Reassessment of Drilled Shafts in Alluvial Soils Using LRFD and ASD: The Motilones Bridge Case Study

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Abstract*– This paper presents a retrospective comparative analysis of Load and Resistance Factor Design (LRFD) and Allowable Stress Design (ASD) methodologies for drilled shaft foundations in Amazonian alluvial soils. Using the Motilones Bridge in Peru as a case study, originally designed following LRFD specifications, the foundation is reassessed with contemporary approaches including both updated LRFD standards and ASD methodology. This retrospective perspective allows comparison of design methodologies not considered together during the original design phase. The analysis reveals systematic differences between design approaches, with ASD consistently producing more conservative results than LRFD methodologies. The study also identifies significant variability in results from different software implementations of the same design methodology, highlighting the importance of software verification in geotechnical practice. Additionally, the evolution from earlier to more recent LRFD specifications demonstrates how design codes incorporate improved understanding of geotechnical uncertainty. All methodological approaches confirm the adequacy of the original foundation design, while providing insights into how methodological choices influence design outcomes. The study demonstrates the value of retrospective analysis for understanding methodological evolution and offers practical guidance for foundation design in similar tropical alluvial environments. Recommendations include explicit documentation of methodological choices, multi-software verification for critical designs, and consideration of methodological implications when transitioning between design approaches.

Keywords--drilled shafts, bridge foundation, LRFD, ASD, alluvial soils

I. INTRODUCTION

The design of deep foundations for transportation infrastructure in tropical alluvial regions presents distinct geotechnical challenges. Amazonian alluvial soils, characterized by high heterogeneity, alternating layers of cohesive and granular materials, and significant groundwater influence, require careful consideration in foundation design to ensure long-term structural performance [1]. The Motilones Bridge, spanning the Mayo River in the San Martín region of Peru, represents a case study of such challenging conditions, where drilled shaft (bored pile) foundations were employed to support the 163 m long bridge structure.

Over recent decades, geotechnical design practice has undergone a significant transition from traditional Allowable Stress Design (ASD) approaches to Load and Resistance Factor Design (LRFD) methodologies. While ASD employs global safety factors applied to ultimate capacities, LRFD utilizes separate load and resistance factors based on reliability theory and uncertainty quantification [2]. This paradigm shift, codified in successive editions of the AASHTO Bridge Design Specifications [3, 4], represents more than a procedural change, it reflects evolving understanding of geotechnical uncertainty and risk management in foundation design [5].

The Motilones Bridge foundation was originally designed in 2008 following LRFD (2004) specifications using contemporary software tools [6]. This study presents a retrospective comparative analysis that re-examines this design from a current perspective, incorporating both updated LRFD (2017) standards and ASD methodology, the latter not considered during the original design phase. This temporal approach enables unique insights into methodological evolution and inter-method relationships that are typically unavailable in concurrent comparative studies [7].

Retrospective analysis of completed projects offers valuable opportunities for methodological calibration and knowledge development [8]. By examining past designs with current tools and perspectives, the engineering community can better understand how methodological choices influence design outcomes, how software implementations vary, and how design standards evolve through research and field experience. Such analyses overcome the gap between code development and practical application, providing feedback that informs both future designs and potential code revisions.

The primary objectives of this study are: (1) to compare ASD and LRFD methodologies for drilled shaft design in Amazonian alluvial soils; (2) to assess the impact of LRFD code evolution from 2004 to 2017 editions; (3) to evaluate software implementation variability in geotechnical analysis; and (4) to demonstrate the value of retrospective analysis for advancing geotechnical Engineering practice. The Motilones Bridge case study serves as both the subject of analysis and a vehicle for exploring broader methodological questions relevant to foundation design in similar tropical alluvial environments.

This study focuses exclusively on the geotechnical reassessment of drilled shaft axial capacity and does not include structural modeling or analysis of the bridge superstructure. The applied loads correspond to those obtained from the original design and are used as input for the geotechnical evaluation.

