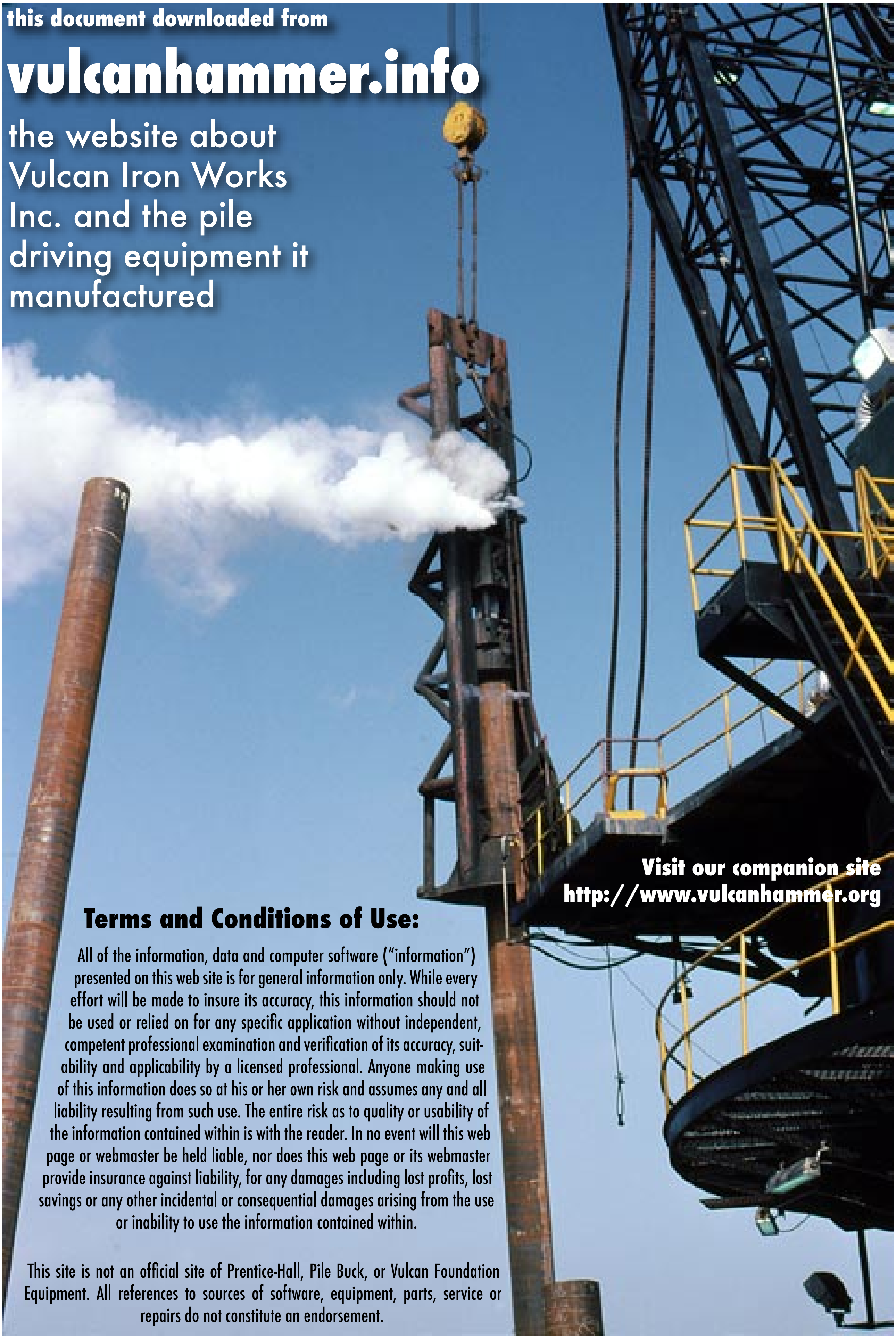

Reliability-Based Specification

for

Driven Piles

by

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Abstract

Resistance factors for steel, timber and concrete piles as structural members, derived with First-Order Second-Moment (FOSM) methods, and an evaluation of the reliability levels inherent in current design codes are presented. The results are included in a proposed format for a pile design and installation specification offering additional resistance factors reflecting the reliability of the means used to establish installed pile capacity and the construction control procedures employed.

Introduction

Structural design philosophy and practice have undergone phenomenal changes over the past thirty years. For the previous hundred years structures were routinely designed by elastic analysis, limiting the allowable stresses such that strength and serviceability requirements were satisfied by insuring the expected load effects induced no structural distress. Loads and resistances were calculated deterministically and all variability was accounted for in one value, a code specified factor of safety.

