LRFD for Geotechnical Applications

By John T. Christian, P.E., Ph.D.

Load and Resistance Factor Design (LRFD) is now a central part of structural engineering. The standard design codes for structural steel and concrete are based on LRFD, and design procedures for highway elements such as bridges are increasingly converting to the LRFD methodology. On the other hand, the geotechnical community has been much slower to adopt LRFD.

> "…different factors of safety might be appropriate for the different soil parameters…"

Some structures, such as earth dams and levees, are entirely – or almost entirely – geotechnical, but others, such as piles and retaining walls, are part of a complex system that includes both structural and geotechnical components. Piles, for example, are mechanisms for conveying structural forces to the supporting ground. Many engineers have observed that, if the structural system is to be designed by the LRFD methodology, then the supporting geotechnical components should too. This perspective is a major reason for the current push to apply LRFD in geotechnical engineering.

Historical Background

LRFD arose from the recognition that structural design codes call for the engineer to evaluate the effects of various combinations of loads – dead, live, wind, snow, and so forth. Different circumstances involve different combinations of loads. Researchers argued that, instead of defining the combinations arbitrarily, engineers should combine the loads rationally and that the probabilities of occurrence of the loading provided a basis for rational combination.

The mathematical statement of the LRFD methodology (TRB 2005) is

$$\Sigma\, \gamma_i\, Q_{ni} \leq \varphi R_n \qquad \text{Equation (1)}$$

where

γ_i = load factor applicable to a specific load component;

Q_{ni} = a specific nominal load component;

$\Sigma\, \gamma_i\, Q_{ni}$ = the total factored load for the load group applicable to the limit state being considered;

φ = the resistance factor;

R_n = the nominal resistance available (either ultimate or the resistance available at a given deformation).

We assume that we know how the loads and the resistance are distributed; we know the form of their probabilistic distributions and the values of the governing parameters such as means and standard deviations. We also know the failure criterion – that is, a mathematical description of the combination of loads and forces that will exceed the available strength, or that will lead to excessive deformation. The mathematical problem is then to determine how far the expected values of the uncertain parameters have to be from the failure condition so that the probability of failure is less than a predetermined value. The result is expressed as a set of load and resistance factors.

The literature contains many books and articles describing the mathematical procedures employed to develop the LRFD formulation for five specific cases, and the techniques used to solve the resulting equations. Melcher (1999), for instance, provides a particularly clear exposition of the subject. It is clear that a great deal of research has gone into establishing the appropriate values of the load and resistance factors, and that the results have become accepted parts of structural engineering practice.

