Implementation of LRFD Methods to Quantify Value of Site Characterization Activities

Mise en œuvre des méthodes de conception LRFD pour quantifier la valeur des activités de caractérisation du site

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ABSTRACT: A comprehensive research program was recently completed to develop "state specific" LRFD guidelines for the Missouri Department of Transportation in the United States of America (USA). The new guidelines implement improvements to current AASHTO LRFD specifications that provide minimum national standards for design of transportation projects in the USA. The most notable of these improvements are specification of resistance factors that are dependent upon the variability of input parameters. One product of these improvements is to produce designs that more closely achieve target levels of reliability. Perhaps more importantly, the guidelines provide designers with explicit means to quantify the potential value of site characterization activities during the design phase. The latter outcome allows designers to make more rational decisions regarding the type and scope of site characterization activities and provides quantitative support for such decisions so that designers can more effectively convey the value of site characterization to others.

RÉSUMÉ : Un vaste programme de recherche a été récemment mené pour adapter des directives LRFD spécifiques au Département des Transports du Missouri (USA). Les nouvelles recommandations apportent des améliorations aux normes actuelles nationales AASHTO LRFD qui fournissent des normes minimales pour la conception de projets de transport aux Etats-Unis. La plus notable de ces améliorations est la spécification de facteurs de résistance qui dépendent de la variabilité des paramètres d'entrée. Un résultat de ces améliorations est de produire des modèles qui permettent d'atteindre un plus grand niveau de fiabilité. Peut-être plus important encore, les directives fournissent aux concepteurs de moyens explicites pour quantifier le niveau de qualité des reconnaissances géotechniques permettant de caractériser un site. Le dernier résultat permet aux concepteurs de prendre des décisions plus rationnelles concernant le type et l'étendue des reconnaissances du site et leur offre un outil quantitatif pour évaluer et transmettre plus efficacement à d'autres la valeur de la qualité des investigations.

KEYWORDS: load and resistance factor design, geotechnical site characterization, variability, uncertainty.

1 INTRODUCTION

Current practice for geotechnical design of transportation infrastructure in the U.S. utilizes load and resistance factor design (LRFD) techniques. In these methods, load factors and resistance factors are respectively applied to different load effects and resistance components to produce designs intended to achieve some established target probability of failure. A national code developed by the American Association of State Highway and Transportation Officials (AASHTO) serves as a baseline for such design, but individual state transportation agencies are allowed to develop their own "state specific" LRFD methods to reflect differences in design practices.

This paper describes characteristics of one such state-specific code developed by the authors for the Missouri Department of Transportation (MoDOT). Unique features implemented in the new MoDOT design guidelines include:

- Resistance factors are explicitly selected based on variability and uncertainty in input parameters, and
- A practical technique to quantify uncertainty in design parameters from lab and field measurements is provided.

Practice using the new MoDOT design guidelines is compared to traditional design practice and current AASHTO practice. Methods used for calibration of resistance factors are then described followed by description of the procedure recommended for quantifying variability and uncertainty from laboratory or field measurements. Finally, an example is provided to illustrate how the methods can be used to quantify the value of potential site characterization activities.

2 SOURCES OF VARIABILITY AND UNCERTAINTY

Variability and uncertainty arise from a multitude of sources in geotechnical design. However, these sources can be generalized into three broad categories:

- Variability and uncertainty in design input parameters,
- Variability and uncertainty in design methods, and
- Variability and uncertainty attributed to construction.

These sources are at times inter-related, especially for empirically based design methods. Nevertheless, it is useful to consider them as being separate because of the degree of influence that designers have over the different sources.

Designers generally have the greatest, and most direct, influence over variability and uncertainty in design parameters, principally through affecting the scope of site characterization activities. Designers can also affect variability and uncertainty in design methods by selecting from among several alternative methods, but this influence often has a lesser effect on resulting designs. Designers can also influence variability and uncertainty in construction, by developing "constructable" designs, as well as by requiring and/or engaging in effective QC/QA. However, the influence is again generally smaller than what can be achieved through effective site characterization.

