1085

GEOTECHNICAL CONSIDERATIONS IN PERFORMANCE BASED EARTHQUAKE-RESISTANT DESIGN

Marshall LEW[1] And Carl C KIM[2]

SUMMARY

Continuing advances in analytical methods and tools are making performance based earthquake resistant design (PBERD) a feasible and often-considered design alternative. The design community has long acknowledged the potential of PBERD to efficiently manage seismic risk. The methodology calls for specifying acceptable levels of damage for given levels of seismic hazard and designing the structure to meet those specific performance objectives.

Performance based design attempts to take full advantage of currently available computer modeling tools to customize and optimize the design based on rigorous simulations. Because PBERD is gaining widespread acceptance in the structural engineering profession and other members of the design community, the geotechnical engineering profession must advance alongside and provide the required contribution to help fulfill the awesome potential of PBERD, which is only possible with an integrated, sophisticated soil/rock-structure model.

Traditional geotechnical engineering has focused on determining ultimate and allowable capacities based on often-arbitrary assumptions of acceptable deformations. The typical non-homogeneity and variation of soil/rock at given sites has traditionally been addressed with conservatism – by using lower bound or near lower bound strength values, which conservatively assumes that the subsurface is as weak as the weakest material encountered/tested or that the weaker materials dominate capacity. For PBERD, however, the emphasis will be on characterizing the deformation characteristics of soil/rock materials supporting foundations. Instead of providing conservative values that may distort the behavior of the model during simulations, the most accurate characterization possible will required for PBERD along with statistical parameters that envelope the uncertainty and variation involved.

In addition to contributing model parameters for the integrated soil/rock-structure system, PBERD requires the evaluation of ground motions corresponding to specific seismic hazards. The likely ground motion corresponding to specific events for the particular site in question must be evaluated and formatted for input into model simulations. This aspect of geotechnical design for PBERD is well-established and currently common for critical structures and structures with base isolators and energy dissipation devices, such as dampers.

Because PBERD will necessarily include simulations to model soil-structure interaction and its influence on structural performance, geotechnical engineers will need to contribute different and additional information for design. Some of the required changes from practitioners will likely include providing site-specific material parameters for constitutive modeling, quantification of variation and uncertainty of geotechnical parameters throughout model volume, routine packaging of design spectra and compatible ground motions, and enhanced interaction between structural and geotechnical engineers.

Because PBERD is gaining widespread acceptance in the structural engineering profession and other members of the design community, the geotechnical engineering profession must advance alongside and provide the required contribution to help fulfill the awesome potential of PBERD, which is only possible with an integrated, sophisticated soil/rock-structure model.

[1] *Law/Crandall, A Division of Law Engineering and Environmental Services, Inc.; Los Angeles, California, USA*
[2] *Law/Crandall, A Division of Law Engineering and Environmental Services, Inc.; Los Angeles, California, USA*

INTRODUCTION

With the continuing advances in analytical methods and tools, performance based earthquake resistant design (PBERD) is quickly becoming a feasible and often-considered design alternative. The design community has long acknowledged the potential of PBERD to efficiently manage seismic risk. After all, the methodology calls for specifying acceptable levels of damage for given levels of seismic hazard and designing the structure to meet those specific performance objectives. The owner explicitly weighs economic considerations and exercises the option to perform more or less maintenance and repair after given seismic events versus the initial financial investment for new construction or retrofit.

Performance based design attempts to take full advantage of currently available computer modeling tools to customize and optimize the design based on rigorous simulations. Ideally, these finite element or finite difference models would be sophisticated enough to test the subject structure under numerous loading conditions to correct weaknesses and to remove excess conservatism in non-critical areas, thus optimizing the design. Unfortunately, the concept of performance based design in geotechnical engineering lags behind the other design professions, specifically, the structural engineering profession.

