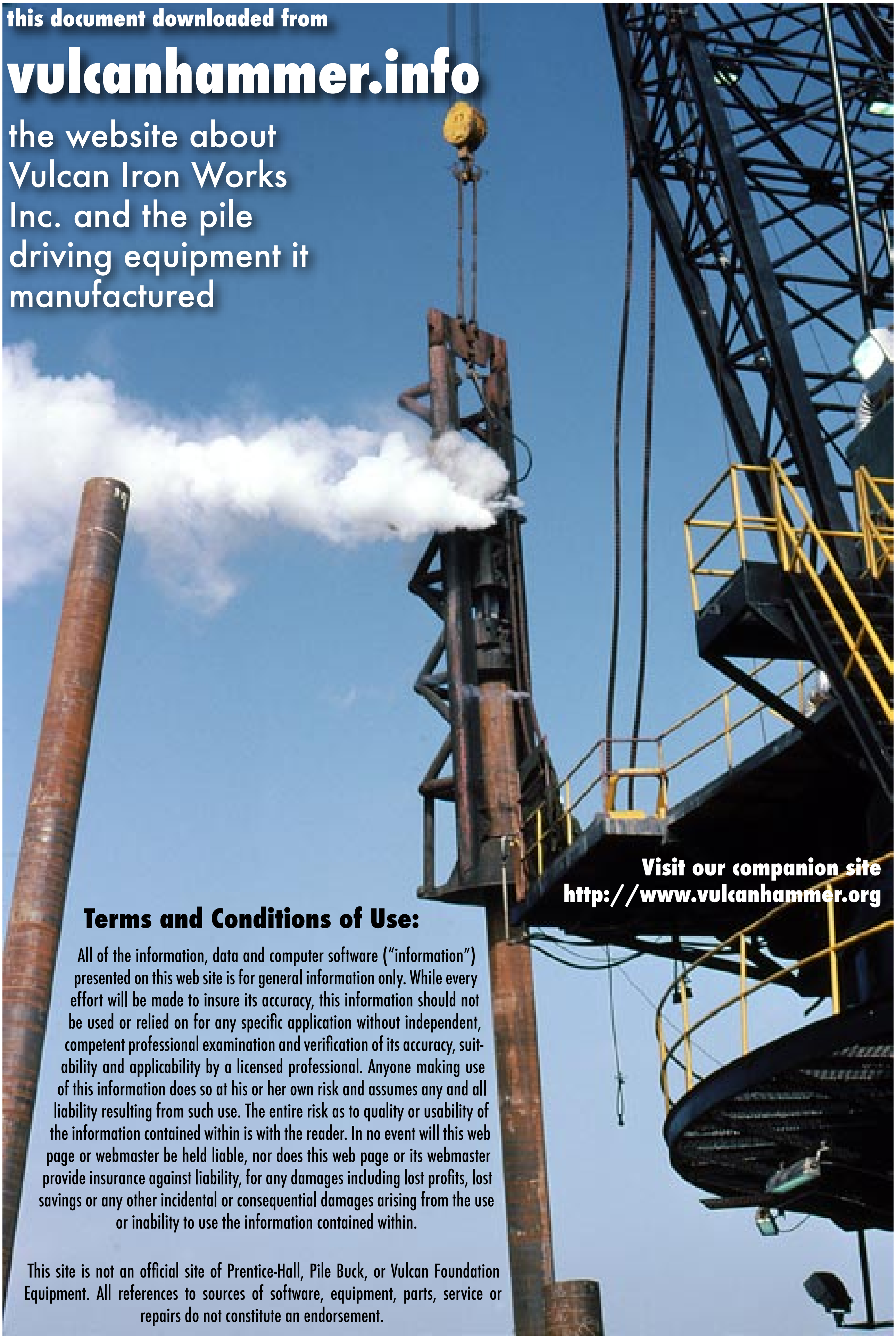


# LOAD AND RESISTANCE FACTOR DESIGN OF PILES

G. G. Goble

Beginning about two decades ago, dramatic changes began to occur in structural design philosophy. Prior to that time in most of the twentieth century, the structural design activity sought to develop a structural system that would resist the effects of an expected load application with no structural distress. This was achieved by requiring that the stresses calculated from an elastic analysis of the structure when subjected to the expected design or working loads not exceed some accepted, allowable stress. These allowable stresses were usually defined either explicitly or implicitly as a fraction of the yield or ultimate strength of the material involved. The fact that the loads had some statistical distribution with substantially differing probabilities of occurrence for different types of loads was ignored. Design loads were developed and their effect on the structures was analyzed deterministically.

There are clear advantages to the above approach. The structure is subjected to an elastic analysis and the limit on allowable stresses is placed well below the elastic limit so it can be expected that even though the structural engineer is primarily concerned with the design of a structure having sufficient "strength", many serviceability questions will be satisfied indirectly. For instance, one can expect in such an approach that deflections will be tolerable and acceptable. The structure is subjected to elastic analysis and, therefore, indirectly deflections are controlled.

Another important but less understood advantage of an elastic analysis and a working stress approach is that there is a clear and direct redesign process available to the structural engineer. Those portions of the structure which are found to be overstressed in the analysis can be increased in size while other parts of the structure where stresses are less than the allowable can be decreased in size. This approach provides a simple redesign algorithm.

There are also important disadvantages in working stress design. For instance, a statically indeterminate structure having a high degree of redundancy will have a different factor of safety to collapse than will a statically determinate structure. When such structures are designed by working stress procedures, the actual factor of safety for particular structures can be quite variable. Since the loads that must be carried by the design can come from a variety of sources (wind, live, dead, etc.) the accuracy and reliability of the determination of their magnitude can differ widely. Likewise, our ability to predict the behavior of various types of structural elements differs as does the consequence of failure (the collapse of a column is usually more serious than is a beam failure). There are other considerations which motivate the change in practice. For instance, the behavior of reinforced concrete members does not satisfy working stress analysis due to time dependent and inelastic deformations.