3 COMPARISON OF TRADITIONAL & LRFD PRACTICE

While traditional "allowable stress design" (ASD) and LRFD practices seek to account for variability and uncertainty introduced by all three sources, they do so differently. Differences among traditional geotechnical practice, current AASHTO specifications, and the new MoDOT guidelines arise primarily from differences in how these sources are addressed.

3.1 *Traditional ASD Practice*

Traditional practice for geotechnical site characterization, in terms of the specific types of measurements made and the quantity of such measurements, is largely dictated by the judgment of the designer. In establishing the scope of site characterization activities, designers generally consider (often local) standards of practice for structures of similar complexity and importance as well as general characteristics about the site. The actual site characterization activities undertaken are also subject to the designer's ability to "sell" the importance of the activities to those that are paying for the characterization. This task is often challenging because it can be difficult to quantify the potential value of site characterization activities in ways that are meaningful to those outside the profession.

Importantly, traditional geotechnical practice also provides some flexibility in selection of appropriate values for the factor of safety to be used in design. In selecting a specific value for a specific project, designers generally consider the importance and complexity of the structure, the complexity of the site, and the appropriateness of site characterization that has been performed. Thus, there is an implicit link between the quality and rigor of the site characterization and the safety margins that are employed in design. This link is clearly subjective, which introduces the potential for inconsistent application and inconsistent reliabilities for resulting designs. The subjectivity may also expose designers to substantial risk, since it can be difficult to justify specific design postures when performance does not meet expectations (e.g. if a problem occurs, one can often easily argue that site characterization was insufficient or that sufficient margins of safety were not used).

3.2 *AASHTO LRFD Practice*

Design according to the AASHTO LRFD specifications largely follows traditional practice, but with two important distinctions. First, the AASHTO LRFD code explicitly establishes minimum standards for the quantity and type of site characterization that must be performed in order for the standards to be used. These minimum requirements enhance the designer's ability to "sell" site characterization and provide some minimum level of confidence in the design parameters. However, the requirements also pose challenges for some regions of practice where traditional site characterization practices do not work well. Secondly, the AASHTO code stipulates fixed values for the margin of safety, via resistance factors. Table 1 shows a listing of resistance factors for side resistance of drilled shafts from the AASHTO LRFD specification (AASHTO, 2010). These "method specific" resistance factors are "lumped" factors in that they account for all three sources of variability and uncertainty collectively.

Fixing the magnitude of resistance factors results in more consistent designs and likely produces the intended effect of achieving more consistent reliability compared to ASD practice. However, fixing the magnitude of resistance factors also eliminates the flexibility provided in ASD to select appropriate safety margins and limits the capability to improve design efficiency through improved site characterization. Conducting more tests, or higher quality tests, to improve confidence in design parameters does not allow one to use more advantageous resistance factors. Improving the scope or quality of site characterization may have a second order effect of changing predictions of nominal capacity, but it does not allow designers to exploit the improved confidence in design parameters.

Table 1. Resistance factors from AASHTO LRFD Specifications for side resistance of drilled shafts (AASHTO, 2010).

Soil/Rock Type	Design Method	Resistance Factor, φ
Clay	O'Neill & Reese (1999)	0.45
Sand	O'Neill & Reese (1999)	0.55
IGM	O'Neill & Reese (1999)	0.60
Rock	Horvath and Kenney (1979)	0.55
	O'Neill & Reese (1999)	0.55
	Carter & Kulhawy (1988)	0.50

The AASHTO code may reduce the risk to geotechnical designers in the sense that they may have stronger defense against litigation as long as the minimum requirements are satisfied. However, the code also requires designers to employ judgment to expand the site characterization where conditions warrant so the practical truth for this is at least debatable.

3.3 *MoDOT LRFD Practice*

The MoDOT design guidelines seek to address limitations in traditional ASD and AASHTO LRFD practices by linking the resistance factors used with the quality of site characterization performed, and simultaneously improving consistency by restricting this link so that the target reliability is more consistently achieved. The "link" in this case is formed by implementing resistance factors that depend on the variability and uncertainty in design input parameters, which in turn depends on the quality of the site characterization conducted. In implementing this link, the guidelines also provide designers with practical means to estimate the potential value of site investigation activities on a project specific basis so that more effective site characterization decisions can be made.

