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**NCDOT**

**RESEARCH PROPOSAL**

**STRUCTURES RESEARCH SUBCOMMITTEE**

# PILE BENT DESIGN CRITERIA

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# Executive Summary

Pile foundations are normally used to support bridges and are subjected to axial and lateral forces produced by dead loads, winds, traffic, waves, and ship impacts. Support configuration takes the form of a pile bent where the support members extend from the superstructure continuously below grade. Support members such as this are often termed 'pile-columns.' Resistance, within each bent, arises from pile–soil–pile interaction, and pile cap carrying capacity components. For pile foundation design, the current practice of NCDOT is to specify a long enough length to provide a point of fixity (along the length of the pile) on the basis of 1 inch lateral deflection at the top of the pile bent. The pile bent is then analyzed using frame analyses to estimate bending moment and shear forces for structural design. An equivalent length K-factor of 2.1 is assumed in the longitudinal direction (assuming free head conditions) while a K-factor of 1.2 is used in the transverse direction (assuming translation with no rotation). The shear and moment computations using frame analyses do not consider the presence of the soil around the pile from the point of fixity to the ground surface. In addition, the one-iteration moment distribution analysis does not properly take into account the impact of pile cap rigidity on the distribution of the applied load to each pile within the bent. As has been recognized by NCDOT, such limitations are excessively conservative and lead to costly specifications.

The objective of this study is to develop improved analysis criteria for design of pile bents in a cost-effective manner while maintaining adequate safety margin. Specifically, the work will be focused on the following aspects:

i) Evaluating the impact of the pile cap rigidity in the transverse direction, and superstructure rigidity in the longitudinal direction to loads transferred to each pile within the bent,

ii) Specifying appropriate K-factors for pile analysis under varying boundary conditions appropriate to the problem geometry and boundary connection scenarios,

iii) Proposing appropriate "point of fixity" taking into account the presence of the soil around the pile from the ground surface down to the point of fixity, and,

iv) Proposing appropriate values for maximum lateral deflection and pile shear capacity for various structure types and soil properties in order to achieve 'uniform risk' designs.

The proposed work will be accomplished through a combined structural and geotechnical effort as the scope is truly an issue of soil-structure interaction. The scope will also require both detailed finite element analysis, and simplified frame analysis, for assessment of design recommendations. The analysis model will be developed using the finite element analysis software, ANSYS, which will be utilized to build model for the pile bent with the surrounding soils. The use of other programs such as FL –Pier will be explored once their robustness is confirmed. The computer programs Response 2000 and ANDRIANNA will be utilized to model the structural cross-sections and provide details required for implementing a simplified 2D plane frame analysis for estimation of pile forces, moments, and lateral deformations, as well as for aiding in the estimation of pile member limit state. While these advanced computer programs are available in the market and will be utilized for analysis of the pile bent,

columns and foundation in this proposed work, it is not the intent of this research to change the current practice tools of NCDOT, but rather to explain limitations and opportunities and recommend ways for using NCDOT tools more efficiently.

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## Background

Current pile bent design criteria for NCDOT involves limitations on lateral displacement of the pile cap (1”) under a lateral force of 2 kips per pile. The design process includes conducting analysis using the computer program Georgia Pier to estimate the load combination on the pile bent under various loading conditions. Geotechnical analyses of the laterally loaded single piles are then conducted to estimate the pile length and designate a corresponding point of fixity. The pile bent is then analyzed using simple frame approach to estimate bending moment and shear forces for structural design. An equivalent length K-factor of 2.1 is assumed in the longitudinal direction (assuming free head conditions) while a K-factor of 1.2 is used in the transverse direction (assuming translation with no rotation).

