Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1897

FUTURE DIRECTIONS IN GEOTECHNICAL EARTHQUAKE ENGINEERING

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ABSTRACT

Future directions in geotechnical earthquake engineering that are promising for advancing our profession and reducing earthquake risks are discussed under five topic groupings: predicting ground deformations, remediating ground deformations, predicting performance of soil-structure systems, resiliency and performance-based design, and sensing for risk reduction and resiliency. The potential for advances in many of these areas can draw on technological advances and opportunities afforded by large-scale experimental facilities. Progress will also be affected by the interactions between teaching, research, and practice.

Introduction

This paper presents some thoughts on future directions in geotechnical earthquake engineering that could be particularly effective for advancing our profession and reducing earthquake risks. Future directions for research, teaching, and practice in geotechnical engineering or geotechnical earthquake engineering have been discussed and articulated in several different venues and reports in recent years (e.g., EERI 2003, NRC 2006, EERI 2008, NEHRP 2008), with many of these views and writings sharing a number of common features and themes. Certainly, most people's thoughts have been directly or indirectly influenced by these writings and workshops and by discussions with numerous colleagues and friends. The ideas presented herein are similarly draw from numerous sources, including portions that build upon opinions previously expressed in Dobry and Boulanger (2010). Thus, the ideas presented herein are not the author's alone or an exhaustive coverage of the many opportunities that the future offers, but instead represent a few ideas that are particularly promising from the author's perspective.

The future directions discussed herein are grouped into five different topics for convenience, although there are clear connections and overlap across topics.

- Predicting ground deformations
- Remediating ground deformations
- Predicting performance of soil-structure systems
- Resiliency and performance-based design
- Sensing for risk reduction and resiliency

Additional factors that can have a strong effect on progress in any of these areas are discussed in a following section.

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Predicting Ground Deformations

The prediction of earthquake-induced ground deformation has been a focus of considerable research over the past forty plus years, and yet there remain a number of major holes in our fundamental knowledge of deformation mechanisms and limitations in our practical capabilities for predicting deformations for a range of difficult geologic conditions. These knowledge gaps and practice limitations apply to site-specific studies and become even more challenging when evaluating distributed systems or networks that can traverse a broad range of geologic conditions. In either case, advances in probabilistic methods for evaluating risk and performance have demonstrated the need for a formal understanding of bias and uncertainty in our predictions of ground deformations. Making progress requires that we understand the nature of the challenge we face, and then design the research program to address it.

Difficult Soils

One research priority should be developing better ways to characterize the properties and variability of the wide range of geologic materials that we currently have difficulty characterizing. These difficult-to-characterize soils include soils with large particles (e.g., cobbly and gravelly sands), soils with intermediate gradations and plasticity (e.g., clayey sands, low-plasticity sandy silts), soft highly organic soils, aged or cemented soils with low penetration resistances but high shear wave velocities, and residual soils that have low penetration resistances. These soils can be susceptible to deformation and strength loss if they are sufficiently loose to be contractive in shear, are saturated, and are subjected to sufficiently strong earthquake shaking. They are, however, extremely difficult and time consuming to work with in the laboratory, and their characteristics can be so distinct as to make empirical generalizations rather suspect. Past research on seismic behavior has been dominated by studies of liquefaction of clean sands or cyclic softening of sedimentary clays, with significantly less effort on the testing or in situ characterization of these other soils.

In order to make progress, we will need an integration of parallel efforts on in-situ testing, laboratory testing, and physical modeling in these various difficult soils.

- We need improved in-situ tests and improved methods for interpreting in-situ tests. This should include interpretive methods that synthesize information from multiple sources (e.g., in-situ V_s and CPT data, along with laboratory test data), and which relate to the soils' generalized constitutive behavior (as opposed to empirical approaches).
- We need improved methods for high-quality sampling and laboratory testing of these difficult soils, including means for evaluating the degree and effects of sampling disturbance. This may require block sampling and specialized adaptations of laboratory test devices.
- We need physical model test data on the seismic response of these difficult soils to a range of static and seismic loads. Ideally, we would also have field data from well-instrumented sites, and efforts toward acquiring such data are noted later in relation to sensing.

Large-scale shaking tests of these difficult soils could enable: (1) obtaining unique experimental data on the seismic behavior of such soils, (2) evaluating both existing and new in-situ test methods in the model before and after dynamic shaking, (3) obtaining high-quality samples from the model for laboratory testing and comparing the results to those obtained using specimens reconstituted the same way the model was constructed, and (4) evaluating engineering methods for predicting ground deformations based on the in-situ and laboratory test data. Supporting studies using smaller scale-centrifuge or shaking table tests, field studies, and laboratory studies would also be necessary, but the large-scale experiments would provide the essential means for tying it all together.

