PILE DESIGN AND INSTALLATION SPECIFICATION BASED ON LOAD-FACTOR CONCEPT

G. G. Goble[1], Fred Moses[2], and Richard Snyder[3]

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ABSTRACT: The use of load-factor procedures for the design of bridge superstructures is expanding rapidly. However, substructure design is still based exclusively on allowable stress methods. This paper presents an approach to load-factor design for pile foundations. The load factors suggested follow the current American Association of State Highway and Transportation Officials recommendations, while the resistance factors recommended are based on the capacity-determination methods and the construction control procedures used. Actual values are selected to be consistent with currently used procedures where they are available. The proposed specification can provide a framework for the use of more-appropriate resistance factors as they become available from ongoing research.

INTRODUCTION

About two decades ago, dramatic changes began to occur in structural design philosophy. Before that time, structural designers sought to develop structural systems that would resist the effects of expected load applications with no structural distress. This was achieved by requiring that the stresses calculated by an plastic analysis of the structure when subjected to the expected design or working load 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 were statistically distributed with

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[1] Prof., Dept. of Civil, Environmental and Architectural Engineering, Univ. of Colorado, Boulder, CO
[2] Prof. of Engineering, Case Western Reserve University, Cleveland, OH
[3] Graduate Student, Case Western Reserve University, Cleveland, OH

substantially different probabilities of occurrence of different types of loads was ignored, Design loads were developed, and their effects on the structure were analyzed deterministically.

There are clear advantages to this approach. The structure is subjected to an elastic analysis, and the limit on allowable stresses is placed well below the plastic region, 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, in such an approach, one can expect 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-working-stress approach is that there is a clear and direct redesign process available to the structural engineer. Those portions of the structure that are found in the analysis to be overstressed can be increased in size while 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 to working-stress design. For instance, a statically indeterminate structure that has 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 (FOS) for a particular structure can vary considerably. Because the loads that must be carried by the design can come from a variety of sources, the accuracy and reliability of the determination of their magnitude can vary widely. Likewise, our ability to predict the behavior of various types of structural elements varies, as does the consequence of failure (the collapse of a column is usually more serious than is a beam failure). There are other considerations that motivate the change in practice. For instance, the behavior of reinforced concrete members does not satisfy working-stress analysis because of 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. For example strength evaluation procedures completely neglect questions of deflection.

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

One solution is the procedure known as limit-state design or load-and-resistance-factor design. This procedure deals directly with the questions involved in structural design. The structure is designed to satisfy requirements of strength and serviceability, both directly and separately. By serviceability in structural design, we are referring to such considerations as deflection, long-term deformation, vibration, and corrosion control.

Strength considerations are solved directly by specifying the FOS of component behavior. This FOS, however, can vary because the method recognizes that, under different conditions, different FOSs are appropriate, For instance, if the magnitude of the load applied to a structure is well known, then it is reasonable to use a smaller FOS than that used when the load magnitude is variable.

Other factors that affect such design procedures include considerations of the reliability of member performance. For example, the flexural behavior of an under-reinforced concrete beam can be accurately predicted and, furthermore, the member will show a substantial deflection before it loses the capability of carrying a small amount of increasing load. It gives a strong warning of impending failure. On the other hand, in a reinforced-concrete column, the same material will exhibit less ductility and give much less warning of failure. It is appropriate that the FOS in the first case be smaller than that in the second. An example of this development is the American Concrete Institute (ACI) F-factor for different concrete elements. This kind of an approach to design is particularly well suited to the design of pile foundations. In fact, it may be well suited to all kinds of foundations, although only pile foundations will be discussed here.

Let us consider one further problem currently faced by the structural designer when he or she 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 are collected. However, these loads, which are 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, and 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 by using a load-and-resistance-factor procedure. This approach is not only inconvenient but also lacks philosophical clarity. It means, for example, that a footing is proportioned for loads that are above the values permitted for the foundation soil.

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 she or the structural engineer will then assign a rather arbitrary FOS. Traditionally, for well-controlled designs, this number is approximately two. In current practice in the United States, however, it varies widely. Surely, it should be related to the procedures that are used in design and construction control.