Granted, material properties that structural engineers deal with, such as steel, concrete, and wood, are easier to test and simpler to model, and with proper quality control during construction, those materials can generally be expected to perform as modeled. The slow advancement of the performance based design concept in geotechnical engineering may be partly due to the difficulty in sampling, testing, and modeling of soil and rock, which demand a greater investment in time, effort, and cost. Another contributing factor is the typical non-homogeneity of soil and rock and the relatively large uncertainties involved in characterizing their engineering properties, which traditional geotechnical design accounted for with appropriately conservative factors of safety. Although performance based design could be accomplished with lower bound geotechnical parameters, because of the complex effects of soil-foundation interaction, iterative design optimization by accurate identification and modification of critical and non-critical areas, perhaps the greatest advantage of PBERD, would be largely negated.

Because PBERD is gaining widespread acceptance in the structural engineering profession and other members of the design community, the geotechnical engineering profession must advance alongside and provide the required contribution to help fulfill the awesome potential of PBERD, which is only possible with an integrated, sophisticated soil/rock-structure model. Although PBERD can be as relevant to embankments and slopes as well as for buildings, the discussion herein will focus on buildings.

GEOTECHNICAL DESIGN ISSUES

Traditional geotechnical engineering has focused on determining ultimate and allowable capacities based on often-arbitrary assumptions of acceptable deformations. The typical non-homogeneity and variation of soil/rock at given sites has traditionally been addressed with conservatism – by using lower bound or near lower bound strength values, which conservatively assumes that the subsurface is as weak as the weakest material encountered/tested or that the weaker materials dominate capacity. Sacrificing accuracy for safety in light of the relatively large uncertainties involved with limited exploration, sampling, and testing appeared to be appropriate for the conventional working stress design and ultimate design concepts.

For PBERD, however, the emphasis will be on characterizing the deformation characteristics of soil/rock materials supporting foundations. Instead of selecting an allowable or ultimate capacity value corresponding to given deformations deemed acceptable, the entire range of the intrinsic relationship between deformation and force (capacity) for model materials will be specified, often from the elastic through the plastic ranges. These values will likely be provided in constitutive models or geotechnical parameters that can be input into canned constitutive models. Furthermore, instead of providing conservative values that may distort the behavior of the model during simulations, the most accurate characterization possible is required along with statistical parameters that envelope the uncertainty and variation involved. Sensitivity analyses can then be performed to address the uncertainties by modifying the model.

In addition to contributing model parameters for the integrated soil/rock-structure system, geotechnical engineers must provide the seismic demand used to test the model. Performance based earthquake resistant design requires the evaluation of ground motions corresponding to specific seismic hazards. For instance, if the target performance of a structure is only cosmetic damage after an earthquake corresponding to an event with a 475 year return period (10 percent probability of exceedance in 50 years), the likely ground motion corresponding to this event for the particular site in question must be evaluated and formatted for input into model simulations. This aspect of geotechnical design for PBERD is well-established and currently common for critical structures and structures with base isolators and energy dissipation devices, such as dampers.

The procedure typically involves evaluating the anticipated seismic response spectra for given seismic hazard levels using a probabilistic seismic hazard analysis and matching appropriate ground motion records from actual earthquake events to the design response spectra. However, even in this regard, ground motion evaluations can be further refined with consensus attenuation relationships and standardized methodologies of characterizing site conditions and near source effects.

REQUIRED CHANGES IN GEOTECHNICAL ENGINEERING PRACTICE

Because PBERD will necessarily include simulations to model soil-structure interaction and its influence on structural performance, geotechnical engineers will need to contribute different and additional information for design. A better understanding of seismic loading on geotechnical materials, such as cyclic loading, will likely only be developed and disseminated through research at academic institutions. In the meanwhile, some of the required changes from practitioners will likely include the items discussed below.