In the United States today both the steel and concrete design codes are based, in part, on limit state principles and employ load and resistance factor procedures. The design community has gradually accepted the "new" methods for superstructure design. But, what about substructure, or foundation, design? In this country it is still exclusively based on allowable stress methods. Both the reasons and framework for a pile design and installation specification based on load factor concepts have been presented elsewhere (Goble et al, 1980). They discussed the dilemma that structural engineers still face when designing a spread footing or pile foundation. The loads that have been collected and carried down the superstructure to the foundation are factored loads that would be applied to the ultimate strength of the foundation. However, permitted soil strengths are defined in terms of working loads. The engineer must now back up and recalculate the

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working loads. Once the strength limitations are satisfied, the spread footing or pile cap is designed by LRFD methods. A powerful argument is made for a more consistent, rational approach to foundation design.

Pile failure can occur in three distinct modes. First, the capacity of a pile as a structural member may be inadequate. This is a structural problem and can easily be addressed as such. The second mode for pile failure is the inability of the soil to support the applied pile loads. This requirement most often controls pile foundation design. The third mode of pile failure is the inability to drive the pile to the required capacity. The drivability problem often calls for very creative solutions. Proposals have been fashioned for probability-based LRFD resistance factors governing the structural and soil failure (by static analysis) modes (Berger, 1989). Inclusion of construction control procedures in generating reliability-based resistance factors for LRFD and modifiers for FOSD (Factor of Safety Design) is the next logical step.

This paper will review the results of research on developing reliability-based resistance factors for pile material types and soil strength predictive methods. A review of and proposal for inclusion of field capacity determination and construction control procedures in the selection of resistance factors and factors of safety will be presented.

Background

In 1969 Cornell proposed a probability-based structural code based on a second-moment format. This work provided an analytical basis for the ACI Code. Because it had the promising ability to produce a set of safety factors on loads and resistances, something that code-writing committees insisted on, it garnered much attention and caused others to research safety methods. The approach suggested by Cornell became known as a Level II technique. It can be described as a First-Order, Second Moment (FOSM) method.

The predictions of the resistances and loads, as well as measures of uncertainty in those predictions, are founded on the statistical data available. It is assumed that any uncertainties inherent in the loads or resistances can be depicted by the expected, or mean, values and the coefficients of variation of the pertinent variables. Here is the attractiveness of the FOSM approach: without requiring the complexity of full probabilistic analysis, the variability of pertinent variables can still be incorporated in a rational design process. The use of only the currently accepted nominal values, as is the case in working stress design, tells us nothing of the variable dispersion.

The foundation and direction for reliability-based standards are provided by target reliabilities, or safety indices, and the variability in the associated material and load parameters. The establishment of the target reliabilities is dependent on existing codes. Therefore, the transition from prevailing methods to more rational and reliability-based methods produces designs that iron out the existing unacceptable variability in relative reliability and, at the same time, does not present unwarranted risks.

Once safety indices are calculated for existing designs, based on collected data concerning the variability and randomness in specified loads and resistances, a target reliability index is selected. In most cases there will be a range of existing safety indices that requires an averaging and interpretation to arrive at the most rational target index. The discovered range in variability of the reliability index in present design gives comparative values of reliability in, and underscores the necessity for, developing design codes that insure a more uniform level of safety.

The development of a universal set of load factors for inclusion in the 1982 ANSI A58.1 building design load standard was accomplished by Ellingwood, Galambos, MacGregor and Cornell. The resultant publication was the "Development of a Probability Based Load Criterion for the American Standard A58," NBS Special Publication No. 577. Adoption of the ANSI load factors, or another set of load factors (e.g. AASHTO), permits the consistent use of load factor combinations for superstructure and substructure design.

Resistance Factors

A target reliability index, β, of 3.0 was selected for determining resistance factors. The results of the calibration process for steel, concrete and timber materials ranged from 2.5 to 3.7. The target reliability index of 3.0 was a compromise and agrees well with reliability indices selected for most superstructure members. The same target reliability index was chosen for static and dynamic analysis methods of soil resistance.

Current allowable stress levels permitted by U.S. codes for steel piles resulted in reliability indices, at a live to dead load ratio equal to 1.0, of 5.9 and 5.2 for 9 and 12 ksi allowable stresses, respectively. A check at an allowable stress of 22 ksi provided a reliability index of 3.1. These results clearly demonstrate the overconservativeness of limiting allowable stresses for steel piles to 9 or 12 ksi. If the concerns include drivability and/or soil capacity issues then they need to be dealt with separately rather than limiting loads on all steel piles. A resistance factor of 0.82 was computed for steel piles for use in LRFD specifications utilizing dead and live load factors of 1.2 and 1.6.