Pile group response and the corresponding behavior of the super structure are of soil-pile-structure interaction nature. Similar to NCDOT approach, standard practice is to estimate the response of a single pile and use it as the design basis. When a group of piles, however, is subjected to a vertical or lateral load (i.e. dead and live loads including wind, earthquake, etc.) their vertical or lateral responses are not equal to the sum of the individual pile resistance (depending on spacing) and point of fixity of a single pile is not necessarily equal to the point of fixity when the piles are treated as a group. Most common spacing specifications follow the US Army Corps of Engineer which suggests that piles in a group should not be placed less than 2.5 times the pile diameter apart, and not greater than 7 times the pile diameter away from the next closest pile (Technical Report K-83-1 (1982). Chen and Poulos (1993) provided similar recommendations and they stated that piles are typically not installed less than 2.5 times the pile width with optimal spacing should be 3 to 4 times the width of the pile. Pile stiffness reduction factors for group action is usually accomplished following recommendations given in the U.S. Navy’s *Foundations and Earth Structures—Design Manual 7.2*. These factors are developed based on the assumption of linear system components. Such assumption, however, may lead to errors in the moments and shears estimation versus results obtained assuming cracking, yielding, and plastic hinges. In order to understand the interaction that occurs between pile cap, the piles, and the soil, the system created by the structure and the soil must be examined and treated as non-linear to closely model realistic responses.

Once the point of fixity is defined, the pile bent is analyzed using simple frame approach. Frame analysis does not consider the presence of the soil around the piles, from the point of fixity up to the ground surface. In addition, performing frame analysis with one-iteration moment distribution does not properly capture the impact of pile cap rigidity on the distribution of the applied load to each pile within the bent. While several of the analyses assumptions may be acceptable for very short piles, they become overly restrictive for longer piles. In addition, the depth to fixity and effective length factors, as currently evaluated, may not be suitable for all conditions especially when the pile top boundary condition can be characterized as partially fixed. It seems that the general consensus among NCDOT engineers is that, in many cases, pile bent designs are overly conservative and more costly than required to ensure safety and serviceability.

## Significance of Proposed Research

The proposed research aims to address the areas of conservatism mentioned above through analyses that aim to:

(i) Characterize the impact of the current practice and various design assumptions on the sizing of the various components of a pile bent and,

(ii) Recommend modified design procedures, within the framework of frame analysis, for an improved design outcome. While there are other advanced computer programs available in the market for the analysis of pile bents, columns and foundation, it is not the intent of this research to change the current practice tools of NCDOT but to rather recommend approaches for the use of these tools more efficiently.

It is anticipated that the resulting recommendations will not only yield more efficient and cost effective designs, but will also provide NCDOT engineers with a better understanding of actual pile-column performance under loading conditions. In addition to the improved design procedures, such understanding also serves as a powerful tool in the sense of empowering NCDOT engineers with the flexibility of specifying the level of conservatism to be built into a specific design.

## Scope of Work

The proposed work can only be accomplished through a combined structural and geotechnical effort as the scope is truly an issue of soil-structure interaction. The scope will also require both detailed finite element analysis, and simplified frame analysis, for assessment of design recommendations. Tasks needed to accomplish the research objectives are presented below. These tasks are interrelated, and progress on several of them will proceed in a parallel manner:

**Task 1: Review of current NCDOT design practices, and other state of the art approaches.** This first task is essential as a detailed understanding of the current design and analysis procedure is fundamental to providing NCDOT with a useful product. While the PI's have an understanding of the assumptions made by both geotechnical and structural engineering units, the method by which those assumptions are implemented into practice must be reviewed. The work of this task will be aided by interaction between the PI's and NCDOT structural and geotechnical engineers.

The variables considered in this, and other tasks, consist of superstructure type (voided slab, AASHTO girders, and steel girders), span width, span length, number of spans, number of pile-columns per bent, pile-column batter profile (straight, alternating batter in longitudinal direction, a-frame, and end piles batter only), pile cross section (square concrete piles of 12", 16", 20", and 24" in dimension; hollow circular steel piles 24" in diameter with 0.5" wall thickness; steel H-pile columns: W12x53 and W14x73), reinforcement details (pre-stress level, where applicable), and soil type. Final selection of details regarding the analyses variables will be conducted in conjunction with

NCDOT engineers and will aim at considering the applications where pile-bent bridges are most often utilized.

**Task 2: Development of detailed 3D analysis model of pile bents to be used as benchmarks for comparison and development of design specifications for current practice.**

Although the final work product will be aimed at utilizing existing NCDOT computer applications such that immediate benefit to the department is realized, it is essential to have an understanding of how the pile-bents and bridge structure behave under the various applied loading conditions without extended simplifying assumptions and idealizations. The robust 3D analytical model to be developed in this task will allow the researchers to investigate design factors including soil properties, pile cross section type and design details, pile length, group action, pile to cap connection, cap-beam flexibility, and superstructure contributions to the computed responses. The variables described in Task 1 apply to this task as well.