On the other hand, if working stress analysis is completely abandoned for an exclusively strength-design based procedure, then difficulties can arise with other performance aspects of the structure. With strength evaluation procedures questions of deflection are completely neglected.

In summary the traditional working stress design procedures have come under criticism because they do not recognize the statistical distribution of loads and the non-deterministic character of structural element strength. The above factors together with considerations of the varying consequences of failure for different element types all point to the need for a design procedure that will produce factors of safety that include these consequences.

As a solution, a procedure known as load and resistance factor design has evolved which is becoming increasingly accepted in the design of various kinds of structural elements. This procedure deals very directly with the questions involved in structural design. The structure is designed to satisfy requirements of strength and serviceability, directly and separately. By serviceability in structural design we are referring to such considerations as deflection, long term deformation, vibration, corrosion control, and a variety of other such influences.

Strength considerations are solved directly by insuring a specific factor of safety. This factor of safety, however, can be quite variable since the method recognizes that under different conditions different factors of safety are appropriate. For instance, if the magnitude of the load applied to a structure is very well known, then it seems reasonable that a smaller factor of safety can be used than when the load magnitude might be quite variable.

Other factors which come into such a design procedure include considerations of the reliability of member performance. As an example, the flexural behavior of an under-reinforced concrete beam can be accurately predicted and furthermore, the member will show a substantial deflection prior to losing the capability to carry a small amount of increasing load. It gives a strong warning of impending failure. On the other hand, the same material in a reinforced concrete column will exhibit less ductility and give far less warning of failure. It is appropriate in the first case that the factor of safety be smaller than in the second case.

This kind of an approach to design is particularly well suited to the design of pile foundations. In fact, it may be very well suited to all kinds of foundations. Only pile foundations will be discussed here.

