NCDOT’s Experience in Load and Resistance Factor Design and Construction of Driven Pile Foundations

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ABSTRACT
NCDOT’s LRFD practice of driven pile foundations for highway bridges is presented and the issues encountered in both design and construction stages of the LRFD projects are discussed. Also, case studies of three projects are presented. The NCDOT LRFD policy generally follows the procedures and requirements of the AASHTO LRFD Bridge Design Specifications with some exceptions in the use of the resistance factors. The LRFD practice results in somewhat more conservatively designed and costly bridge foundations due to the fact that NCDOT used a safety factor of two as the minimum safety factor to compute both nominal static bearing capacity and required driving resistance in the ASD practice and the resistance factors used in the LRFD practice are equivalent to safety factors larger than two. Exceptions to the policy were allowed in the design of a few projects to avoid overly conservative design compared to the ASD practice. The AASHTO’s requirement of dynamic tests with signal matching analysis of at least one production pile per pier to use the RF of 0.6 seems to be irrational and impractical, and it should be reevaluated and revised. The transition of the NCDOT’s bridge foundation design from ASD to LRFD has been done successfully with a minimal disruption to the projects’ schedule. NCDOT plans to recalibrate the resistance factors when sufficient design, construction, and load test data become available.

INTRODUCTION
The North Carolina Department of Transportation (NCDOT) began its implementation of Load and Resistance Factor Design (LRFD) for highway projects in October 2007, and LRFD is now used to design and construct both superstructure and substructure of almost all bridges in NCDOT highway projects. More than 180 bridges have been designed in an LRFD format since October 2007, and about 40 of them have been constructed or currently under construction. This paper presents NCDOT’s LRFD experience in both design and construction of driven pile foundations supporting highway bridges. General practices and issues of design and construction of driven pile foundations and case studies of three projects are presented. Lessons learned from the experience discussed, and recommendations for improvement of LRFD practices are presented.

DESIGN PRACTICE AND ISSUES
The Vesic method (1) was the NCDOT’s standard tool of a driven pile’s static bearing capacity analysis in the allowable strength design (ASD) practice. Since the Vesic method was not adopted in the AASHTO LRFD Bridge Design Specifications, NCDOT changed their standard design method to the α-method and Nordlund method of the computer program ‘DRIVEN’ (2) with the change from ASD to LRFD. The NCDOT’s LRFD policy and procedures for driven piles generally follow the AASHTO LRFD Specifications with the following two exceptions. First, a resistance factor (RF) of 0.7 is used for static bearing capacity of steel H-piles in the coastal region based on the results of the NCDOT’s calibration of its own resistance factors for driven piles (3). The AASHTO resistance factors are used for all other driven pile types and steel H-piles in other geologic regions. Second, a RF of 0.6 or 0.75 is used for dynamic bearing capacity analysis of all driven piles by using pile driving criteria established by wave equation analysis without or with dynamic tests with signal matching, respectively. These factors replace the AASHTO resistance factors of 0.45 and 0.6, but the requirements of number of dynamic tests with signal matching are the same. The
decision to use these higher resistance factors than those in the AASHTO Specifications was due to the concern that the pile length designed and constructed following the LRFD procedures would be much longer than that would have been done by the ASD procedures. NCDOT used a safety factor (SF) of two in estimating pile length by the static bearing capacity analysis as well as in developing pile driving criteria by wave equation analysis. A SF of two is equivalent to a RF of 0.73 by the fitting method (4) assuming the dead load over live load ratio of 1.5, which is most common for North Carolina bridges as reported by Kim (5). Though it was rather arbitrary, the decision was made based on the condition that a further evaluation and recalibration of the resistance factors will be done when sufficient design, construction, and load test data become available. The computer program ‘L-Pile’ is generally used for point of fixity estimate and lateral stability analysis of driven piles, and the computer program ‘FB-Pier’ is occasionally used for more complex or important structures. This practice has not changed following the transition of ASD to LRFD.

