AASHTO LRFD AXIAL DESIGN OF A DRIVEN PILE AT THE STRENGTH LIMIT STATE (BRIEF DESCRIPTION).

By:

Naser M. Abu-Hejleh, Ph.D., P.E.
Geotechnical Engineer Specialist
FHWA Resource Center
Olympia Fields, IL 60461
Ph. 708-283-3550, Fax. 708-283-3501
E-mail: naser.abu-Hejleh@fhwa.dotgov

Jerry A. DiMaggio, P.E.
Principal Geotechnical Engineer and National Program Manager
The Office of Bridge Technology
FHWA-Headquarters
1200 New Jersey Avenue, SE.
Washington, DC 20590
Ph. 202-366-1569; Fax: 202-366-3077
E-Mail: jerry.dimaggio@fhwa.dot.gov

William M. Kramer, P.E.
State Foundations and Geotechnical Unit Chief
Bureau of Bridges and Structures
Illinois Department of Transportation
2300 S. Dirksen Parkway
Springfield, IL 62764
Phone: (217) 782-7773
E-mail: WILLIAM.KRAMER@ILLINOIS.GOV
ABSTRACT: This paper describes the axial compression design of a single-driven pile at the strength limit in accordance with AASHTO LRFD Design Specifications (2008). This paper was prepared to help State departments of transportation (DOTs) with interpretation and proper integration of AASHTO’s LRFD design specifications for driven piles into their design and construction practice. The design values needed for a single pile design are: a) for a friction or end-bearing pile, the maximum factored axial structural load that can be applied to top of the pile, and b) for a friction pile the maximum pile penetration length a pile can be driven to without damage, and the required pile length for a given factored axial load, Qp. The calculations of these values are demonstrated using AASHTO static analysis methods, field methods (including those that consider and verify setup), and the wave equation analysis. The LRFD design procedure is demonstrated for two common driven pile types: H-Piles and Cast-in-place (CIP) pipe piles. A properly implemented AASHTO geotechnical LRFD specification would allow for higher pile design loads and shorter pile length than commonly employed in the traditional ASD practices. Recommendations for the development of accurate and economical local geotechnical design methods are furnished.

NOTE: The comments received on this paper from the TRB Reviewing Committee suggest there are several issues to address and resolve before this paper is ready for publication. Since this was not possible with the short deadline available for submittal of the revised paper (11/15/2008), the authors decided to submit a very short version of this paper that present the Abstract of this paper, issues and objectives of this paper, brief description of the technical details, and the conclusions. A much better draft of this paper and new examples is under development. Interested reader in this work should contact Dr. Naser Abu-Hejleh from the FHWA Resource Center, naser.abu-hejleh@dot.gov.

INTRODUCTION

In 2000, the AASHTO (members from all U.S. State DOTs) recommended, and FHWA concurred, that all state DOTs will follow the LRFD principles in the design of all new highway bridges by October 2007 (http://www.fhwa.dot.gov/bridge/062800.htm.) This change in design platform provides many direct and indirect advantages compared to traditional methods of allowable stress design (ASD) and load factor design (LFD). At this time, the DOTs are at different stages of implementing of the LRFD specifications. The FHWA has been very active in helping the DOTs with a successful and smooth transition to LRFD. NHI Course 130082, LRFD for Highway Bridge Substructures and Earth Retaining Structures, has been presented in almost all States. The FHWA is also working to develop LRFD based technical manuals for foundations and earth retaining structures and has provided LRFD technical services to engineers at many DOTs.

The FHWA has developed a companion paper that provides a general practical guidance for implementation of AASHTO’s LRFD platform for design of foundation. This paper addresses
the changes in AASHTO LRFD geotechnical design specifications as compared to the AASHTO Standard Specification, the development and basis of AASHTO’s resistance factors at the strength limit (e.g., site variability). For the pile axial compression strength limit, the main changes from ASD to LRFD are

a) In the LRFD, design MUST meet all structural and geotechnical strength limits (including drivability).

b) Replace safety factor (FS) with load factor (γ) and resistance factor (ϕ)
   - Replace service axial loads, Qs, with factored axial loads, Qf. Axial loads should include downdrag loads, DD, in addition to the structural axial loads acting on top of the pile.
   - Replace the allowable design loads with factored resistance.

The LRFD design equation for the axial compression strength limit is \((Q_f + \gamma_p DD) \leq \phi R_n\) for LRFD, where \(\gamma_p\) is the load factor for downdrag loads, and \(R_n\) is the foundation nominal bearing resistance. Reliability-based geotechnical resistance factors are employed in AASHTO for a number of pile geotechnical design methods. Finally, the companion paper presents an implementation plan of AASHTO LRFD Design Specifications for foundations which should be considered by the DOTs in the development of their own plans to transition to LRFD. The implementation plan covers the options available to the DOTs for selection of LRFD geotechnical design methods (AASHTO or local methods).

- Adopt AASHTO’s LRFD methods.
- Develop local LRFD methods by calibration to local ASD methods that have track records of long-term and successful experience. In this case, the level of safety or probability of failure remains unknown and the design could be conservative. Hence, a significant advantage of LRFD will be lost.

For both options, local calibration of geotechnical resistance factors (ϕ) based on static load tests is recommended to account for the State’s specific geology, testing, design and construction practice.