Ground Deformations in Heterogeneous Profiles

Progress on predicting ground deformations will require improved means for defining the subsurface stratigraphy and an improved understanding of deformation mechanisms in heterogeneous profiles. The influence of subsurface stratigraphy on liquefaction-induced deformations is an essential consideration in some cases, such as when liquefiable soils are limited to river channel deposits that are cut into otherwise nonliquefiable sediments; The fact that the channel deposits may not be continuous over distances large enough to affect a specific structure is something that is only crudely accounted for in current practice. These types of geometric constraints or 3D boundary effects are also often conservatively neglected for the lack of a proven means to account for them.

An equally important and fundamental concern is that the mechanisms of ground deformation can be strongly dependent on the stratigraphy details, such as where the pore water flow, which occurs in response to any earthquake-induced excess pore pressures, is trapped at interfaces between lower- and higher-permeability soils (i.e., resulting in void redistribution). This trapping of water can cause localized loosening or shear deformation that contribute to ground deformations, as has been observed in physical and numerical modeling studies.

We need to continue advancing our means for imaging the subsurface so that we can better define the subsurface stratigraphy. This includes the goal of being able to quantify the spatial distribution of weaker materials sufficiently well for inclusion in numerical models. Improved imaging would also be invaluable for quality control on ground improvement projects, as discussed in the next section.

We need more rigorous computational models that can capture the physical mechanisms of ground deformation, have been adequately validated and benchmarked, and are reasonably accessible for engineering application. These computational tools will need to include a range of proven constitutive models, account for transient pore water flow, and account for localization phenomena such as cracking of overlying crust layers. The validation of these computational tools will require: (1) detailed protocols be established for constitutive model calibration and all essential numerical procedures, (2) formal requirements for the systematic evaluation of the models, with allowance for uncertainty in the input parameters, against a broad set of physical model and case history data covering a range of soil, structure, and ground motion conditions, and (3) an assessment of the computational tool's potential biases and dispersion in predicting different measures of performance for the different types of cases evaluated. The eventual utility of such computational tools to advancing the engineering practice will require that they eventually be packaged, maintained, and serviced in a way that is reasonably tractable for application on larger engineering projects.

The large-scale experimental facilities and the archives of test data from these facilities offer an excellent means for making advances in the above areas. Large-scale testing offers the ability to construct models with stratigraphic details that are not possible in smaller models. Subsurface imaging methods can be evaluated on such large-scale models to see if they can pick up the known details. The mechanisms of deformation associated with void redistribution or particle intermixing can be better observed and investigated on larger-scale models. Smaller-scale shaking table or centrifuge tests could certainly add to such an effort, but the larger-scale tests would provide the means to confirm details with less concern over scaling effects and with greater instrument detail.

We will also need to better understand the impacts of ground deformations on the built infrastructure, so that we better quantify the risks and make better investments in remediation or mitigation. The uncertainties in predicting ground deformations leads to conservative designs, and particularly when dealing with deformations that are just enough to trigger the decision to perform ground improvement or other remediation works. A better understanding of structural performance may provide the means to accept more ground deformation, and hence limit the need for ground remediation in some cases. Large-scale experimental testing and detailed documentation of field case histories would offer the means for making future progress in this area.

Remediating Ground Deformations

Cost effective remediation against the potential effects of earthquake-induced ground deformations on our civil infrastructure will require developing new ground improvement techniques, improving the efficiency and effectiveness of existing ground improvement techniques, reducing the conservatisms in many of our current design methods for ground improvements, and advancing performance-based design methods that allow targeting different levels of performance and improved resiliency of systems and networks.

Innovative ground improvement methods, such as biocementation, colloidal silica grouting, air sparging, and rammed aggregate piers, may offer potential economy over existing options, expand the range of conditions over which ground improvement is possible, or provide options for reducing energy demands and associated environmental impacts. Structural approaches to resisting or restraining ground deformations, such as the use of large-diameter shafts or the introduction of flexible joints in tunnels and pipelines, can also be an effective remediation strategy in some cases.

Opportunities for innovation in existing ground improvement techniques may include developing smart equipment that optimizes mixing, vibration, or other processes, and more effective use of information technology for processing, visualizing, and interpreting the huge volumes of quality control data that can now be gathered electronically on ground improvement equipment. Improved methods for subsurface imaging also offer the potential for better quality control or quality definition, which can then be used for guiding the use and interpretation of more rational construction specifications.