Let us consider one further problem currently faced by the structural designer when he approaches the design of either a pile supported foundation or a spread footing. As elements are proportioned, usually from the top of the structure downward, the loads are collected and carried along. At the base of the structure the foundation loads have been collected. However, these loads, derived from the structural design, will be in the form of a factored load to be applied to the ultimate strength of the foundation. But, current practice requires that soil limitations be handled in terms of working loads, so working loads appropriate to the design of this particular element must be assembled. After the allowable soil loads imposed by the foundation engineer are satisfied, the design of the footing element itself must be accomplished using a load and resistance factor procedure. This approach is not only inconvenient, but it lacks a great deal in philosophical clarity.

The problem is further complicated by the fact that during the evaluation of the strength of a pile foundation, the foundation engineer will probably determine the ultimate capacity of an individual pile. He or the structural engineer will then assign a rather arbitrary factor of safety.

Traditionally, for well controlled designs, this number is usually approximately two. In current practice in the United States, however, it can vary widely. Surely it should be related to the control procedures that are used in design and construction.

This paper will propose the framework for a design specification for pile foundations which will avoid the inconvenience of dealing with both factored and working load and at the same time provide a more rational approach for dealing with pile design. The specification which has been used as the framework is the American Association of State Highway and Transportation Officials' Bridge Design Specifications.

The idea of safety factor has been rather loosely used in working stress design. The designer generally would define factor of safety as the structural strength divided by the working loads. In the context of load factor based design more care must be used with the nomenclature. The structural strength is actually not so easily defined. This is also true with pile performance where as yet we have no generally accepted procedure for evaluating the results of a static load test. In the remainder of this paper the term safety factor will refer specifically to the ratio between the defined or nominal element strength and the working load.

This specification, as is the case with most load factor design procedures, divides the safety factor into two parts. The first part is the factor which is applied to the design load. It is usually expressed as a constant appropriate to the particular load type times the load in question. A much larger factor is used for live loads since their magnitudes are not as accurately predicted as is the dead load. On the other hand, factors for many loads having sources such as earthquake, wind or stream runoff must be related to the occurrence frequency assumed in selecting the design load. For instance, it would be expected that, if the design load were based on a 100 year frequency event, it would have a smaller factor than if it came from a 25 year frequency. The other portion of the factor of safety is used to reduce the predicted strength of a structural element based on an evaluation of the accuracy with which this element capacity can be predicted, the variability of the element capacity, the warning of failure that it will give, and the consequences of failure.

As indicated above serviceability conditions are handled directly in load factor design procedures. This specification divides the problem of determining an acceptable pile design into three separate considerations: strength, serviceability, and installability. In the context of pile foundations serviceability refers to such factors as long term settlements, corrosion and other such considerations. These factors, while frequently difficult to analyze, are very important in pile design.

One reason for the low allowable stresses that are enforced on some piles is the consideration that sometimes they cannot be installed to higher working loads due to driving difficulties. It seems unrealistic to limit allowable stresses in all piles because some of them cannot be installed for those stresses. Installability should be evaluated as a separate consideration.

## Design for Strength

The selection of a pile design for strength considerations involves assuring that the applied load is less than the pile strength. Recognizing that there is a statistical variation in the load and likewise a variation in the strength, the purpose of the factor of safety is to assure that the probability of the strength being less than the load is sufficiently small. This requirement is illustrated in Figure 1. In Figure 1(a) and (b) hypothetical distributions of load and strength are shown with a normal distribution assumed. When they are superimposed, the cross-hatched area indicates that portion of the cases where failure occurs (the load is less than the strength). In Figure 1(d) the effect of increased strength variability is shown. Even though the average strength is the same in both cases, the probability of failure will be greater for the case with the greater variability.