II. BACKGROUND OF THE ORIGINAL FOUNDATION DESIGN

The foundation design of the Motilones Bridge was originally developed using the Load and Resistance Factor

Design (LRFD) methodology in accordance with the provisions in force at the time of design, as established by the AASHTO LRFD Bridge Design Specifications [3]. The selection of the foundation type and geometry was based on the available geotechnical information from site investigations [9] and on design criteria commonly adopted for bridge foundations in alluvial environments.

Drilled shafts were selected as the foundation solution due to their suitability for transferring axial loads through heterogeneous alluvial deposits and their ability to mobilize resistance at greater depths, where soil conditions are generally more competent. This choice is consistent with widely accepted bridge foundation practice in fluvial environments [10,11]. The original design adopted drilled shafts with a diameter of 1.20 m and an embedded length of 25 m, dimensions that satisfied the axial capacity and serviceability requirements established by the applicable LRFD provisions.

The design process considered the contribution of both shaft resistance and base resistance to the total axial capacity, using empirical correlations [12] and resistance factors recommended by AASHTO for drilled shafts in soil [3]. Conservative assumptions were adopted for the selection of geotechnical parameters, reflecting the inherent variability of alluvial deposits and the limited lateral continuity that characterizes such environments. As a result, the selected shaft geometry provided adequate margins of safety under the design loads considered [13].

At the time of the original design, the adopted LRFD framework represented the state of practice for bridge foundation design [14] and complied with all relevant normative requirements. The resulting foundation configuration was therefore considered appropriate and consistent with the design standards and geotechnical understanding available during that stage of the project.

Following the publication of updated LRFD provisions and considering the continued use of the Allowable Stress Design (ASD) methodology in local engineering practice, a subsequent technical reassessment of the original foundation design was performed. This reassessment did not involve any modification to the original shaft geometry or soil parameters. Instead, it aimed to verify the axial capacity of the drilled shafts using updated LRFD resistance factors and to apply the ASD methodology as an additional verification framework, enabling a direct comparison of safety margins and design consistency across different design philosophies [5].

III. Site conditions and subsurface characterization

The Motilones Bridge is located in the Motilones sector of the Moyobamba District, San Martín Region, in northeastern Peru (approximately 6°00′ S, 76°58′ W) [15]. The structure crosses the Mayo River, one of the principal tributaries of the Amazon River system, within a geomorphological environment dominated by fluvial processes. The total length of the bridge is approximately 163 m and consists of two approach spans of 28.30 m each and a central arch span of 105 m. The regional and local location of the Motilones Bridge is shown in Fig. 1.

The project site is situated within the Amazon foreland basin, where the regional geology is characterized by Quaternary alluvial deposits overlying tertiary sedimentary formations [16]. These alluvial materials are the result of long-term fluvial sedimentation associated with the Mayo River and its tributaries and are typical of low-relief floodplain environments in the Peruvian Amazon [16]. Such deposits commonly exhibit significant vertical and lateral variability in grain size, stiffness, and strength, which poses challenges for the design of bridge foundations [1].

Fig. 1. Location of the Motilones Bridge: (a) regional setting in San Martín Region, Peru; (b) local location along the roadway alignment and river crossing. (Source: OpenStreetMap; Ministry of Transport and Communications of Peru (MTC), Directorate General of Roads and Railways, 2016).

The subsurface investigation program was conducted to characterize the stratigraphy and engineering properties of the foundation soils governing the axial behavior of the drilled shafts [9]. Field exploration included two boreholes drilled at selected locations along the bridge alignment to depths exceeding 25 m. Standard penetration tests (SPT) were performed at regular depth intervals to assess soil resistance and to evaluate the variability of subsurface conditions with depth. During drilling, disturbed and undisturbed soil samples were recovered for visual classification and laboratory testing, and groundwater conditions were documented.

Laboratory testing was carried out to determine index properties and representative strength parameters of the encountered soils. These parameters constituted the basis for the estimation of shaft resistance and base resistance in the original drilled shaft design [12]. The scope of the field and laboratory investigation was consistent with standard practice for bridge foundations in alluvial environments and was considered adequate to characterize the vertical stratigraphic profile at the foundation locations [10,11].