Substantial economy may be gained by developing ground improvement design methods that reduce inherent conservatisms and can confidently predict different levels of seismic performance. Existing design methods tend to be inherently conservative in representing certain behaviors due to the absence of seismic performance data; e.g., reinforcement and drainage effects of sand/stone columns, cracking potential in soil-cement walls, influence of spatial variability in treatment/densification results. An improved understanding of how spatial variability of improved ground affects performance should enable the development of better statistics-based design specifications, which in turn should result in substantial economy.

Performance-based design methods offer a useful framework for evaluating the relative benefits of targeting different performance levels (e.g., different amounts of ground deformation) in site-specific remediation works and for strategically targeting remediation efforts to improve the resiliency of lifeline systems and networks. This can be particularly important where the cost of remediation along a distributed system becomes impracticable. Achieving this goal will require increased confidence in our ability to predict the performance of improved ground.

Large-scale shaking table tests in combination with advanced computational models offer the potential means for making progress on many of the above issues. Large-scale physical tests would enable more detailed modeling of: (1) the ground improvement processes at a scale closer to those used in the field, (2) the interaction of structural elements with the deforming ground, and (3) ground improvement strategies that involve complex spatial arrangements of improvements or structural features. The ability to evaluate new ground improvement techniques, validate numerical models, and explore the issues previously described would provide the means for more rapidly moving from discovery to practice.

Performance Evaluations for Soil-Structure Systems

Future efforts can be expected to include advancing analysis and design tools for predicting the performance of various soil-structure interaction systems. This area of research will require further strengthening of communications and merging of numerical tools between geotechnical and structural engineers. Reasonably accurate predictions of the post-earthquake functionality of civil infrastructure components are a necessity for achieving the goal of planning and designing resilient systems and communities.

Design methods that allow for rocking of foundations can be expected to develop further and eventually become an acceptable condition in practice. The acceptance and understanding of rocking foundation effects is an example of how recent and ongoing research has advanced an important area of soil-structure interaction analysis and produced the means for significantly reducing costs for many projects. Progress in rocking foundations has been made possible by the synthesis of results from physical model experiments (shake table and centrifuge), the development of numerical models for rocking foundations, the analyses of soil-structure systems with nonlinearities in the foundation and structure, and the collaborative efforts of geotechnical and structural researchers and practitioners in evaluating potential design methodologies.

Structural approaches to accommodating ground deformations may be a preferred alternative for some structural systems, such as introducing flexible joints into pipeline or tunnel structures. Reducing the sensitivity of a structure to ground deformation may be more economical than reducing ground deformations in many cases. Issues in design may include the optimal placement of flexible connections and the deformation demands placed on those elements.

Large-scale physical model tests offer the advantage that they enable more detailed modeling of different soil-structure interaction systems and configurations. For example, physical model tests of buried structures could explore the structural demands imposed on them by liquefaction, including how the structural demands change as the structure extends across geologic boundaries between soils that do, and do not, liquefy during shaking. They could also investigate the behavior of flexible structural connections and how they reduce demands placed upon them in challenging ground conditions. In all of these areas, large-scale testing provides the ability to model the geometric complexity of the problems in greater detail. Supporting studies using smaller-scale physical model tests and computational efforts would be important, but would not eliminate the need for the large-scale capstone tests.

Resiliency and Performance-Based Design

Future progress can be expected in probabilistic methods for performance-based evaluation and design, and in their use for the planning and designing of resilient systems and communities. Performance-based design procedures have the particular advantage that they provide valuable insights on the dominant sources of uncertainty and help users focus their attention on those aspects where research efforts can be most effective. The extension of these methods to the more general issue of resiliency for a network or community will be a natural focus of effort in coming years. The challenge for both performance-based and resiliency-based procedures will be simplifying the processes, filling in the knowledge gaps, demonstrating their utility in decision making, and ultimately demonstrating their effectiveness in reducing the impacts of future earthquakes.

The impacts of ground deformations on distributed systems or lifelines are an example of where designing for resiliency could offer significant advantages. The cost of remediating against potential ground deformations along a distributed system, which may cross a wide range of poor ground or slope conditions, can be prohibitive. Future efforts can be expected to more formally take advantage of the common sense approach of designing to minimize the impacts of the ground deformations, focusing any ground improvement efforts on the essential components, being prepared to re-operate systems in response to actual damages, and being prepared to repair damages in a timely and effective sequence. The challenge will be having the means to predict the extent and location of damages, the ability to intelligently and quickly assess damages and re-operate, and the means to maintain preparedness for rapid repair works.