In this paper, the framework for a design specification for pile foundations is proposed that avoids the inconvenience of dealing with both factored and working loads and, at the same time, provides a more-rational approach for dealing with pile design. The specification used as the framework is the American Association of State Highway and Transportation Officials (AASHTO) bridge design specification.

The definition of FOS has been rather loosely used in working-stress design. The designer generally defines the FOS as the structural strength divided by the working load. In the context of load-factor-based design, the nomenclature must be used more carefully. The structural strength is actually not so easily defined. This is also true for pile performance where we do not yet have a generally accepted procedure for evaluating even the results of a static load test. In the remainder of this paper, the term FOS will refer specifically to the ratio between the defined or nominal element strength and the working load.

This specification, as is the case for most load-factor design procedures, divides the FOS into two parts. The first part is the factor that is applied to each design load. It is usually expressed as a constant appropriate to the particular type of load multiplied by the nominal load in question; a much larger factor is used for live loads because their intensities and load effects are not as accurately predicted as is the dead-load effect. The other portion of the FOS is used to reduce the predicted or nominal strength of a structural element and is 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.

Thus, 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 driveability. In the context of pile foundations, serviceability refers to such factors as long-term settlements, corrosion, and other such considerations. These factors, although frequently difficult to analyze, are very important in pile design.

One reason for the low allowable stresses that are enforced on some types of 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. Drivability should be evaluated as a separate consideration.

DESIGN FOR STRENGTH

The selection of a pile design based on strength considerations involves ensuring that the applied load is less than the pile strength. Because both the load and the strength show a statistical variation, the purpose of the FOS is to ensure that the probability that the strength will be less than the load is sufficiently small. This requirement is summarized in Fig. 1. Figs. 1a and 1b illustrate hypothetical distributions of load and strength (normal distribution assumed). When these curves are superimposed (Fig. 1c), the crosshatched area is related to the portion of the cases where failure will occur (the load is less than the strength). Fig. 1d shows the effect of increased variability. Even though the average strength is the same in both cases, the probability of failure will be greater for the case having the greater variability.

In the AASHTO bridge code, the load expression is currently defined in load-factor form as

$$U = 1.3\,[D + (5/3\ L)] \tag{1}$$

where U = factored load, D = actual dead load, and L = working live load. (The AASHTO bridge design specification also contains additional ultimate-load equations that must be satisfied, and Equation 1 is in a more-complex form, but these complicating details will not be discussed here.)