The majority of the LRFD geotechnical questions the FHWA receives from the DOTs are on driven piles. Therefore, the FHWA decided to develop a 2nd LRFD paper specific to driven piles. This paper describes the main components of AASHTO’s LRFD axial compression design of a driven pile at the strength limit and address the common LRFD issues raised by the DOTs (See Figure 1):

- Determination of the maximum factored axial structural load (load from structure) that can be applied to the top of the pile, \(Q_{f\text{max}}\).
- Determination of the the maximum pile length that the pile can be driven to without damage, \(L_{\text{max}}\).
- Consideration of a driveability analysis and setup in the LRFD pile design.
- Improve the agreement in estimated pile length, L, between the static analysis and field verification methods, for a known factored structural axial load applied
- Similarities/Differences between ASD and LRFD and advantages of LRFD.
- Development of more accurate local geotechnical design methods.
Note that $Q_{f_{\text{max}}}$ and $L_{\text{max}}$ are function of the pile structural and geotechnical resistances as will be discussed later.

![Diagram](image)

**Figure 1. Information Needed in the Design of a Single Driven Pile**

For a single specific pile type/size driven into a soil/rock layer, the design of a pile group requires the calculations of $Q_{f_{\text{max}}}$, $L_{\text{max}}$ (See Figure 1) to

- Estimate preliminary number of piles in the pile group = Total factored axial structural load applied to the top of the pile group/$Q_{f_{\text{max}}}$. The rigid cap analysis is often used to compute the top factored axial load carried by various piles in the pile group, and determine the piles that carry the maximum factored top axial load, $Q_f$.
- Ensure that $Q_f$ does not exceed $Q_{f_{\text{max}}}$. The pile length (for all piles in the group) to meet the axial compression strength limit, $L$, is often computed based on $Q_f$. If $Q_f$ is smaller than $Q_{f_{\text{max}}}$ (larger number of piles), $L$ would be smaller than $L_{\text{max}}$ (smaller pile lengths).
- Ensure that the pile lengths to meet these other design requirements (AASHTO Section 10.7.6.; e.g., lateral loading, settlement, uplift) do not exceed $L_{\text{max}}$.

The designer should consider alternative pile types/sizes or increase the number of piles to meet the last two requirements. $Q_{f_{\text{max}}}$ and $L_{\text{max}}$ for all alternative pile type/sizes should be developed and provided to the foundation designer.
The LRFD design of a friction paper is discussed in Section 1 and the LRFD design of a pile seated on top of hard rocks is discussed in Section 2. The LRFD design procedure is demonstrated for two common driven pile types: H-Piles and Cast-in-place (CIP) pipe piles.

**Notes.**

- It is assumed that readers of this paper are familiar with the AASHTO LRFD design specifications for driven piles, and the ASD design of driven piles (common terms for piles such as setup, downdrag, and wave equation analysis) as discussed by Hannigan et. al. (2005).
- Only axial compression geotechnical strength limit for a single pile is discussed in this paper. Other LRFD Limits and design requirements for a single and group of piles should be evaluated & met in the final design.

1. **DESIGN OF A FRICTION PILE (H AND CIP PIPE PILES)**

The design procedure based on both the static and field methods is discussed in the following five topics.

1.1 Pile Nominal Static Geotechnical Resistances.
   1.1.1. Predictions of Resistances for the Field Methods in the Design Phase.

1.2. Determination of \( Q_{\text{fmax}} \) and \( L_{\text{max}} \)
   1.2.1. Based on Correlation to Past ASD Practices.
   1.2.2. By Meeting Structural and Geotechnical Strength Limit States (including driveability).

1.3. Determination of Pile Length.
   1.2.1. Based on Static Analysis Methods.
   1.2.2. Based on Field Methods.

1.4. Design of a Friction H-Pile into soft rocks and glacial tills.

1.5. Field verification of Pile Bearing Resistances. This is needed when the pile length will be finalized based on the field methods.

2. **LRFD DESIGN OF H-PILE SEATED ON HARD ROCK**

H-piles are specifically considered here as they are almost exclusively used when hard rock is present. The design procedure presented in this section cover the following topics:

- Definition of hard rock.
- LRFD Analysis.
- Required driving resistances.
- Driveability Analysis in the design phase for construction control.
- Field Construction Control.
CONCLUSIONS AND RECOMMENDATIONS

The paper provides an interpretation of the AASHTO LRFD design specifications for the axial design of a single driven pile at the strength limit state. The provided content should be helpful to highway agencies to implement LRFD and may be appropriate for inclusion within their respective design and construction manuals. Illustrated examples demonstrate that H-piles (50 ksi steel) seated on hard rock should be designed for design service stresses of 18 ksi and that friction piles can support design service stresses up to 22 ksi with easy driving conditions (or up to 18 ksi with hard driving conditions). If implemented, it would lead to significant savings to DOTs when compared to their existing ASD practice. Consideration of setup and conducting drivability analysis in the design phase and PDA during construction would lead to more savings. Static analysis method should be considered by the highway agencies, at minimum to supplement the field methods.

Local setup factors based on EOD and BOR resistances from field methods should be collected. Local bias information between the resistance measured by the field methods and predictions from the static analysis methods and wave equation analysis should also be collected to improve and optimize local design methods. Local calibration of $\phi$ based on a program of load tests is strongly recommended to account for the State’s specific geology, testing, construction conditions. Other recommendations to benefit from setup in the calibration of local resistance factor are discussed in the companion paper.

With larger loads allowed at the strength limit, it becomes more critical to evaluate the serviceability limit in the LRFD design.

REFERENCES