North Carolina has three distinct geologic regions: coastal, piedmont, and mountain regions. Pile foundation design of most projects in the piedmont and mountain regions is relatively simple due to the presence of a rock layer at a shallow depth, and there have not been major issues brought by the LRFD implementation. Whereas, there have been a few issues brought from design or construction of the LRFD projects in the coastal region. Overall, the NCDOT’s transition from ASD to LRFD has been carried out smoothly with a minimal disruption to the projects’ schedule. LRFD policy and procedures for driven piles were developed by a joint effort of the geotechnical engineers and the structure design engineers, and an in-house training was given to all engineers with examples of foundation design for both bridge end bents and interior bents. Most of the NCDOT geotechnical engineers were able to adapt themselves to the LRFD practice with a minimal amount of training. No revision was needed in the geotechnical software such as DRIVEN, GRLWEAP, L-Pile, and FB-Pier for LRFD use. However, the structure engineers needed more time and effort to adjust themselves to LRFD mainly because the bridge design software required a significant revision for LRFD use. In addition, the standard truck load for bridge design was changed from HS 20 to HS 25, which significantly increased the applied loads to the foundations. The NCDOT geologists in the coastal region were also needed to adapt themselves to the LRFD practice because LRFD requires significantly deeper subsurface investigation for bridge foundations due to the higher axial resistance than that needed in the ASD practice. Deeper boring usually reduces the productivity and increases the cost per linear foot of boring.

The most important issue in the NCDOT’s transition from ASD to LRFD of driven piles has been over-estimate of pile lengths by using the AASHTO resistance factors in the static bearing capacity analysis. The AASHTO resistance factors of $\alpha$-method and Nordlund method for static bearing capacity are 0.35 and 0.45, respectively. They are equivalent to safety factors of 4.1 and 3.2, respectively, which are much larger than the SF of two that NCDOT used in the ASD practice. Twenty LRFD bridges on steel H pile foundations in the coastal region were randomly selected, and the pile lengths were estimated for the design axial loads by the Nordlund method based on two different resistance factors: 1) AASHTO resistance factor of 0.45 (equivalent SF of 3.2), and 2) NCDOT resistance factor of 0.7 (equivalent SF of 2.1). The pile lengths based on the AASHTO RF were longer than those based on the NCDOT RF by a margin of 9\% to 44\%, with the mean value of 22\%. This is a significant difference in the estimated pile lengths, and it indicates that LRFD may cause a
substantial increase in foundation construction cost. Though the actual pile lengths should be determined by the pile driving criteria during construction, the contractors usually use the design pile lengths to order the piles and tend to drive the full pile lengths even the required driving resistance is achieved at a pile tip elevation higher than the design tip elevation estimated by the static analysis. In a number of projects where prestressed (P/S) concrete piles were chosen as the bridge foundation mainly due to corrosion issues of steel piles, LRFD required a larger pile size than that would have been designed in the ASD practice for the same reason of the RF of 0.35 or 0.45 used in the design. A larger size or longer concrete pile may require a larger hammer and crane to drive the pile, which may make top-down construction not feasible. This may increase the construction cost and the environmental impact of the project. Exceptions to the policy were allowed in the foundation design of a few projects based on the project specific conditions to avoid overly conservative design compared to the ASD practice.