In the case of the AASHTO Bridge Code the load expression is currently defined in load factor form as

$$U = 1.3\left(D + \frac{5}{3} L\right) \qquad (1)$$

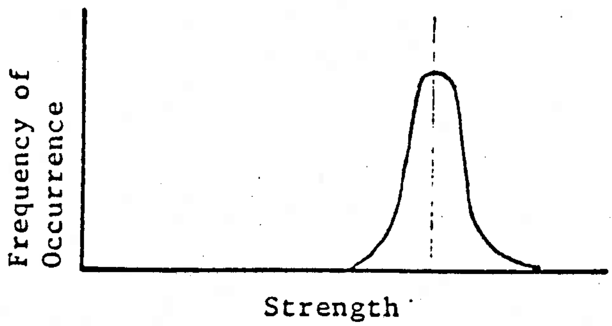
where U is the factored load, D is the actual dead load, L is the working live load. The AASHTO Bridge Design Specification contains additional ultimate load equations that must also be satisfied but they will not be discussed here.

In foundation design for bridges the contribution of the dead load is usually the dominant influence. Therefore, the foundation loads can be approximated by

$$U = 1.3\,D \qquad (2)$$

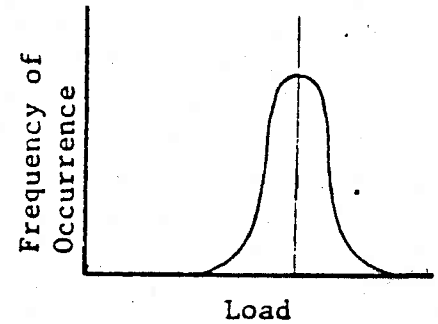
In order to assure adequate safety against failure the nominal ultimate strength of the pile, R', must be reduced by a factor, $\phi$. Thus,

$$R = \phi R' \qquad (3)$$



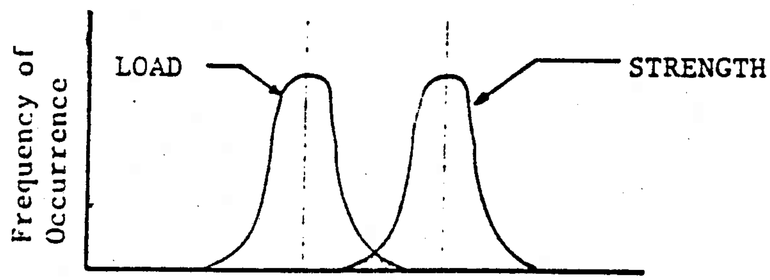

(a)

Strength Distribution



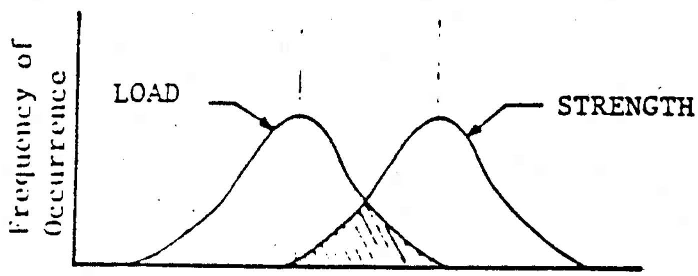

(b)

Load Distribution




(c)

Load and Strength Distributions
with Frequency of Failure




(d)

Effect of Variability on Frequency of Failure

Figure 1

Frequency Distributions for Strength and Load for a Structure where $\phi$ is the resistance factor or, according to the AASHTO specification, the capacity modification factor and R' is the nominal ultimate strength. A design is acceptable if

$$R > U \tag{4}$$

Since the factors to be applied to the load are already specified, it is only necessary to determine appropriate values for $\phi$. Consider the ways in which a pile can fail. First it can fail due to structural failure of the pile (an infrequent occurrence) and second by penetration into the ground. In the first case $\phi$ values have already been defined for columns in specifications such as the ACI Building Design Specification and a value of 0.7 seems appropriate when applied to piles.

The establishment of $\phi$ for the second and most likely failure mode is more difficult. In order that $\phi$ be related to the variability of the pile strength it should be dependent on the means used to establish pile capacity, the variability of the soil and the construction control procedures used. Six different procedures now in use can be defined.