An important future need will be improving the completeness and accuracy of geotechnical hazard maps, so that the extent and distribution of damages from slides, liquefaction, surface rupture, or other geotechnical hazards in future earthquakes are well anticipated. These efforts will benefit from the establishment and use of regional geotechnical databases, with due recognition that the quality control of data being entered into such databases will be an important factor in their success. Regulatory policies that improve the community's awareness (e.g., owners, renters, taxpayers) of geotechnical hazards may also be an important factor as well. The more people are aware of the hazards they are exposed to, the better the chances are that market forces and general awareness will lead over time to reductions in the potential impacts of those hazards.

Sensing for Risk Reduction and Resiliency

Sensing technologies offer a wide range of opportunities for reducing seismic risks and improving resiliency. Sensors offer a means for near real-time assessments of system performance, which can be used to guide or automate re-operation of damaged systems, improve safety, and direct effective repair works. For example, local sensor networks on pipeline systems could be used to detect damage with a resolution that could be used to automate re-operation of the pipeline and guide repair efforts. Sensors on landslides and bridges could detect damages that pose a threat to automobiles, and in the future could communicate directly with the navigation systems in the automobiles to immediately alert them to the most appropriate action.

Sensor networks and remote sensing will eventually contribute to a more accurate mapping and documentation of geotechnical hazards, including their updating based on future earthquake experiences. Improved maps will in turn contribute to better planning and design for resiliency, as discussed previously.

Detailed sensor arrays on key infrastructure are needed so that future earthquakes can provide us with lessons and understanding that we cannot achieve through experimental work alone. For example, how much deformation might occur in the young soft Bay Mud around San Francisco Bay during a large event on the San Andreas or Hayward faults? Well designed sensor networks in a few key locations could address that issue much more definitively than can be achieved through reconstituted physical models, laboratory tests, and numerical simulations alone.

Detailed sensor networks can also be expected to advance our understanding of local site effects, particularly with regard to topographic and basin effects. The opportunities for improved ground motion prediction equations, simulation methods, and micro-zonation are numerous.

Other Aspects Affecting Future Progress

Past advances in geotechnical earthquake engineering have often been achieved by the combination of case history experiences, fundamental research, and demonstrations on large projects in practice. Several earthquake case histories have been transformative by identifying an unanticipated or under-appreciated problem or phenomena, and so history suggests we may suffer additional surprises in the coming years. Fundamental research, both experimental and theoretical, has provided the means for understanding our case history observations and for developing design methodologies. Engineering practice has provided the money and motivation for the demonstration of new technologies, tools, or methods on a scale that university-based research cannot realistically achieve. These aspects of past advances are useful reminders that we will undoubtedly follow a similar path of advancement in our future endeavors.

Case histories and large civil engineering projects should, and likely will, continue to play a major role in defining new directions and advancing our profession because it is on those projects where the added value can often first be demonstrated. In recognizing this fact, the onus is on our industry and industry groups to find the way to systematically support research activities that could broadly benefit the community and society. It would be desirable to see such support become the cultural or institutional norm and thus be less prone to cuts in tough economic times. If our industry supports and contributes to the advancements that benefit our communities, then it would seem more likely that we can demonstrate the added value of such research activities and hence maintain research support from our governments.

The growing complexity of the geotechnical engineering field will benefit from efforts to generalize and simplify the discipline by reducing empiricism where possible and furthering the use of mechanics-based models that are more portable across applications. Expert systems that assemble information and knowledge in ways that make it more rapidly accessible to engineers will likely play an important role as well.

Shortening the time from discovery to practice has proven to be a difficult challenge in the past. The impediments are complicated, but efforts to reduce the time from discovery to practice would seem to be improved by the ability to perform near-full-scale tests. In addition, there is a continuing need to support the advancement of numerical simulation software that can model a broad range of geotechnical and structural components simultaneously, so that findings from either the geotechnical or structural fields can be brought to bear on a common platform. This will require considerable investment from the community, recognizing that such complex software packages require considerable expertise and effort to maintain, optimize, and manage.

Conclusions

Our challenge continues to be doing things better, quicker, and cheaper so that we can effectively reduce earthquake hazards and improve resiliency with limited resources. Opportunities to meet this challenge are afforded us by the wide range of ongoing technological advances, our investments in large-scale experimental facilities for earthquake simulation, and the ability of our community to engage in sustained programs of interdisciplinary, collaborative research.

One aspect of geotechnical engineering and geotechnical earthquake engineering that will stay the same in the future will be the need for common sense and judgment guided by a sound synthesis of theory and observations that span the disciplines of geology, soil mechanics, construction, and technology.

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