Model Uncertainties in Foundation Design

Naresh C. Samtani*

Introduction

In April 2021, the book titled “Model Uncertainties in Foundation Design” was published by CRC Press which is an imprint of Taylor & Francis Group, LLC. The authors of this book are Chong Tang and Kok-Kwang Phoon. The book is available in electronic and hard-copy format from the publisher as well as other distributors such as Amazon and Barnes & Noble.

The book includes 8 chapters as follows:

Chapter 1. Geotechnical Engineering in the Era of Industry 4.0
Chapter 2. Evaluation and Incorporation of Uncertainties in Geotechnical Engineering
Chapter 3. Basics in Foundation Engineering
Chapter 4. Evaluation of Design Methods for Shallow Foundations
Chapter 5. Evaluation of Design Methods for Offshore Spudcans in Layered Soil
Chapter 6. Evaluation of Design Methods for Driven Piles and Drilled Shafts
Chapter 7. Evaluation of Design Methods for Helical Piles
Chapter 8. Summary and Conclusions

The book is well-organized and supported by an exhaustive list of references. Depending on the foundation type of interest, it is tempting for a reader to proceed directly to the applicable chapter. However, the reviewer found that it is important to read the first three chapters rather than going directly to a chapter for a particular foundation type. The first three chapters contain discussions that lay the groundwork with respect to definitions and terminology. Of particular relevance is the discussion related to model uncertainty in Section 2.4.1 of Chapter 2 where the model factor is defined and explained. The model factor (also referenced as bias factor) is a key concept that is carried through in Chapters 4 to 8.

Contribution to the Field of Foundation Design

The book focuses on providing a foundation designer information on the model factor and its statistics for conventional foundation types such as shallow foundations, driven piles, and drilled shafts as well as special foundations such as spudcans and helical piles. Besides foundations, the book also provides information for other geostructures such as mechanically stabilized earth (MSE) walls, soil nail walls, pipes and anchors, slopes, and braced excavations.

Many analytical models for foundation design are available in the geotechnical literature. Every model has some level of uncertainty in the values predicted by it. This is because a model is based on idealizations of physical processes and assumptions for loads and resistances. The level of uncertainty in predicted values from a model and whether it can be accepted with confidence is of considerable interest to a foundation designer. The difference between model predictions and measured values can be used to assess the level of uncertainty associated with the model. The difference can be expressed using measures such as the ratio of measured to predicted values (referenced as “model factor” in the book), statistical parameters (mean (μ), standard deviation (σ), and coefficient of variation (COV)), probability distribution functions (PDFs), and/or some combination of these measures.

Regardless of the measure used to express model uncertainty, the key element is availability of databases of measured values for comparison against predicted values. These databases must be of high-quality in that they: (a) are correctly sourced (i.e., verifiable), (b) contain data appropriate to the intended use (e.g., calibrations based on Load and Resistance Factor Design (LRFD) methodology), (c) are maintained with support (in this case by the authors), (d) allow query, i.e., searching and parsing, of data (as is possible with the availability of the databases in electronic format upon request to the authors), and (e) can be expanded in the future (which appears to be the intent of the authors). The primary contribution of the book to the field of foundation design is collection and presentation of many models and high-quality databases that can permit a systematic evaluation of model uncertainties for a variety of foundation types.

The availability of data provided in the book rises to the level of essential information for those who are involved in evaluation of the level of uncertainty in foundation design.

Modern Foundation Design Guidelines

Most modern foundation design guidelines are based on the philosophy of limit states. A limit state is a condition beyond which the structure no longer satisfies its stated design criteria. An example of modern foundation design guidelines based on consideration of limit states is the Section 10 (Foundations) and Section 11 (Walls, Abutments, and Piers) of Bridge Design Specifications (BDS) of the American Association of State Highway and Transportation Officials (AASHTO)
based on the LRFD methodology; these specifications are herein noted as AASHTO LRFD. Similar foundation design guidelines based on concept of limit states can be found in the Eurocode and design guidelines in many countries (e.g., Canada, Australia, Japan, etc.). Although the nomenclature may be different across these guidelines, foundation design processes are performed based on the following considerations:

- Failure or collapse condition due to exceedance of strength (i.e., ultimate resistance) of a material. Examples include bearing failure, sliding, etc. This condition is evaluated at the Ultimate limit state (ULS). In AASHTO LRFD, the ULS is also referenced as the Strength limit state.
- Serviceability concerns which include events that occur before attainment of failure condition and affect functionality of a structure. Examples include misalignment of components, rideability issues, cracks in a structure, etc. This condition is evaluated at the Service limit state (SLS).