(1) Case Method Analyzer with Static Load Test

One of the initial production piles shall be driven to the required ultimate capacity as determined by the Case Method Analyzer (Ref. 1) with allowance made for the estimated setup or relaxation. Blow counts shall be recorded. After a wait time sufficient to allow pore water pressure to dissipate, a static load test shall be performed to failure. After completion of the static load test, the pile shall be restruck while tested with the Case Method Analyzer and the blow count shall be recorded. The dynamic record shall be examined for pile damage (Ref. 2). Any necessary adjustments shall be made in the driving criteria. Additional pile tests shall be by the Case Method Analyzer.

(2) Static Load Test

One of the initial production piles shall be driven to the required ultimate capacity as determined by wave equation analysis. Allowance shall be made for estimated setup or relaxation. Blow count shall be recorded. After a wait time sufficient to permit excess pore water pressure to dissipate, a static load test shall be performed to failure. Any necessary adjustments shall be made in the driving criteria using the wave equation analysis. Additional piles shall be proof load tested statically to the specified ultimate capacity.

(3) Case Method Analyzer

One of the initial production piles shall be driven to the required ultimate capacity as determined by the Case Method Analyzer. Allowance shall be made for the estimated setup or relaxation and blow count shall be recorded. After a wait time sufficient to permit excess pore water pressure to dissipate, the pile shall be restruck while tested with the Case Method Analyzer and the blow count recorded. The dynamic record shall be examined for pile damage. Any necessary adjustments shall be made in the driving criteria. Some additional piles shall be tested by the Case Method Analyzer.

(4) Wave Equation Analysis

The driving criteria shall be set by Wave Equation analysis with allowance made for setup or relaxation. Blow count shall be recorded. After a wait time sufficient to permit excess pore water pressure to dissipate, selected piles shall be restruck and the blow count carefully measured at the beginning of the restrike.

(5) Analysis Based on Soil Data (Static Analysis)

The required depth of penetration shall be set by an appropriate static analysis based on soil boring data. The piles shall be driven to that penetration independent of blow count.

(6) Dynamic Formula

The driving criteria shall be set by use of the dynamic formula with allowance for setup or relaxation. The formula shall be written without a safety factor. Blow count shall be recorded. After a wait time sufficient to permit excess pore water pressure to dissipate, selected piles shall be restruck and the blow count carefully measured at the beginning of restrike.

It is difficult to arrive at rational values for $\phi$ since sufficient data is not available for a thorough systematic analysis. Recommendations are contained in Table I together with the factor of safety that exists when used with the AASHTO load factors, assuming dead load is dominant.

TABLE I

$\phi$-FACTORS FOR PILE-SOIL FAILURE

| Inspection Class | Soil | |
|---|---|---|
| | Uniform | Variable |
| 1 | .70 (1.86)* | .70 (1.86) |
| 2 | .65 (2.00) | .60 (2.17) |
| 3 | .55 (2.36) | .55 (2.36) |
| 4 | .45 (2.89) | .45 (2.89) |
| 5 | .35 (2.89) | .35 (3.71) |
| 6 | .22 (5.91) | .22 (5.91) |

*Quantities in parentheses give the total factor of safety under the assumption that the applied load is exclusively dead load, i.e. 1.30 is the load factor.

It should be emphasized that the values given in Table I were selected by calibrating the factor of safety with current practice. Therefore, Inspection Class (2) has a total factor of safety of 2.0 (assuming very dominant dead loads). This case is judged to be the best of currently established practice. Likewise, the use of a dynamic formula only gives the traditional factor of safety of 6.0. The other values were interpolated in between. If load test data are assembled, it is possible to arrive at $\phi$ values rationally but this quantity of information is not now available.

## Design for Serviceability

Serviceability considerations are very important in pile foundation design. Of primary interest are long term deformations (settlements). Settlement computations for pile foundations are very difficult to make with any reliability and accuracy. They must be made using working loads and they should be calculated independently of strength evaluations. Other serviceability limitations (for example, durability) tend to involve subjective judgements and are not directly related to structural considerations. Further discussion of serviceability considerations is beyond the scope of this paper.