CONSTRUCTION PRACTICE AND ISSUES
NCDOT uses the computer program GRLWEAP to develop pile driving criteria for each hammer the contractor proposes to drive piles, and the NCDOT inspector uses the driving criteria to measure piles’ bearing capacity and to ensure no overstressing of piles during pile driving. Pile driving should stop when the pile achieves both its required driving resistance based on the driving criteria and the design minimum pile tip elevation. The contractor is given the option of driving five more feet after achieving the design requirements as long as the pile is not overstressed. This practice remains unchanged with the implementation of LRFD. As mentioned earlier, NCDOT uses a RF of 0.6 (equivalent SF of 2.4) or 0.75 (equivalent SF of 1.9) for dynamic analysis of pile bearing capacity without or with dynamic tests and signal matching analysis, respectively. The NCDOT policy requires a Pile Driving Analyzer (PDA) test with signal matching analysis at every bent to use the higher RF of 0.75, and this requirement makes the option of using the RF of 0.75 unfavorable for many projects. A RF of 0.6 combined with the increase in the superstructure live load from HS 20 to HS 25 results in higher required driving resistances in the LRFD practice than those in the ASD practice for the same pile type. A higher required driving resistance may need a higher capacity hammer than that could have driven the same type of pile successfully to the required driving resistance in the ASD practice. The contractors working for NCDOT projects were informed of the changes in the design method and the design load prior to the LRFD implementation, but they did not realize the effects of the changes until they encountered the issues in the construction of the LRFD projects. Six hammer submittals of LRFD projects have been rejected so far because the GRLWEAP run showed that the hammers did not have a sufficient capacity to drive the piles to the required driving resistance. The contractors complained that they could use the same hammer to drive the same size of piles in the past and they did not understand why the hammers were not big enough to drive the same piles now. The NCDOT's LRFD implementation in construction is still at an early stage since only about 40 projects have been under construction until now. More issues are expected to be brought up by both the contractors and the NCDOT construction personnel as more LRFD projects move to construction.

CASE STUDY #1: PROJECT B-3809
This project is to replace the bridge over Pungo Creek on NC 99 in Beaufort County. The new bridge consists of 15 spans of 30 to 55 foot long and a P/S concrete cored slab superstructure. A concrete pile foundation would have been used for this type of stream crossing bridge in a highly corrosive environment, but steel pipe piles with metallization coating were chosen as the foundation for the interior bents due to the presence of limestone layer at a relatively shallow depth as shown in Figure 1. Twenty-four inch diameter pipe piles were designed for bents 3 through 12, and 18 inch diameter pipe piles for all other interior bents. Steel H piles were designed for the end bents. The pipe piles were either closed or open ended depending on the presence and depth of the limestone layer at each bent location. The factored design load of the 24 inch pipe piles was 145 tons per pile. As an exception to the policy, a resistance factor of 0.6 was used in lieu of the AASHTO RF of 0.35 for nominal static bearing capacity and pile length estimate. This RF was chosen arbitrarily for an equivalent SF of 2.4 to make the foundation design closer to the ASD practice. Also, a RF of 0.75 was used for dynamic nominal resistance of the pile on the condition that five PDA tests with signal matching analysis to be performed to develop pile driving criteria. These exceptions were made due to the concern of unusually high cost of the foundation if the resistance factors had been chosen based on the policy. Thus, the nominal static bearing capacity was 242 tons, and the required driving resistance was 193 tons. If the ASD method had been used, the design load would have been 100 tons per pile. By applying a safety factor of two, both the nominal static bearing capacity and the required driving resistance would have been 200 tonnes per pile. By using the resistance factors higher than those required by the policy as a design exception, LRFD resulted in a foundation design comparable to that would have been done by the ASD method. A PDA test at both the end of initial driving and the beginning of restrike has been done on four production piles so far after they were driven to the design pile tip elevations. None of them achieved the required driving resistance at the end of the initial driving, but all of them achieved a driving resistance much higher than the required driving resistance at the beginning of restrike after a minimum 24 hours of waiting time due to a pile set-up effect.