It is envisioned that a parametric study will be undertaken where each of these variables will be explored and their effect on lateral force vs. displacement response analyzed and presented for the foundation and then carried out to the super structure. Developing this detailed analytical model will serve two purposes. First, it will form the basis against which current practice can be evaluated and explained. Accordingly, suggestions can be made such that NCDOT engineers will have a better understanding of actual pile bent performance, while still utilizing applications and methods currently employed by NCDOT. Second, the analysis will form the basis by which the next generation of NCDOT analysis and design approaches for pile-bents can be developed. Although the development of a next generation approach is outside the scope of the work for this proposal, the work of this task will provide a basis by which future methods could be developed considering the new AASHTO LRFD design specifications.

The 3D analysis model for this task will be developed using the finite element analysis software, ANSYS. North Carolina State University currently has a license for ANSYS and as a result there is no additional cost to NCDOT. Furthermore, this software is perhaps the best suited to accomplishing the objective of soil-structure interaction studies to be undertaken in this research. While there are programs such as Florida Pier **(**FL Pier**)** that are specifically developed for analysis of pile groups, group caps, and supported superstructures, Brown et al (2001) cited erroneous results when attempting to estimate the measured behavior of pile groups tested in the field. They indicated that FL Pier did not provide reasonable results when the pile heads were specified to be partially fixed and the program did not predict accurately the distribution of either head shears or bending moments among the various piles. These aspects are important to the results of the proposed research and therefore the research approach is to use a finite element program such as ANSYS to build various models representative of pile bent cases commonly encountered by NCDOT. If, however, the bugs in FL-Pier have been fixed, it is possible to also utilize it for the purpose of the analysis.

**Task 3: Comparison of Model results with current practice and development of model recommendations**. For the configurations considered in the analysis models, current NCDOT practice will be employed and the outcomes tabulated. By comparing the results in terms of axial forces, lateral forces, displacements, shear and moment distributions, the research team will reconcile differences, and make recommendations regarding the appropriate analysis approach/parameters such that current NCDOT practice will provide a result that is consistent with behavior predicted by the robust analysis model. Target parameters will include depth to fixity and pile head rotation as a function of bent type.

**Task 4: Recommendations for pile-bent performance limit states**. Currently, NCDOT practice utilizes a displacement limit of 1" to assess pile performance. Utilizing the analytical model developed in task 2, more rigorous guidelines will be provided that will account for the effects of soil stiffness, pile cross section and design details (through the use of moment-curvature analysis), group action, pile to bent cap connection, bent cap stiffness, and superstructure details. Specifically, these guidelines will include specifying appropriate K-factors for pile analysis under varying boundary conditions appropriate to the problem geometry and connection scenarios, proposing appropriate point of fixity taking into account the presence of the soil around the pile above the specified point of fixity, and, proposing appropriate values for maximum lateral deflection based on various boundary conditions and soil properties. In this task, the computer programs Response 2000 and ANDRIANNA will be utilized to model the structural cross-sections. As part of this task, section analysis will be conducted on all pile cross sections considered in the study to develop moment vs. curvature relationships which will allow evaluation of cracking, yield, service, damage control, and ultimate limit states. The implications of the current NCDOT limitations on displacement and drift will then be superimposed onto the analysis results. The expectation is that the existing 1" deflection limit will yield a variety of different 'damage levels' depending on the pile bent details. For example, in the case of a long pile, a 1" deflection will be accommodated by elastic response, while in a very short pile, such deformation may be larger than desired. Similarly, a 1" deflection in a steel pile may result in different performance when compared to a 1" deflection for a concrete pile. Following this, recommendations will be made in an effort to achieve uniform risk across all NCDOT designs. The objective of 'uniform risk' is consistent with AASHTO LRFD objectives and will allow the department to move closer to such an approach. Uniform risk will result in different pile displacement limits that are unique for each bridge. A simplified method for selecting these limits will be proposed. In addition to displacement limits obtained from pile structural performance, limits will be obtained that relate to other items such as bearings and connector bolts. The lesser of the displacement limits from the pile structural behavior and superstructure limit states would then govern the design but decision regarding choice of criteria will be deferred to NCDOT engineers.