To complement the borehole data and to improve the understanding of lateral stratigraphic continuity, a geophysical investigation program was performed by the Japan–Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID) [17]. This program included multichannel analysis of surface waves (MASW) and seismic refraction surveys conducted along the bridge alignment and at the abutment locations. These methods provided estimates of compression wave velocity (V_p) and shear wave velocity (V_s), allowing an indirect assessment of soil stiffness and stratification [18].

The integration of geotechnical and geophysical information enabled a more comprehensive interpretation of subsurface conditions by correlating discrete borehole observations with continuous geophysical profiles [17]. The results indicated that the upper soil layers consist predominantly of relatively soft alluvial materials, while soil stiffness and strength increase progressively with depth. This stratigraphic trend supported the selection of drilled shafts with sufficient embedment to mobilize axial resistance in deeper and more competent soil layers. Groundwater was encountered at shallow depth, consistent with the hydrological conditions of the Mayo River basin, and was considered in both the original design and the subsequent reassessment.

For the purposes of the retrospective analysis presented in this paper, the subsurface model and geotechnical parameters established during the original investigation were retained without modification. No additional field exploration or laboratory testing was introduced during the reassessment stage. This approach ensured that differences observed in axial capacity estimates are attributable solely to the application of different design methodologies rather than to changes in subsurface characterization.

IV. Methodology for Reassessment Using LRFD and ASD

This paper adopts a retrospective analytical framework to reassess the axial capacity of the drilled shafts designed for the Motilones Bridge [6]. The original foundation design, completed in 2008, was developed using the Load and Resistance Factor Design (LRFD) methodology in accordance with the AASHTO LRFD Bridge Design Specifications available at that time [3].

The reassessment is based exclusively on the subsurface model, soil parameters, and geometric configuration established during the original investigation and design stages. No additional field exploration, laboratory testing, or modifications to shaft geometry were introduced. This approach ensures that observed differences in axial capacity estimates are attributable solely to changes in design methodology and resistance factors, rather than to variations in site characterization.

A. *Original LRFD Design Framework*

The original design employed drilled shafts with a nominal diameter of 1.20 m and an embedment depth of approximately 25 m. Axial capacity was evaluated as the sum of shaft resistance and base resistance:

$$Q_n = Q_b + Q_s \tag{1}$$

where Q_n is the nominal axial resistance, Q_s is the nominal shaft resistance, and Q_b is the nominal base resistance [12].

Factored resistance was obtained by applying resistance factors to the nominal components, and the resulting design resistance was compared against factored loads to satisfy strength limit state requirements [14]. This procedure reflected standard LRFD practice for bridge foundations in alluvial soils at the time of design [3].

B. *LRFD Reassessment Using Different Specification Editions*

To evaluate the influence of evolving LRFD provisions, two editions of the AASHTO LRFD Bridge Design Specifications were considered in the reassessment. The first corresponds to the LRFD 2004 edition, which governed the original design [3], while the second reflects the updated LRFD 2017 edition [4].

Under the LRFD (2004) specifications, the resistance factors adopted for drilled shaft axial capacity were:

- Tip (base) resistance factor, φ_b: 0.55 for clay, 0.50 for sand
- Shaft resistance factor, φ_s: 0.65 for clay, 0.50 for sand

These values were consistent with the reliability calibration available at the time and represented the state of the art in LRFD implementation for deep foundations [14].

The reassessment using LRFD (2017) incorporated revised resistance factors reflecting advances in reliability analysis, construction experience, and performance data from drilled shafts [4]. The resistance factors applied in this evaluation were:

- Tip (base) resistance factor, φ_b: 0.40 for clay, 0.50 for sand
- Shaft resistance factor, φ_s: 0.45 for clay, 0.55 for sand

For both LRFD editions, the factored axial resistance was calculated as:

$$\varphi Q_n = \varphi_b Q_b + \varphi_s Q_s \quad (2)$$

Identical nominal resistances were used in both cases, ensuring that differences in factored capacity result exclusively from the evolution of the resistance factors prescribed by the specifications [5].