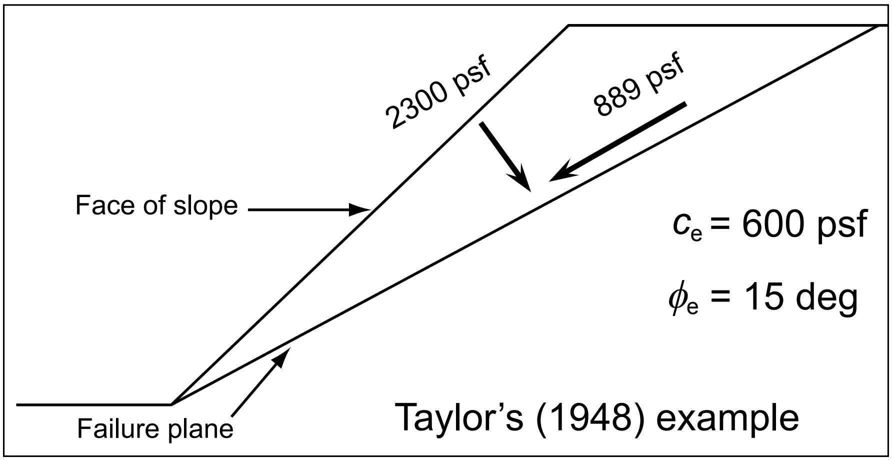

Figure 1: Geometry, loads, and parameters for Taylor's (1948) example

It should not come as a surprise to geotechnical engineers that different parameters and loads contribute in different ways to the possible failure of a facility and are known with different degrees of certainty. In his classic book on soil mechanics, Taylor (1948) described an idealized problem of a critical failure plane on which the normal effective stress $\overline{\sigma}_n$ = 2300*psf* and the average shear stress τ = 899*psf*. The effective stress parameters (cohesion and friction angle) for the soil at the failure surface are $\overline{c}_e$ = 600*psf* and $\overline{\phi}_e$ = 15°. *Figure 1* illustrates the geometry, loads, and strength parameters for this example. He proposed that different factors of safety might be appropriate for the different soil parameters, and, if $\overline{c}_d$ and $\overline{\phi}_d$ are the cohesion and friction angle mobilized, the two factors of safety are

$$F_c = \frac{\overline{c}_e}{\overline{c}_d} \qquad F_\phi = \frac{\tan \overline{\phi}_e}{\tan \overline{\phi}_d} \qquad \text{Equation (2)}$$

The term "mobilized" in the previous sentence means that these are the values of cohesion and friction that are needed to keep the slope in equilibrium with the forces of gravity. He then showed that there are many possible combinations of the two factors, specifically the five combinations listed in *Table 1*.

Table 1. Taylor's (1948) Partial Safety Factors

F_c	1.00	1.26	1.37	1.50	2.20
F_N	2.13	1.50	1.37	1.26	1.00

Taylor (1948) goes on to comment, as quoted below from his book on soil mechanics:

"In the final combination of values given in the above table F_c equals 2.20 and F_N equals unity. The value 2.20 may be defined as the ratio between the actual cohesion and the cohesion required for stability with full friction mobilized, this ratio sometimes being called the *factor of safety with respect to cohesion*. . . . [T]he cohesion required for stability is directly proportional to the height of the slope. From this it may be concluded that the factor of safety with respect to cohesion is equal to a more significant quantity called the *factor of safety with respect to* *height*. This factor is designated by F_H, and it is the ratio between the critical height and the actual height, the critical height being the maximum height at which it is possible for the slope to be stable. This case may be expressed as shown below.

For the case in which F_N is arbitrarily taken equal to unity, F_c becomes equal to F_H and

$$F_H = \frac{c_e}{c_d} \quad \text{and} \quad \tau = \frac{c_e}{F_H} + \bar{\sigma} \tan \phi_e$$

The cross section of the example used in this section would be thrown into a condition of incipient failure if the shearing strength were suddenly divided by F_S or 1.37. Failure would also be incipient if the cohesional strength were suddenly divided by 2.20, or if the height were suddenly multiplied by F_H, which equals 2.20. These statements can be reworded to give alternate definitions of safety factors that in some respects are preferable to those previously given . . ."

As this passage shows, many of the ideas underlying the LRFD approach to design have been part of geotechnical engineering for decades. It is therefore worthwhile to ask why the acceptance of LRFD has been so slow in the geotechnical community, and what are the obstacles to its adoption.

The Geotechnical LRFD Problem

Although geotechnical engineers and researchers have long recognized that soils and rocks have uncertain properties and Taylor proposed partial factors of safety as long ago as 1948, the geotechnical profession has been slow to adopt LRFD methodology. It is worthwhile to investigate the sources of this situation.

First, *Equation (1)* implies that there are several loads to be factored and combined in the final design, but only one resistance factor. In effect, all the resistance factors are folded into one term (φ). However, the resistance of soils and rocks reflects a complex interaction amongst a large number of parameters – cohesion, friction, unit weight, joint spacing, etc. – each of which must be defined probabilistically and some of which are correlated. This creates a complicated analytical problem that is only now being addressed by researchers.

