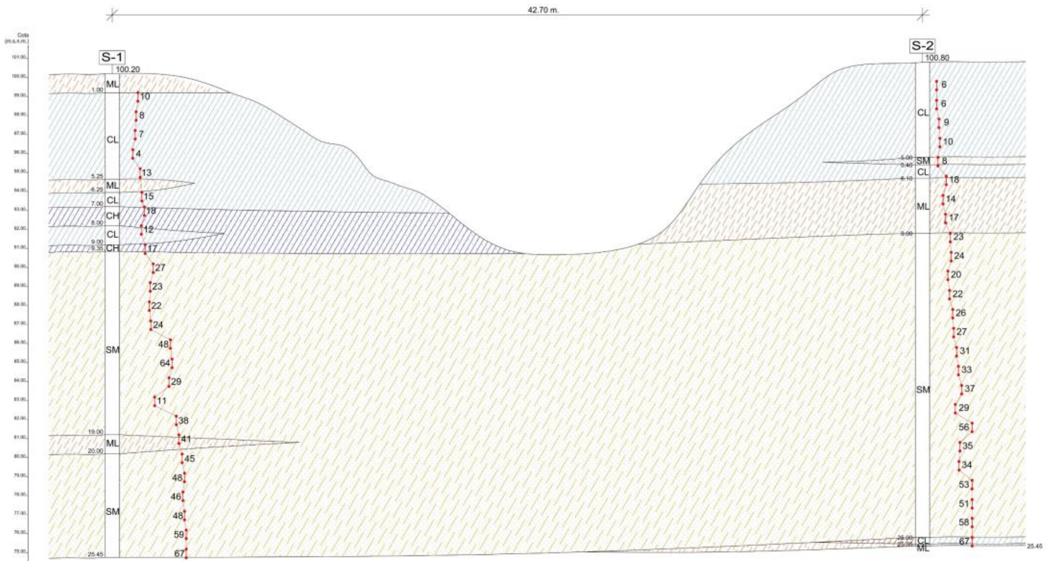

Fig. 4. Stratigraphic profile of the area where the Noaya Bridge is located

María Cristina Bridge

Located at kilometer 162 of the Puerto Maldonado – Iberia road, this bridge spans 30 m. In April 1994, four geotechnical boreholes were performed to depths between 11.45 and 14.45 m, as two alternative locations were evaluated: the existing bridge site and another 80 m upstream. The stratigraphic profile consisted mainly of sandy soils, as shown in Fig. 5. The recommended foundation solution included driven steel piles 8 m in length, with both 0.25 m and 0.30 m diameters evaluated. Allowable capacities ranged from 300 to 330 kN at the left abutment and from 410 to 510 kN at the right abutment, with a group efficiency of 1. Settlements for individual piles ranged from 2.7 to 3.3 mm, and up to 19.6 mm for the group.