The foundation design based on ULS and SLS is further examined for events such as earthquakes and collision, which are categorized as Extreme Events in AASHTO LRFD or as Accidental or Rare events in other design guidelines. The book focuses primarily on the LRFD approach to account for model uncertainties. In addition to AASHTO LRFD, the book includes discussions with respect to guidelines such as ISO (International Organization for Standardization), Eurocode, and CSA (Canadian Standards Association).

With respect to AASHTO LRFD the book primarily references the 8th Edition that was released in 2017 with some references to older editions (e.g., the 4th Edition from 2007). The latest (9th) Edition of AASHTO LRFD was released in 2020 about a year before the publication of the book. The 9th Edition contains significant updates particularly with respect to SLSs and foundation design that have not been reflected in the book and, therefore, the reader is not made aware of the latest information in the foundation design practice based on AASHTO LRFD and its inherent reliability-based calibration processes.

The Model Factor Approach

Model uncertainty may be evaluated at the parameter level or overall level. In the first approach, uncertainty is incorporated into design through factors applied to parameters in the model. In the second approach, a single factor is usually applied to the final result from the model. In either case, these factors are an attempt to “calibrate” the model results such that they best match the measured data within the constraints of target reliability index (or probability of occurrence of adverse events, e.g., sliding, bearing failure etc.). Using the concept of model factor, the book concentrates on the second approach which is used by AASHTO LRFD.

The model factor, M, is defined as the ratio of the measured value (X_measured) to the calculated value (X_calculated). The quantity X could be a representation of a load, resistance, movement, etc. as long as the same quantity and units are consistently used in the numerator and denominator. The book explores the treatment of the model factor as a random variable and uses its statistics (mean and COV) to evaluate uncertainty in a model. Approaches to remove the statistical dependency of the model factor are discussed and explored. Consideration of statistical dependency and data correlation is important in addressing data that: (a) are counter-balancing (e.g., effects of regional geology which can result in data from different regions to show opposite trends), (b) are confounding (i.e., data that include correlated variables and where one variable can affect both independent and dependent variables), and/or (c) exhibit cause-and-effect relationship (i.e., where change in one variable can cause a change in another variable). The discussions on statistical dependency in the book can help the reader better appreciate the nuances of data evaluation processes, interpretation of results, and comparison of results from different sources.

The authors propose plotting the mean and the COV of the model factor in the first quadrant of a cartesian graph with the mean on the x-axis and the COV on the y-axis. Using certain demarcations for the mean and COV values of the model factor, the graph is then used to categorize a model in terms of:
- (a) conservativeness based on the mean value as “Unconservative,” “Moderately Conservative,” or “Highly Conservative,” and (b) dispersion based on the COV value as “Low,” “Medium,” or “High.” This approach permits assignment of a model in 9 categories, e.g., unconservative with low dispersion, highly conservative with medium dispersion, and so on. Thus, a system for categorizing model uncertainty has been proposed and evaluations in Chapters 4 through 8 are presented in a consistent manner using this system. The end-user should critically study: (a) the limiting values of the mean and COV of the model factor used to demarcate the 9 categories, and (b) the source data used to generate the model factor values in such graphs to ensure that the original information is commensurate with the foundation design model, foundation sizes, and the design guidelines (e.g., AASHTO LRFD, CSA, etc.) being considered by the end-user. The book includes the necessary data and source references to permit this type of study.