New Orleans, LA, 2-12-06 -- 9th Ward, U.S. Army Corps of Engineers remove dirt from the failed 9th Ward Levee in preparation to remove the old Sheet Piling and replace it with Cat 4 Sheet Piling and reinforcement "H" Piling. Courtesy Marvin Nauman/FEMA.

A second issue is that water contributes to geotechnical problems. Geotechnical engineers recognize that the first principle of intelligent geotechnical design is to get the presence and the flow of water right. Unfortunately, water conditions differ from one site to another, so it is hard to see how a general factor-based formulation can be applied across the range of practical conditions. It is worth noting that many of the developments of LRFD methods for geotechnical problems ignore the effect of water. The National Cooperative Highway Research Program (NCHRP)12-55 report (2004) avoids some of the difficulties of dealing with water pressures by stating all strengths as total-stress strengths or undrained strengths, and not in terms of cohesion and friction.

Perhaps the geotechnical element that most closely resembles a steel or concrete structure is a pile. It is essentially a structural element that happens to be embedded in soil. It is not surprising that some of the most detailed studies of LRFD applications to geotechnical problems have been studies of different methods of designing and testing piles.

Current Applications

Perhaps the most comprehensive efforts to apply LRFD methodology in geotechnical engineering are those described by Eurocode 7 (Frank 2006). This is an attempt to codify most of geotechnical practices along the lines of limit state design. It is also part of an overall system of Eurocodes that cover all structural disciplines. One criticism of the Eurocode effort is that some of the results are attempts to select the LRFD parameters to recover the same designs and factors of safety used in prior design codes. In this author's opinion, this is misguided. There seems to be little point in developing a new design methodology that has the same effect as existing codes. One motivation for LRFD is to improve design, making some portions of the system more robust while in other portions removing excess capacity.

The NCHRP 12-55 (2004) study is now under review to determine if the databases used for the study are adequate. The study considered five types of laterally loaded structures:

- Inverted T-type cantilever retaining walls on spread footings and deep foundations
- Inverted T-type cantilever bridge abutments on spread footings and deep foundations
- Prefabricated modular walls or bin-wall type structures
- Flexible cantilever walls with discrete and continuous vertical elements (i. e., soldier-pile and sheet-pile walls)
- Single and multiple-level anchored walls with discrete vertical wall elements

As mentioned above, the issue in the current review is the adequacy of the data used to support the recommendations. However, even if some of the recommendations are found to require more supporting data, the report will represent a significant advance in developing rational load and resistance factors for geotechnical applications.

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The Future

Several universities and other organizations are actively pursuing LRFD applications in geotechnical engineering. Developing LRFD for geotechnical problems is not simply a matter of applying a well-defined structural engineering methodology to a different but closely related field. There are differences between structural and geotechnical engineering, reflecting the differences of the behavior of the materials, their distribution in space and time, and the analytical tools available to deal with them. These problems are now being worked out.

Probabilistically based design is increasingly becoming attractive in geotechnical practice, as in other aspects of civil engineering. LRFD is one methodology for applying probabilistic concepts. LRFD is increasingly popular in the highway engineering community, and the federal highway establishment is one of the major proponents of its application. Others have suggested that, in view of the complexities of describing local geotechnical conditions, it may be preferable to perform a direct reliability-based design including the uncertainties in the parameters for the specific problem at hand rather than to rely on more generalized LRFD parameters. It is fair to say that the jury is still out on a general decision as to which approach is best.

One point that is clear to this engineer is that it is a mistake to develop LRFD parameters simply to recreate the same designs as are achieved by current methods. LRFD design must be based on fundamental studies of the behavior of the materials. If LRFD is to bring significant improvement, it will inevitably identify some current designs as overly conservative and others as not conservative enough. The purpose of LRFD is to improve design. ▪

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New Orleans, LA., 10-17-2005 – Engineer, Tim Fontenot surveys levee to determine what caused breach in the Lower 9th Ward following hurricane Katrina. Courtesy Andrea Booher/FEMA.

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