C. Allowable Stress Design (ASD) Verification

In addition to the LRFD reassessment, an independent verification of axial capacity was performed using the Allowable Stress Design (ASD) methodology [5]. It is emphasized that ASD was not used in the original foundation design of the Motilones Bridge. Its inclusion in this study serves solely as a complementary evaluation framework and as a reference point commonly used in professional practice [1].

Under the ASD approach, the allowable axial capacity Q_{allow} was obtained by dividing the nominal axial resistance by a global factor of safety:

$$Q_{allow} = Q_n/FS \quad (3)$$

where FS is selected based on soil type, construction method, and uncertainty level, following conventional recommendations for drilled shafts in alluvial soils [4]. The allowable capacity was then compared with service-level axial loads. This verification provides an additional perspective on foundation performance without altering the conclusions derived from the LRFD-based analyses [7].

D. Comparative Metric

The primary comparative metric is the design capacity relative to the required service load of 4,438 kN, facilitating direct comparison across methodologies while focusing on practical design implications.

E. Basis for Comparison and Consistency Assumptions

To ensure a consistent and transparent comparison among the three evaluation frameworks, LRFD (2004), LRFD (2017), and ASD, the following assumptions were maintained throughout the analyses:

1. Identical drilled shaft geometry, including diameter and embedment depth.
2. Identical soil stratigraphy and geotechnical parameters derived from the original investigation.
3. No changes to groundwater conditions or construction method assumptions.
4. Axial capacity evaluated under static loading conditions only.

V. Analysis of Results

The comparative analysis of design methodologies yields the results summarized in Table I. The variations in calculated axial capacities primarily reflect differences in safety philosophy and resistance factor calibration between approaches, rather than indicating deficiencies in the original design [7]. This comparison illustrates how drilled shaft design practice has evolved and demonstrates the practical implications of updated LRFD provisions for bridge foundations in alluvial soil conditions [5].

The load ratio analysis reveals consistent trends for each methodology. The original 2008 design using LRFD (2004) with SHAFT1 produced the highest ratios (1.30 for S-01, 1.19 for S-02), reflecting a conservative approach consistent with engineering practice given site uncertainties. In contrast, the retrospective application of ASD methodology with a safety factor of 2.5 yielded consistently lower ratios (0.86 for S-01, 0.79 for S-02), demonstrating the inherent conservatism of this approach. The contemporary LRFD (2017) analysis provides intermediate values (1.06 for S-01, 0.99 for S-02), indicating good agreement with design requirements and validating the original foundation approach.

TABLE I
COMPARATIVE ANALYSIS OF DRILLED SHAFT CAPACITY (1.20 M DIAMETER, 25 M DEPTH)

Analysis Method	Survey	Ultimate Capacity (kN)	Allowable Capacity (kN)	Load Ratio*
Original Design				
LRFD (2004) ALLPILE vs 6.0	S-01	7622	4616	1.04
	S-02	7164	4317	0.97
LRFD (2004) SHAFT1	S-01	9635	5776	1.30
	S-02	8844	5261	1.19
Current Analysis				
ASD (FS=2.5)-SHAFT 2017	S-01	9553	3821	0.86
	S-02	8819	3528	0.79
LRFD (2017) – SHAFT 2017	S-01	9553	4701	1.06
	S-02	8819	4380	0.99

*Ratio of design value to original design requirement (4438 kN)

Software implementation variability significantly influenced outcomes, as evidenced by the disparity between SHAFT1 and ALLPILE v6.0 implementations of LRFD (2004) (1.19 versus 0.97 for S-02). The designers' decision to base the original design on the more conservative SHAFT1 results constituted appropriate engineering judgment for the heterogeneous alluvial conditions. Soil heterogeneity between locations manifested consistently as an approximate 0.07-0.08 reduction in load ratio from S-01 to S-02 across all methodologies, confirming reliable site characterization.