Providing site-specific material parameters for constitutive modeling

Geotechnical engineers will need to provide not only recommendations for feasible foundation alternatives and parameters for their design, but also estimates of deformations from both static and seismic loading. To facilitate the development of an integrated soil/rock-structure system model, parameters for constitutive modeling will be required, including elastic and post-elastic deformation and strength parameters in addition to the traditional mass/density, ultimate strength, and classification parameters. Deformation characteristics will likely include the elastic modulus, Poisson’s ratio, shear modulus, and bulk modulus. Post-elastic strength characteristics will likely be important in the accurate modeling and performance simulation under seismic demand. These parameters include shear-induced dilatancy or compression and strain hardening or softening.

Automated laboratory testing equipment will likely be required to develop many of these parameters. Manual monitoring of a triaxial test, for example, may be cost-prohibitive. Fortunately, many geotechnical laboratories already have automated instrumentation and the behavior of test samples prior to failure can already be routinely documented. The theory already exists to extract most of the required deformation and strength parameters from triaxial tests on quality samples. By incorporating the appropriate extrapolation to field-scale properties, relatively accurate constitutive models can be developed based on the results of careful triaxial testing on quality samples.

Quantification of variation and uncertainty of geotechnical parameters throughout model volume

To allow an explicit accounting of the variation uncertainties involved with modeling geotechnical materials, values quantifying the anticipated variation and the envelope of possible geotechnical parameters must be evaluated. Most finite element and finite difference modeling programs will allow the designation of materials properties varying linearly with spatial position. Some enhanced models allow more exotic mathematical relationships to vary material properties with position. At the very least, the geotechnical engineer should provide an appropriately detailed characterization of the subject subsurface volume that would allow the manual modeling of different material properties at different positions.

Because of the relatively large uncertainties involved with developing engineering properties for geotechnical materials, it will be important to provide statistical data quantifying these uncertainties. Envelopes of strength and deformation characteristics or mean and standard deviation values for pertinent properties will enable rigorous sensitivity analyses to identify critical parameters that may require further evaluation or areas within the structure that may require additional redundancy or conservatism in the design.

Routine packaging of design spectra and compatible ground motions

A consensus should be reached on the appropriate methodology to perform probabilistic seismic hazard analyses, including the preferred attenuation relationships for given subsurface conditions, preferred fault models, when to apply near-source effects, and site characterization. For PBERD, a set of ground motion records matched to the design response spectra should be provided to model the seismic demand in time domain simulations.

Enhanced interaction between structural and geotechnical engineers

Perhaps the most important change in the process of providing geotechnical consultation for design will be in the required greater interaction and communication between the structural and geotechnical engineers in the design team. Because developing an integrated model of the soil/rock-structure system for PBERD will often necessitate joint analyses and specialized geotechnical input, communication, cooperation, and collaboration between the two professions would be essential. Traditionally, the structural engineer prepares a wish list of geotechnical recommendations, the geotechnical engineer completes the geotechnical investigation and prepares a report addressing the items on the wish list, and the two parties may not communicate until the geotechnical report is submitted unless there is a change in the design. However, due to the significant impact of foundation effects on structural performance, the modeling of the soil/rock-foundation interface may have to be developed jointly. In addition, results of simulations and sensitivity analyses may also require supplemental and different geotechnical analyses. As a result, a significant portion of the geotechnical engineering may be performed simultaneously with the structural design, necessitating a flexible, synergistic relationship throughout the design process.

CONCLUSIONS

Because PBERD is gaining widespread acceptance in the structural engineering profession and other members of the design community, the geotechnical engineering profession must advance alongside and provide the required contribution to help fulfill the awesome potential of PBERD, which is only possible with an integrated, sophisticated soil/rock-structure model. Performance based earthquake resistant design will become more prevalent in new construction with time. It is now being used in some seismic retrofit projects on a routine basis. At this time, however, the geotechnical technology and understanding lags the structural engineering side. We as geotechnical engineers need to develop methodologies to allow for more meaningful and valid analyses and design provide the more sophisticated information required for PBERD.