4 GUIDING PRINCIPLES

The principal objective for development of the MoDOT design guidelines was to provide procedures that would save agency funds by more precisely and consistently achieving target probabilities of failure in design (i.e. applying appropriate conservatism for the variability and uncertainty present for each specific project). The primary means for improving the precision of the procedures is by considering the variability and uncertainty in design input parameters separately from the variability and uncertainty in design and construction methods.

The predominant cost savings are expected to be savings in construction costs rather than savings in site characterization costs. However, it was recognized that conducting advanced or extensive site characterization to reduce variability and uncertainty in design parameters is not always justified and will not always produce net cost savings. The overall intent was therefore to provide the agency with practical procedures to identify conditions where more extensive investigations are likely to produce cost savings, considering the costs for site investigation, costs for construction, as well as potential future costs for maintenance and repair.

Conscious effort was also made to avoid overly prescriptive provisions. Rather, the intent was to provide methods that inform the judgment of the designer about the value of alternative site characterization activities. In this way, the opportunity to apply sound judgment remains, but it can be made more knowledgeably and consistently.

In the context of the guidelines, the probabilities of failure considered were epistemic, or "degree of belief" probabilities, which reflect level of knowledge, rather than aleatory probabilities that are related to actual performance. Thus, the probabilities of failure considered are related to the level of knowledge and confidence in the design input parameters and design methods rather than an actual statement about performance rates, although the two are clearly related.

5 CALIBRATION OF RESISTANCE FACTORS

Calibration of resistance factors to separate consideration of variability and uncertainty in design and construction methods from variability and uncertainty in design parameters requires only minor changes to common procedures. The most significant change is to use a performance function, g, of the form:

$$g = R(x) \cdot M(\bar{x}) - LL - DL \geq 0 \tag{1}$$

where $R(x)$ is a deterministic design relation for geotechnical resistance, x represents the probabilistic design input parameter(s), $\bar{x}$ is the mean value of the design input parameter(s), LL is the probabilistic live load effect, DL is the probabilistic dead load effect, and $M(\bar{x})$ is a probabilistic "model uncertainty" parameter used to represent the bias, variability and uncertainty attributed to design and construction. $M(\bar{x})$ reflects the conditional variability of the design method established from load tests, from numerical analyses, or based on judgment, while x reflects the variability and uncertainty in the design input parameter(s). For design methods without substantial bias, $M(\bar{x})$ is taken to have a mean value of 1.0 and a distribution that reflects the variability of the design method.

Given the performance function for a specific design method, calibrations are then performed for a range of assumed coefficients of variation (COV) for the design input parameter(s). Figures 1 and 2 show results of calibrations conducted for two illustrative design methods: design for tip resistance of drilled shafts in clay and design for side resistance of drilled shafts in rock, respectively. In each figure, curves are shown for four categories of structures. Each of these curves represents resistance factors to achieve a target probability of failure established by agency policy. The curves reflect the magnitude of resistance factor needed to achieve the target probability of failure based on the variability and uncertainty present in relevant input parameters, as represented by the COV.

Simple observation of the curves shown in Figs. 1 and 2 provides valuable qualitative information regarding the importance of site characterization for the respective design methods. Comparison of resistance factors for $COV = 0$ (corresponding to perfect information about the input parameters) reveals that the variability and uncertainty attributed to the method for side resistance in rock (Fig. 2) is substantially greater than that for tip resistance in clay (Fig. 1). Furthermore, the steepness of the curves in Fig. 1 indicate that the resistance factor needed to achieve a given target probability of failure is highly sensitive to the variability and uncertainty of the undrained shear strength, thus indicating that the quantity and quality of site characterization will have a substantial impact on the resulting design. Conversely, the curves shown in Fig. 2 are much flatter, indicating that reduction of the COV for uniaxial compressive strength via expanded testing will have a lesser effect on the resulting design. These simple qualitative comparisons can also be quantified if specific values of COV for the design input parameters are estimated as will be illustrated through a subsequent example.