**CASE STUDY #2: PROJECT B-4238**

This project is to replace the bridge over Hardee Creek on SR1726 in Pitt County. The new bridge consists of two 55-foot long spans and a prestressed concrete cored slab superstructure. Steel H 12x53 and H 14x73 piles were designed for a factored design load of 90 tons per pile at the end bents and 165 tons per pile at the interior bent, respectively. By using the NCDOT resistance factor of 0.6 without the PDA requirement, the required driving resistance was computed as 150 tons for H 12x53 piles and 275 tons for H 14x73 piles. The contractor proposed an MKT DE-42/35 hammer with a rated energy of 42,000 lb-ft and an ICE I-19 hammer with a rated energy of 43,225 lb-ft to drive these piles. The GRLWEAP analysis showed that these hammers would be able to drive the H 12x53 piles to the required driving resistance with acceptable blow counts, but they did not have a sufficient energy to drive the H 14x73 piles to the resistance of 275 tons. These hammers would not have been rejected had the design and construction been done by the ASD method. The contractor submitted an MVE M-30 hammer with a rated energy of 71,700 lb-ft, and it was approved for both H 12x53 and 14x73 piles.
FIGURE 1 PROJECT B-3809 SUBSURFACE PROFILE
CASE STUDY #3: PROJECT B-3611
This project is to replace the bridge over Pantego Creek on NC 99 in Beaufort County. The new bridge consists of eleven 74-foot long spans, twenty seven 94-foot long spans, and a P/S concrete cored slab superstructure. Sixteen-inch P/S concrete piles were designed for a factored design load of 120 tons per pile at the end bents, and 20 and 24-inch P/S concrete piles were designed for a factored design load in the range of 145 to 245 tons per pile at the interior bents. The AASHTO RF of 0.35 was used to compute the nominal static bearing resistances and to estimate the design pile lengths. The subsurface investigation of this bridge site showed the presence of a moderately hard limestone layer at a depth of 52 to 86 feet below the stream bed throughout the entire bridge length. The DRIVEN analysis showed that the piles would achieve the nominal static bearing capacity with a minimum penetration into the limestone layer, and the pile lengths were estimated accordingly. The required driving resistances of the piles were computed using the NCDOT RF of 0.75 (with dynamic tests and signal matching analysis) even though only seven PDA tests were required to be performed to generate pile driving criteria for all piles. The AASHTO Specifications require a dynamic test and signal matching analysis per pier to use the higher RF, but the NCDOT engineers believe this requirement is excessive and irrational.

CONCLUSIONS AND RECOMMENDATIONS
NCDOT began to implement LRFD of highway bridges including foundations in October 2007, and the transition from ASD to LRFD has been done successfully though a few issues were brought up during design or construction of some of the LRFD projects. The NCDOT’s LRFD policy and procedures for driven piles generally follow the AASHTO LRFD Bridge Design Specifications with some exceptions in the use of the resistance factors. The LRFD practice results in somewhat more conservatively designed and costly bridge foundations due to the fact that NCDOT used a safety factor of two as the minimum safety factor to compute both nominal static bearing capacity and required driving resistance in the ASD practice and the resistance factors used in the LRFD practice are equivalent to safety factors larger than two. Therefore, exceptions to the policy were allowed in the design of a few projects to avoid overly conservative design compared to the ASD practice. More than 180 bridges have been designed in an LRFD format since October 2007, and about 40 of them have been constructed or currently under construction. The AASHTO resistance factors of 0.35 and 0.45 for nominal static bearing capacity analysis by the $\alpha$ method and Nordlund method, respectively, result in overly conservative pile lengths for projects in the North Carolina coastal region. In lieu of these factors, a RF of 0.6 or 0.7, which is equivalent to a SF of 2.4 or 2.1, is recommended for all types of driven piles in the NCDOT coastal region projects until the NCDOT’s recalibration of the resistance factors is complete. The AASHTO’s requirement of dynamic tests with signal matching analysis of at least one production pile per pier to use the RF of 0.6 seems to be irrational and impractical. This requirement should be reevaluated and revised. The foundation design engineers should consider project specific conditions such as geology, construction schedule, significance of environmental impact, and level of importance of the structure and exercise his/her own judgment in the selection of the resistance factors to produce a rational foundation design.

REFERENCES