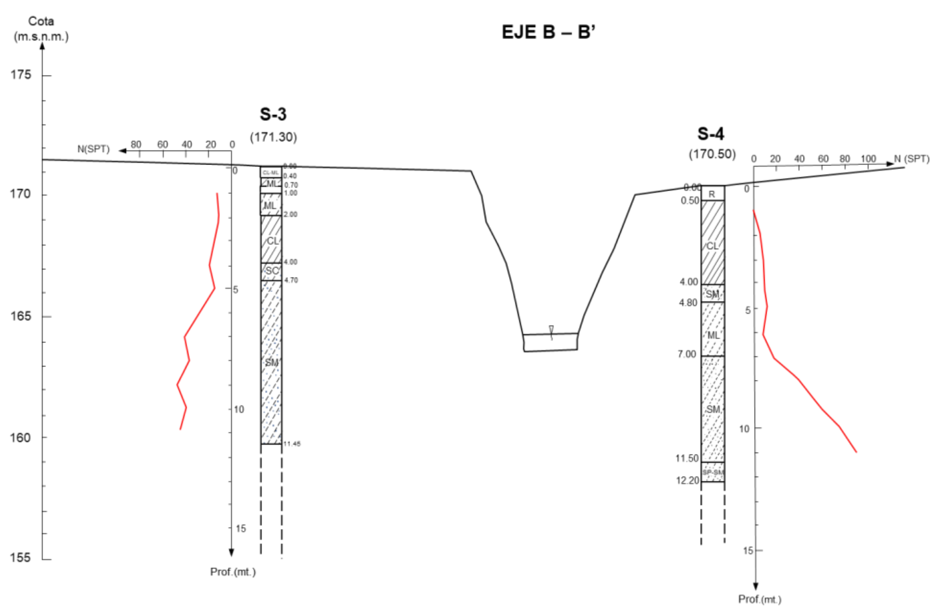

Fig. 5. Stratigraphic profile of the area where the María Cristina is located

The design included recommendations for implementing necessary protective measures along the ravine to isolate the foundation area from potential river scouring effects. These measures were complemented by drainage structures designed to safeguard the riverbanks against erosion caused by rainwater runoff.

Alerta Bridge

Located in the town of Alerta, this bridge spans 25 m. Field investigations were carried out in August 1999 and included two boreholes (17.45 m and 15.45 m in depth), one trench, in situ permeability tests, and piezometer installation. The predominant soils were low- and high-plasticity clays, along with silty sands, as shown in Fig. 6. The foundation design included driven steel piles 10 m in length and 0.30 m in diameter, with an allowable capacity of 300 kN and an estimated group efficiency of 0.85. Estimated settlements ranged from 4.6 to 5.0 mm for individual piles and up to 19.8 mm for the group. At least one pile load test was recommended, along with protective works on both riverbanks to shield the foundation area from potential scour.