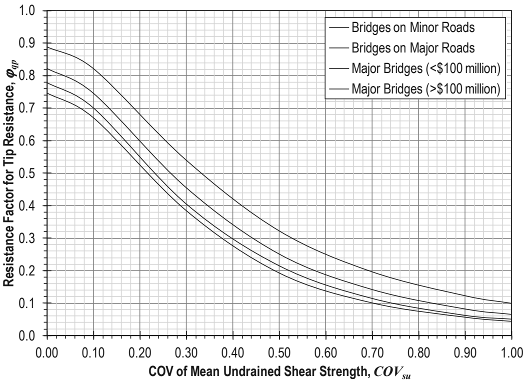

Figure 1. Resistance factors for tip resistance in clay.

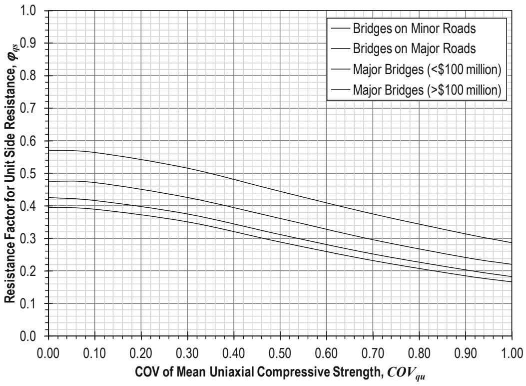

Figure 2. Resistance factors for side resistance in rock.

6 ESTIMATION OF PARAMETER UNCERTAINTY

Use of resistance factors established as described in the previous section is straightforward once COV-values for the input parameters are known. The primary complication introduced compared to current AASHTO specifications is that the MoDOT guidelines require estimation of parameter COVs. Fortunately, COV values can be established using practical means that introduce little complexity to the design process.

The general approach to establishing COV values closely follows conventional procedures for interpretation of design parameters. The process is based on establishing a "design profile" that reflects conditions present at a particular site. These design profiles establish a "model" describing how the magnitude of a design parameter varies with depth or elevation, as well as the variability and uncertainty of the model.

For the MoDOT guidelines, design profiles are assumed to be composed of a number of individual strata. The design parameter within an individual stratum is assumed to have values that are either constant, or linearly varying with depth or elevation as illustrated in Figure 3. As a practical matter, any design profile can be reasonably represented as some combination of strata that have either a constant or linearly varying property within each stratum. Regardless of whether the parameter value is assumed to be constant or linearly varying, the variability or uncertainty in the parameter within a single stratum is assumed to be constant, and represented by a constant value of the coefficient of variation (COV).

Once individual strata are established, design values for parameters in a stratum judged to have constant values are taken to be the arithmetic mean of the available measurements:

$$y = \bar{y} = \frac{\sum_{i=1}^{n} \hat{y}_i}{n} \tag{2}$$

where y is the design, or "model" value of the parameter, $\bar{y}$ is the mean value of the parameter measurements, $\hat{y}_i$ is a measured value of the parameter, and n is the number of measurements. The coefficient of variation of the mean value for the design parameter in a stratum with constant properties is established from available measurements as:

$$COV_y = \frac{\zeta\sigma_y}{y} = \frac{\zeta\frac{\sigma_{\hat{y}}}{\sqrt{n}}}{y} \tag{3}$$

where COV_y is the coefficient of variation of y, σ_y is the standard deviation of y, ζ is an empirical modifier to account for the fact that COV_y may be underestimated for small numbers of tests, and $\sigma_{\hat{y}}$ is the standard deviation of the measurements.

Slightly different equations are used for strata where design parameters are deemed to vary linearly with depth (MoDOT, 2010). Fig. 3 illustrates results of such calculations.

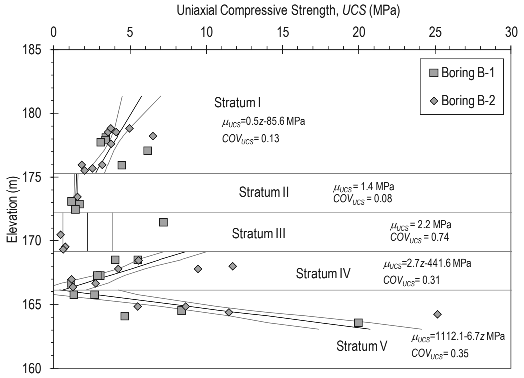

Figure 3. Example "site model" developed for design of drilled shafts.