The methodological comparison quantifies the transition from ASD to LRFD approaches: ASD with FS=2.5 produces load ratios approximately 0.20-0.27 points lower than corresponding LRFD values, a systematic difference that practitioners should consider when comparing designs or transitioning between methodologies. All analytical approaches confirm the adequacy of the 25 m deep drilled shafts, with load ratios consistently close to or above the target value of 1.0 across different soil conditions and analysis methods.

VI. Discussion

A. Practical Implications of Methodology Selection

The comparative analysis demonstrates that the choice between ASD and LRFD methodologies has tangible consequences for foundation design [5]. The consistent 0.20-0.27 point difference in load ratios indicates that ASD with FS=2.5 will systematically yield lower capacities than LRFD for identical soil and pile conditions. This distinction is practically significant: when projects transition from ASD to LRFD, apparent "capacity increases" may primarily reflect methodological differences rather than improved soil characterization or analysis [7].

The evolution from LRFD (2004) to LRFD (2017) demonstrates how code development responds to improved understanding of geotechnical uncertainty [4]. The reduced resistance factors for cohesive soils in LRFD (2017) reflect accumulated experience with clay behavior and construction effects, while adjusted factors for granular soils aim for more balanced reliability across soil types [14]. This evolution suggests that foundation design is not static but continuously refined through research and field observations, particularly in challenging environments like Amazonian alluvial deposits [16].

B. Software Variability in Geotechnical Analysis

A notable finding is the substantial disparity between software implementations: SHAFT1 and ALLPILE v6.0 applying the same LRFD (2004) methodology produced load ratios differing by 0.22 points for S-02. This reveals that software selection can influence outcomes as significantly as methodology choice, due to variations in soil-structure interaction modeling, empirical correlations, and code implementation details. The original designers' decision to base the design on the more conservative SHAFT1 results represents sound engineering judgment that appropriately addressed analytical uncertainty. For critical foundations, verification with multiple software packages is advisable to identify potential implementation biases and ensure robust designs.

C. Value of Retrospective Analysis

This study demonstrates the utility of retrospective analysis in geotechnical practice. By re-examining a 2008 design with contemporary tools and perspectives, we gain insights unavailable during the original design phase. Such analysis allows comparison of methodologies not initially considered together, reveals software implementation variability, and provides temporal perspective on methodological evolution. These retrospective studies serve as calibration exercises, connecting code development with field experience and informing improvements for future projects. They represent a valuable approach for advancing geotechnical practice through systematic learning from completed projects.

CONCLUSIONS

This retrospective comparative analysis of drilled shaft design methodologies for the Motilones Bridge foundation yields the following conclusions:

1. *Methodology selection significantly influences design outcomes***.** ASD with FS=2.5 produces load ratios 0.20-0.27 points lower than corresponding LRFD values, representing a systematic difference that practitioners must recognize when comparing designs or transitioning between methodologies.

2. *Software implementation introduces substantial variability.* Different software packages applying the same LRFD (2004) methodology yielded load ratios differing by up to 0.22 points, highlighting the importance of software verification and the value of engineering judgment in selecting conservative results when faced with analytical uncertainty.

3. *LRFD code evolution reflects progressive refinement***.** The transition from LRFD (2004) to LRFD (2017) shows adjusted resistance factors that incorporate improved understanding of uncertainty, particularly for cohesive soils, demonstrating how design standards evolve through research and field experience.

4. *Retrospective analysis provides unique learning opportunities.* Examining a completed design with contemporary tools and methodologies offers insights unavailable during the original design process, serving as a valuable calibration exercise that connects code development with practical application.

5. *The original foundation design demonstrates appropriate engineering approach***.** The 25-meter deep, 1.20-meter diameter drilled shafts show load ratios at or near required values across different methodologies and soil conditions, confirming the design's adequacy while illustrating the influence of methodological choices on calculated capacities.

*Practical Implications***:** This study underscores the need for clear documentation of methodological choices in design reports, recommends multi-software verification for critical foundations, and highlights the value of understanding methodological differences when interpreting design results or transitioning between ASD and LRFD approaches.

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