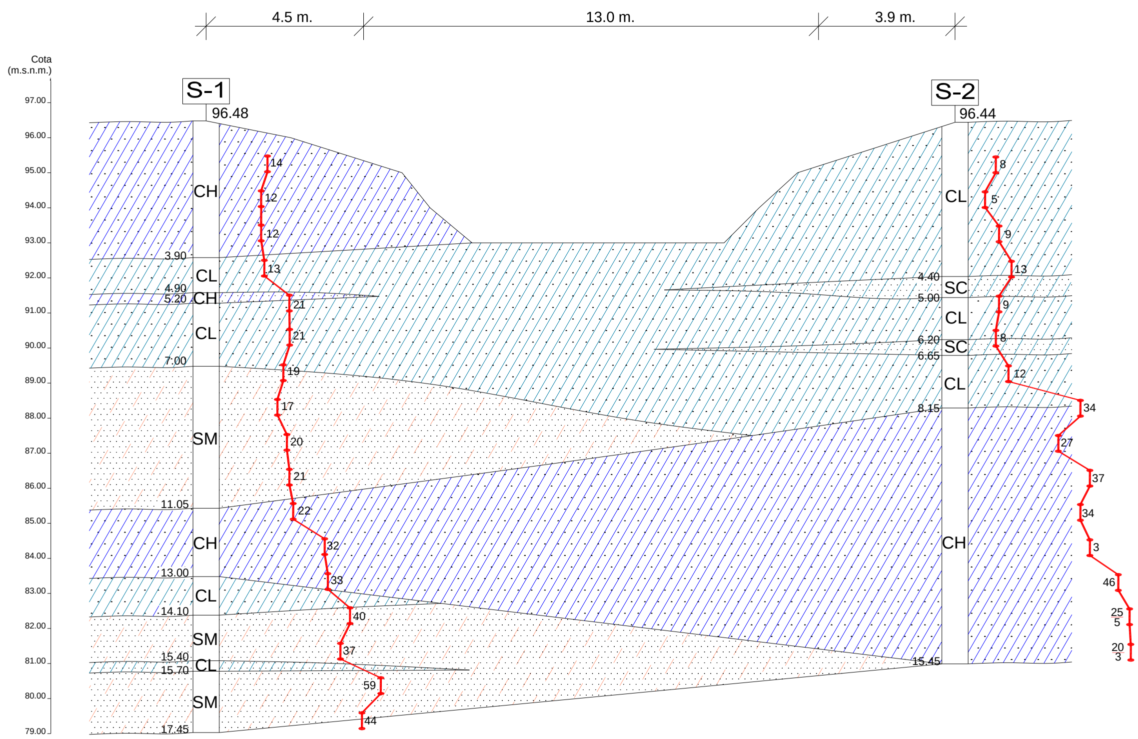

Fig. 6. Stratigraphic profile of the area where the Alerta Bridge is located

5. SUMMARY AND CONCLUSIONS

Table 1 presents a comparative summary of the load-bearing capacities obtained using different methods for the evaluated bridges. Table 2 shows the final allowable capacities considered for the driven open-ended steel piles with 0.30 m diameter and lengths between 8 and 10 m, which were found to be suitable for the site conditions. Final allowable capacities were selected conservatively, prioritizing methods validated by local experience.

Table 1. Allowable load capacity of evaluated bridges determined by different methods

bridge	side	pile length (m)	Empirical Methods					Analytical Method (kN)
			Aoki-Velloso (kN)	Decourt-Quaresma (kN)	Pedro P. Velloso (kN)	Meyerhof s/c (kN)	Meyerhof c/c (kN)	
Yaverija	right	10	350	524	768	304	304	570
	left	10	360	606	760	438	438	
Primavera	right	8	409	707	729	532	532	313
	left	8	446	700	738	379	379	338
Noaya	right	9	374	463	532	275	275	345
	left	9	428	492	598	305	305	370
María Cristina	right	8	836	876	1179	635	635	519
	left	8	807	654	862	337	337	420
Alerta	right	10	339	685	749	500	500	340
	left	10	427	599	720	451	451	267

Table 2. Final allowable load capacities

Bridge	side	pile length (m)	diameter (m)	q_{all} (kN)
Yaverija	right	10.0	0.3	350
	left	10.0	0.3	360
Primavera	right	8.0	0.3	350
	left	8.0	0.3	350
Noaya	right	9.0	0.3	300
	left	9.0	0.3	300
María Cristina	right	8.0	0.3	510
	left	8.0	0.3	330
Alerta	right	10.0	0.3	300
	left	10.0	0.3	300

- This study has documented the geotechnical characterization, analysis, and design of deep foundations for five single-span bridges located in the Madre de Dios region, within the Peruvian Amazon, as part of the Southern Interoceanic Highway Corridor. Field investigations included standard penetration tests (SPT), test pits, piezometer installation, and permeability testing, supplemented by laboratory tests for classification and strength. The data collected enabled the characterization of stratigraphic profiles composed of clayey and silty soils, highly saturated and of low bearing capacity.
- The bearing capacity of the driven steel piles was estimated using empirical methods (Aoki-Velloso, Decourt-Quaresma, P.P. Velloso, and Meyerhof) and analytical methods (SPTSP and SPILE), applying safety factors of 2.5 and group efficiency factors ranging from 0.85 to 1.00. Final allowable capacities ranged from 300 to 510 kN and, in some cases, were confirmed by static load tests.
- The calculated settlements for individual piles (2.7 to 5.6 mm) and pile groups (up to 35.0 mm) were within acceptable limits for bridge structures. Additionally, the need for riverbank protection works against scour was identified, and such measures were implemented to ensure the long-term stability of the foundations.
- The selection of steel piles for bridges in the Madre de Dios rainforest was based on two key factors: first, the need to penetrate deep, dense soil strata that could damage concrete piles during driving; and second, the logistical challenges of transporting heavy equipment to the area. It is concluded that

driven steel piles represent a viable, efficient, and constructionally appropriate foundation solution for the geotechnical and logistical conditions of the Peruvian lowland rainforest.

- For improved geotechnical evaluation of the study area, it is currently recommended to include geophysical surveys as part of the field investigations, particularly using the Multichannel Analysis of Surface Waves (MASW) method. This will allow for the development of a seismic profile based on S-wave propagation velocities, inference of soil compaction states, and determination of elastic parameters that may be used in foundation analysis.

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