**Task 5: Development of Recommendations for more rigorous analysis and design approaches**. As previously discussed, the development of next generation LRFD design approaches for NCDOT is outside the scope of this work, however, there is a value regarding providing guidance as to how such an approach may unfold for implementation in concert with AASHTO LRFD Bridge Design Specifications (1998).

As a first level of implementation, details required for implementing a simplified 2D plane frame analysis for estimation of pile forces, moments, and lateral deformations will be suggested. Such a model will be developed as part of this task. This model will be developed using the frame analysis software, SAP2000. Within this task, the project team will communicate with NCDOT engineers currently developing analysis software titled NCPIER.

## NCDOT Application of Proposed Research

The research results will be used by NCDOT design engineers and contractors who regularly design pile bents to achieve the following: 1) Development of a draft design policy memo incorporating research findings for use by design engineers, 2) Achieve a better understanding of actual pile-column performance under design loading conditions, and 3) Use such understanding as a powerful tool in the sense of giving engineers the flexibility of specifying the level of conservatism to be built into a specific design and therefore a cost effective approach to design of pile-supported bridge bents.

Furthermore, the outcome of this research will serve as a springboard for the development of a complete analysis and design package for a future project, after the work of this project is completed, in order to aid NCODT in complying with AASHTO LRFD Bridge Design Specifications.

While there are advanced computer programs available in the market for the analysis of the pile bent, columns, and foundation (and will be utilized as a research tool in this project), it is not the intent of this research to change the current practice tools of NCDOT, but rather to explain limitations and opportunities within the current practice framework as well recommend ways for using current NCDOT tools more efficiently.

## Technology Transfer

Technology transfer will be accomplished through the usual quarterly and final reports. In addition a draft of proposed changes in design policy incorporating research findings will be provided for use by design engineers. Given the urgent importance and compressed time schedule of this project, more regular meetings with NCDOT will be essential as described in the following paragraph.

## Resources Supplied by NCDOT

The resources provided to the project team will include drawings of existing NCDOT pile-bents and computer programs and manuals for programs currently employed by NCDOT. In addition, NCDOT engineers will need to be involved in this project rather regularly to ensure that the project outcome is of the highest value to the NCDOT. In addition to the usual project kickoff meetings, we plan to have meetings with NCDOT engineers as needed – perhaps monthly or more often in the early phases of the project, and less frequently as time progresses. Both PI’s have worked on several NCDOT projects in the past and are very much interested in ensuring that this applied research project provide an outcome of high value to NCDOT – this will require regular conversations with NCDOT engineers.

## Time Requirements

The scope of the project will formally be accomplished over a 12 month period starting July of 2004. Given the tight time schedule, once the researchers receive notice that the project will be supported preliminary work may commence prior to July of 2004, including familiarization with the current NCDOT software, and selection of students for the project. A timeline is shown below, as well as an indication of the project personnel leading the specific task. In the table below, MS refers to an MS level graduate student, while the number following it refers to the individual student that will be working on that task. It is important to note that entire project team will be involved in all tasks; however, certain members will be more heavily involved in some aspects.

## Timeline

| Task and Personnel | July – Sept. | Oct. – Dec. | Jan. – Mar. | Apr. – June |
|---|---|---|---|---|
| 1. Review of current NCDOT practice and other approaches.<br>*Kowalsky, Gabr, MS 1 | X | | | |
| 2. 3D Analysis.<br>Kowalsky, Gabr, MS 2 | X | X | X | X |
| 3. Comparison with current and other approaches.<br>Kowalsky, Gabr, MS 1 | | X | X | X |
| 4. Pile and bent performance limit states.<br>Kowalsky, Gabr, MS 3 | X | X | | |
| 5. 2D Plane frame model.<br>Kowalsky, Gabr, MS 3 | | | X | X |

## Qualifications of Research Team

The research project team will consist of PI's Mervyn J. Kowalsky and Mohammed A. Gabr of the Department of Civil, Construction and Environmental Engineering. Dr. Kowalsky received his PhD in Structural Engineering from the University of California,