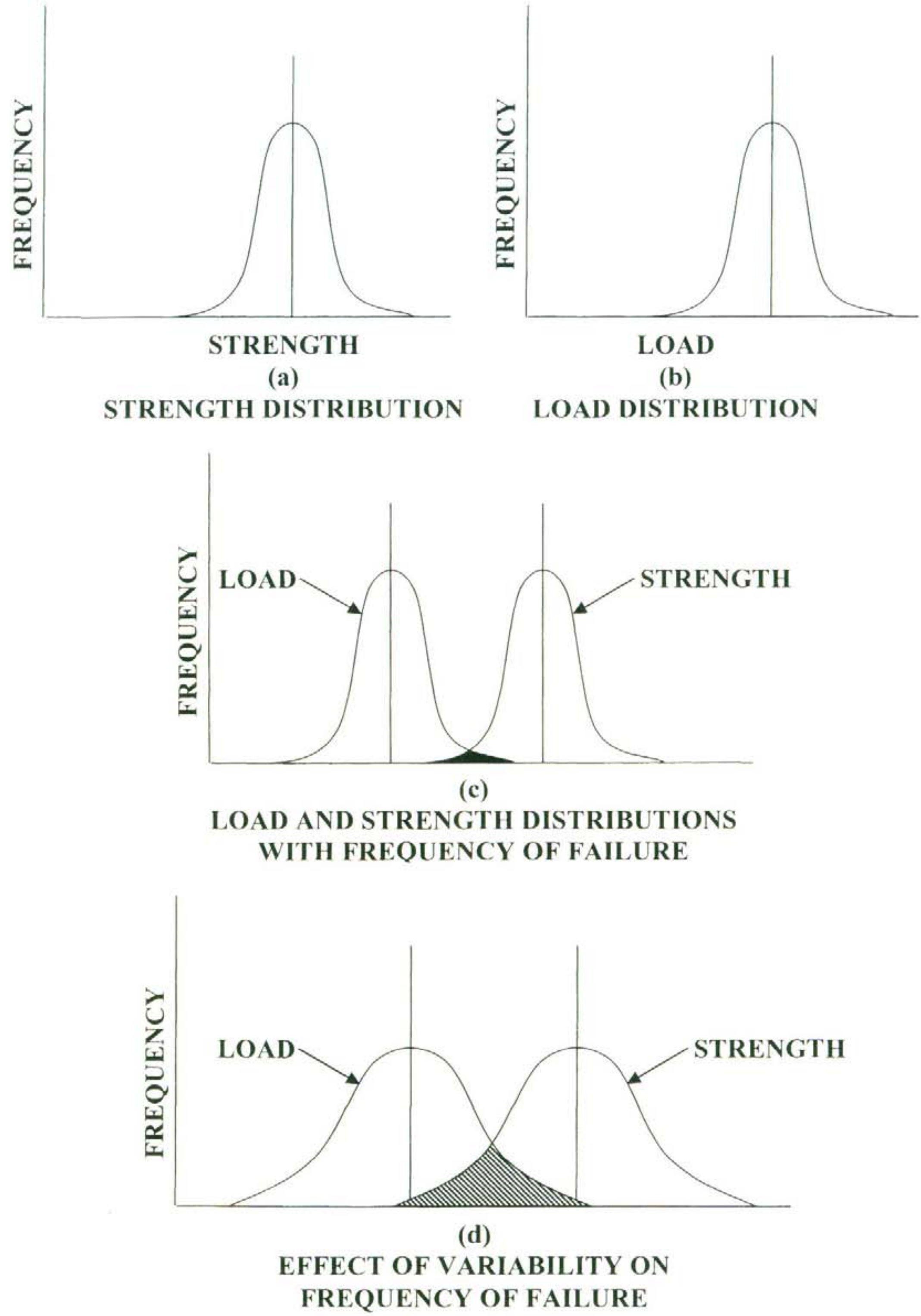

FIG. 1. Effect of variability of distribution of load and strength on frequency of failure

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

$$U = 1.3D \tag{2}$$

To ensure adequate safety against failure, the nominal ultimate strength of the pile (R') must be reduced by a strength safety factor (ϕ). Thus,

$$R = \phi R' \tag{3}$$

where ϕ = resistance factor (in the AASHTO specification, this is called the capacity-modification factor) and R' nominal ultimate strength. A design is acceptable if

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

Because the factors to be applied to the load are already specified, it is only necessary to determine appropriate values for ? . Consider the ways in which a pile can fail. First, it can fail due to structural failure (an infrequent occurrence) and, second, it can fail by penetration into the ground. In the first case, values of ϕ have already been defined for columns in specifications such as the ACI building design specification a value of 0.7 seems appropriate when applied to piles. Further refinement of this value for particular pile types will probably be necessary.

The establishment of ϕ for the second failure mode is more difficult. In order that ϕ 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 is driven to the required ultimate capacity as determined by the case method analyzer (1), making allowance for the estimated setup or relaxation. Blow counts are recorded. After a wait time sufficient to allow the pore water pressure to dissipate, a static load test is performed to failure. After completion of the static load test, the pile is restruck and tested by the case-method analyzer, and the blow count is again recorded. The dynamic record is examined for pile damage (2), and any necessary adjustments are made in the driving criteria. Additional pile tests are made by the case method analyzer.
2. Static load test: One of the initial production piles is driven to the required ultimate capacity as determined by wave equation analysis, making allowance for estimated setup or relaxation. Blow counts are recorded. After a wait time sufficient to allow the excess pore water pressure to dissipate, a static load test is performed to failure. Any necessary adjustments are made in the driving criteria by using the wave equation analysis. Additional piles are proof-load-tested statically to the specified ultimate capacity.
3. Case-method analyzer: One of the initial production piles is driven to the required ultimate capacity as determined by the case-method analyzer, making

allowance for the estimated setup or relaxation. Blow counts are recorded. After a wait time sufficient to allow the excess pore water pressure to dissipate, the pile is restruck and tested by the case-method analyzer, and the blow count is again recorded. The dynamic record is examined for pile damage, and any necessary adjustments are made in the driving criteria. Some additional piles are tested by the case-method analyzer.