LRFD Calibration Processes

The book provides detailed information on the processes to calibrate resistance factors for ULSs and SLSs. The processes for ULSs are in general conformance with those used for AASHTO LRFD with some minor differences that do not substantially change the final values of the computed resistance factors. A comparison of the resistance factors computed by the authors with those in AASHTO LRFD and CSA is presented in the book.

The SLS calibration processes presented in the book are fundamentally different than those used by AASHTO LRFD. The SLS calibrations relate to the evaluation of models used to predict foundation movements such as vertical (i.e., settlement) and lateral directions. The processes used in the book are built on the concept of developing a resistance factor for a given prediction model with target reliability indices similar to those that were used for ULS evaluations for foundation design, i.e., 2.33 to 3.00. In the United States in 2007-2008, the second Strategic Highway Research Program (SHRP2) of the Transportation Research Board (TRB) initiated Project R19B
whose primary task was to calibrate structural and geotechnical SLSs as part of continued development of AASHTO LRFD. After consideration of several approaches, including those based on the resistance factor approach, a new approach was developed for calibration of foundation movements for AASHTO LRFD based on the philosophy that the structural consequences of foundation movements must be considered while calibrating for the uncertainty in a foundation movement model. The structural consequences occur because foundation movements induce additional force effects such as moments and shears in a structure which can lead to undesirable events, e.g., cracking. The structural consequences of foundation movements are widely known and accepted. In fact, since its 1st edition in 1994, the AASHTO LRFD developers recognized this key point and introduced the “SE” load factor to account for the induced additional force effects due to foundation movements. A key task of Project R19B was to evaluate structural limit states from a serviceability viewpoint. A review of several international guidelines reported by Project R19B indicates target reliability index values for SLSs smaller than 1.50, including value of 0.00, are used with the values often expressed in terms of severity of structural consequences. After considerable deliberations by SHRP2 review panel, AASHTO committees, and representatives of the Federal Highway Administration (FHWA), it was decided that the target reliability indices for serviceability aspects of a structure due to foundation movements for AASHTO LRFD are in the range of 0.50 to 1.00 depending on whether the structural consequences of the foundation movements are reversible or irreversible, respectively. The use of smaller target reliability indices is consistent with the philosophy that the structural consequences of exceeding SLSs are more manageable compared to the life-safety (collapse) related consequences related to ULS.

Thus, the SLS calibration approach in the book differs fundamentally from the approach used in AASHTO LRFD. The SE load factors resulting from the new calibration processes for foundation movements were incorporated in the 9th Edition of AASHTO LRFD released in 2020. The supporting documentation for the calibration processes are referenced in the 9th Edition of AASHTO LRFD. The 8th Edition of AASHTO LRFD from 2017 to which the discussions in the book refer does not include the latest information regarding consideration of foundation movement SLSs in AASHTO LRFD.

The AASHTO LRFD approach for SLS calibration has its basis in consideration of the load-movement behavior as the key component of its calibration process and it is recognized that the ULS and SLS are simply certain points along the load-movement curve. Indeed, the book also mentions the importance of consideration of the entire load-movement curve in the evaluation of SLSs. Thus, even though the SLS calibration processes noted in the book are not those used by AASHTO LRFD, the book offers a significant contribution by reporting database of parameters that can be used to develop hyperbolic load-movement models. Combination of the information provided in the book along with the latest AASHTO LRFD calibration processes for foundation movements can spawn numerous opportunities for additional research and information that can help AASHTO LRFD further develop (refine) its SE load factors as well as for other international guidelines to consider different approaches for consideration of uncertainties in foundation design. This observation underscores the tremendous value of the information in the book.

Summary

The book is an excellent contribution in the field of foundation design. If for no other reason, this book should be read to appreciate the level of uncertainty in foundation design processes. Nowhere else has such a vast compilation of foundation design models and databases been systematically organized and presented. The exhaustive list of references in the book is noteworthy. The information in this book along with the information included in the 9th (2020) Edition of AASHTO LRFD will serve as a valuable resource for those involved in research and development of guidelines for foundation design. Practitioners will be able to better understand performance-based foundation design with the knowledge gained from the book. The book can serve as a good resource for graduate (advanced) level foundation design classes.