Prestressed concrete piles were subjected to the same analysis as steel piles. At an allowable stress of 0.33f'c and a live to dead load ratio of 1.0, the calculated safety indices for 3000 and 5000 psi concrete were 4.3 and 4.5, respectively. If the allowable stresses were increased to 0.50f'c the safety index would drop to 3.2 for both concrete strengths. Resistance factors were computed for the target reliability index of 3.0 and a live to dead load ratio of 1.0. The resultant resistance factors were 0.75 and 0.72 for 3000 and 5000 psi concrete, respectively. Because most prestressed piles are at least 5000 psi today, and in an effort to have only one resistance factor for concrete piles, 0.72 was selected for all concrete piles.

Reliability indices for Douglas fir and Southern Pine treated and untreated timber piles were calculated for 600, 1000 and 12000 psi allowable stresses. At 1200 psi, the level permitted by most codes, the indices at a live to dead load ratio of 1.0 ranged from 3.2 for untreated Southern Pine to 3.7 for all Douglas fir. At these levels, efforts to reduce allowable stresses in timber piles to near 600 psi appear unwarranted. Calculated resistance factors were modified by a load duration factor to account for loss of strength over time, a phenomenon well documented for structural timber elements. Load duration adjustment factors were selected as functions of the live to dead load ratio. The adjusted resistance factor for Douglas fir and Southern Pine timber piles at a target reliability index of 3.0 and a live to dead load ratio of 1.0 was 0.65.

Two studies (Dennis and Olson, 1983) comparing predicted soil resistance by static analysis to measured static load capacity were utilized to provide the resistance distributions and parameters for probabilistic analysis. Reliability indices and resistance factors were calculated for soil classifications and analysis methods. Results from both studies indicated that the static analysis methods employed were significantly more accurate for piles in clay than in sand. Piles driven through layers of sand and clay with the tip in sand resulted in the lowest reliability levels. At a target reliability index of 3.0, the computed resistance factors ranged from 0.11 for an American Petroleum Institute method for pipe piles in sands to 0.70 for a new method, NCL1, designated for steel pipe piles in clay. The limited data base for this portion of the study severely hindered the application of these results. At most they should be viewed as preliminary indicators of relative performance of static soil analysis methods.

Development of resistance factors for dynamic capacity predictive methods required comparisons of static load test results with capacity predictions by dynamic formulas, wave equation analysis, Case Method analysis with the Pile Driving Analyzer and CAPWAP analysis. As with the static soil analysis results, severe limitations and deficiencies in the available data base currently restrict the application of the results. The CAPWAP and Case Method results from one study provided an average reliability index of 3.4 for designs utilizing a factor of safety of 2.0. Dynamic formulas, on the other hand, produced an average reliability index of only 0.84 for the same factor of safety. At a factor of safety of 4.0 the average reliability index for dynamic formulas increased to only 1.63. Computed resistance factors displayed a similar spread of values, dependent on the sophistication of the predictive method. They ranged from 0.31 for the ENR formula to 0.85 for CAPWAP at a target reliability index of 3.0.

Design and Installation Specification

Consider now the procedures that might be used in the application of these methods in design and installation. Assume that at a particular site a driven pile foundation is to be used. The factored load would presumably be known. A decision must be made to select the pile type, length, and required nominal strength consistent with the site conditions and the available pile driving resources in the area. Each design selection must be checked against the design requirements as follows:

1. Check structural capacity of pile material type - material ϕ-factor.
2. Check soil resistance by static analysis with the requirement that it be verified in the field.
3. Establish driving criteria by wave equation analysis.

After a satisfactory combination has been assembled the design is proven in the field. The required nominal strength in the field is set based on the ϕ-factor associated with the pile capacity and construction control procedures used. The procedures could be one of the following:

1. Driving resistance determined by wave equation analysis and restrike blow count.
2. Capacity determined by static load test.
3. Capacity determined by dynamic monitoring on re-strike with CAPWAP analysis.
4. Capacity determined by dynamic monitoring with static load test calibration.

A ϕ-factor would be associated with each of these procedures.

Conclusions

A procedure has been described that can be used to implement LRFD methods in pile foundation design. This method is based on a limited reliability analysis of available data. Further work will be required to establish final values for resistance factors.

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