## Design for Driveability

In the past attempts have been made to place simple limitations on some pile and driving system parameters to make sure that critical driving stresses are not exceeded. Of particular concern is the question of tension stresses induced in concrete piles during easy driving. The most common approach has been the arbitrary limitation of pile-ram weight ratios. These limitations have been shown to be inadequate and even incorrect (Ref. 3).

The problem may be solvable with closed form solutions of the one-dimensional wave equation, but this has not been done as yet. The most reliable approach is the use of a "wave equation" computer program. However, the program must properly model the driving system and proper input data must be used.

If a wave equation analysis is used, the next question that arises is the determination of acceptable values for dynamic driving stresses. Since this is a short term load that can be controlled, it is reasonable to approach closely to the failure stress. Furthermore, the consequence of failure during installation is only that a pile must be replaced (providing that proper inspection methods are being used).

Suggested values for allowable driving stresses for steel and concrete piles are given in Table II.

TABLE II

ALLOWABLE DRIVING STRESSES

| Material | Allowable Stress |
|---|---|
| Steel | 1.1 Fy |
| Concrete* | |
| Compression | $.85\ f'_c$ |
| Tension | $3\sqrt{f'_c}$ |

## Comments and Discussion

The load factor design procedure is now the dominant method for accomplishing structural design. Its use is increasing and expanding. However,

*The allowable dynamic stresses for prestressed concrete piles refers to the total pile stress including prestress.

it has not been used for foundation design even though it fits well philosophically with the methods of foundation design, and particularly for deep foundations. The AASHTO Bridge Design Specification load factor expressions were used in organizing this specification. Of course, other codes could have been used equally well since they all have the same general form.

Other construction control procedures can be inserted in this framework and improvements in the state-of-the-art can be readily incorporated. A proper and reasonable $\phi$ factor must be used. Hopefully, the use of such a procedure will encourage the assembly of additional pile load test data (to failure) so that improved $\phi$ factors can be determined.

One of the important attractions of the procedure described here is that the cost trade-off of improved field testing and construction control can be directly evaluated. Thus, the engineer can show the owner the advantages of improved engineering on large jobs.

The field testing and construction control procedures are not described in detail since those aspects are beyond the scope of this paper. It should be noted that emphasis is placed on restrike testing. This procedure is one of the most important tools for improving pile capacity analysis. It is usually quite inexpensive to perform and will probably justify increased capacities. On the other hand, one of the most dangerous problems is the relaxation of pile capacity. Relaxation will be detected by restrike.

One of the principle advantages of the load factor philosophy is the separation of strength and driveability considerations. Currently used allowable stresses in steel and timber piles are being held at a low level because sometimes they cannot be driven to higher capacities due to excessive driving stresses. The two problems must be separated and dealt with independently since they are quite unrelated. The above procedure accomplishes this separation.

Pile foundation design specifications have remained essentially unchanged for several decades. During this same time, structural design codes and procedures have undergone a gradual change to greater rationality and realism. The procedures suggested here will accomplish the same thing for pile foundation design.

## Acknowledgements

The work discussed here was sponsored by the Federal Highway Administration. However, they have not adopted these procedures and they do not necessarily support the opinions expressed in this paper.

## References

1. Goble, G.G., Likins, G.E., and Rausche, Frank. "Bearing Capacity of Piles from Dynamic Measurements", Final Report for Ohio D.O.T., Dept. of Civil Engineering, Case Western Reserve University, March 1975.

2. Rausche, Frank and Goble, G.G. "Determination of Pile Damage by Top Measurements", ASTM Symposium on Behavior of Deep Foundations, Boston, Massachusetts, June 1978.

3. Goble, G.G., Linins, G.E., and Fricke, Kenneth. "Driving Stresses in Concrete Piles", PCI Journal, Vol. 21, No. 1, January-February 1976.