4. Wave equation analysis: The driving criteria are set by wave equation analysis, making allowance made for setup or relaxation. Blow counts are recorded. After a wait time sufficient to allow the excess pore water pressure to dissipate, selected piles are restruck, and the blow count is carefully measured at the beginning of the restrike.
5. Analysis based on soil data (static analysis): The required depth of penetration is set-by an appropriate static analysis based on soil boring data. The piles are driven to that penetration independent of blow count.
6. Dynamic formula: The driving criteria is set by use of the dynamic formula, making allowance for setup or relaxation. The formula is written without a safety factor. Blow counts are recorded. After a wait time sufficient to allow the excess pore water pressure to dissipate, selected piles are restruck, and the blow count is carefully measured at the beginning of the restrike.

It is difficult to derive rational values for ? because sufficient data are not available for a thorough, systematic analysis. The table below presents recommended values together with total FOSs that exist when used with the AASHTO load factors, assuming dead load (1.30) is dominant.

Inspection Class	Uniform Soil		Variable Soil	
	ϕ	Total FOS	ϕ	FOS
1	0.70	1.86	0.70	1.86
2	0.65	2.00	0.60	2.17
3	0.55	2.36	0.55	2.36
4	0.45	2.89	0.45	2.89
5	0.35	3.71	0.35	3.71
6	0.22	5.91	0.22	5.91

These values were selected by correlating the FOS with: current practice. Therefore, inspection class 2 has a total factor of safety of 2.0 (assuming dominant dead loads). This case is judged to be the currently widely used and well-established practice. The use of a dynamic formula gives the traditional FOS of 6.0. The other values were established by interpolation.

DESIGN FOR SERVICEABILITY

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

DESIGN FOR DRIVABILITY

In the past, attempts have been made to place simple limitations on some pile and driving system parameters to ensure that critical driving stresses are not exceeded. The question of tension stresses induced in concrete piles during easy driving is of particular concern. 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 (3).

It may be possible to solve the problem by using closed-form solutions of the one-dimensional wave equation, but this has not yet been done. 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 to the determination of acceptable values for dynamic driving stresses, because this is a short-term load that can be controlled, it is reasonable to approach closely to the failure stress. Furthermore, the only consequence of failure during installation is that a pile must be replaced (providing that proper inspection methods are being used).

Allowable driving stresses for steel and prestressed concrete piles are usually given in terms of yield stress (F_y) and 28-day cylinder strength (f'_c), respectively.

Material	Allowable Stress
Steel	0.85 Fy
Concrete	
Compression	$0.8 f'_c$
Tension	$3(f'_c)^{1/2}$

COMMENTS AND DISCUSSION OF PROCEDURE

The load-factor design procedure is now the dominant method for structural design, and its use is increasing. However, it has not yet been used for foundation design, even though it fits well philosophically with the methods of foundation design, 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 into this framework, and improvements in the state-of-the-art can be readily incorporated. Proper and reasonable ? factors must be used. The use of such a procedure may encourage the assembly of additional pile load test data (to failure) so that improved ? factors can be determined.

One of the important attractions of the procedure described in this paper 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 because 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, which can be detected by restrike testing.

One of the principal advantages of the load-factor philosophy is the separation of strength and drivability considerations. At present, allowable stresses in steel and timber piles are held at a low level because sometimes such piles cannot be driven to higher capacities due to excessive driving stresses, The two problems are quite unrelated and should be separated and dealt with independently.

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 in this paper will accomplish the same thing for pile foundation design.

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