7 EXAMPLE APPLICATION

To illustrate how the methods described can be used to quantify the potential value of site characterization activities, a conceptual design of drilled shafts for a highway bridge was conducted using measured values of uniaxial compressive strength for a shale site. Two designs were completed: the first using a small randomly selected subset of the available test measurements (Fig. 4) to reflect design based on a limited site investigation and testing program; the second was completed using a larger subset of the available measurements (Fig. 5) to reflect design based on a more typical site investigation for a bridge design. As shown in the figures, the more extensive investigation produces a slightly greater mean value for the uniaxial compressive strength in Maquoketa Formation C, but reduces the COV of the mean value by a factor of two. This, in turn, allows greater resistance factors to be used for design. Considering the same 13 MN axial load for both designs, the design completed based on the limited site investigation (Fig. 4) leads to use of 7.5 m long, 1200 mm diameter drilled shafts while the design completed based on the more typical site investigation (Fig. 5) leads to use of 5 m long, 1200 mm diameter drilled shafts. The estimated cost differences between these two designs is approximately \$5,000 per shaft. Thus, the value of the additional testing is approximately \$5,000 per shaft.

In practice, such direct comparisons are not possible *a priori*. However, designers can estimate how increasing the number of measurements will affect the COV of design parameters to develop estimates of potential costs savings as in the example. The estimated cost savings can, in turn, inform judgement regarding the scope of testing that may optimize final designs. If costs for additional characterization are not commensurate with estimated cost savings, then the additional characterization should not be undertaken as it is unlikely to "pay off". While such estimation is unfamiliar, it is likely that one's judgment regarding expected reductions in the COV with additional testing will improve with experience so that practices regarding effective scoping of site investigations will improve over time.

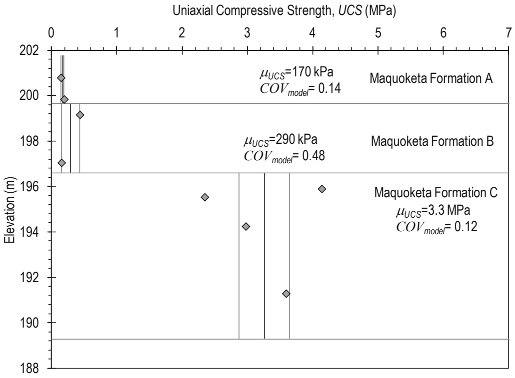

Figure 4. Uniaxial compressive strength measurements from site characterization with limited scope.

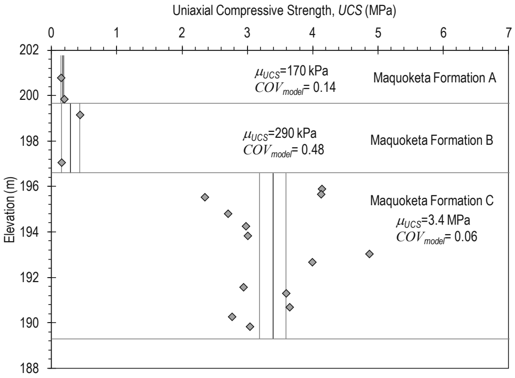

Figure 5. Uniaxial compressive strength measurements from more extensive site characterization.

8 CONCLUSION

Variability and uncertainty attributed to design parameters and due to design and construction methods can be practically separated within an LRFD framework by using resistance factors established as a function of the COV of the design parameter(s). Use of such resistance factors can improve the efficiency of geotechnical designs by more precisely and consistently achieving target probabilities of failure. This implementation also provides means to practically quantify the potential value of additional site characterization during design, which can improve design decisions and help convince owners/clients of the value of additional characterization.

9 ACKNOWLEDGEMENTS

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10 REFERENCES

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