Modeling Techniques in Geomechanics

Prepared by Members of the TRB Committee on Modeling Techniques in Geomechanics

The field of modeling techniques in geomechanics encompasses analytical and experimental methods of geomechanics modeling and their application to the design and construction of transportation facilities. These techniques include approaches in numerical modeling, such as finite-element and discrete-element methods, and experimental methods, such as laboratory testing and centrifuge modeling.

The use of these techniques in practice has been limited. Therefore, there is a great need for the exchange of experience and knowledge among researchers and practitioners in geotechnical engineering modeling techniques applied to transportation facilities. This information exchange should include the use of existing modeling techniques, the development of new techniques, obstacles to the application of modeling to practice, model verification, and case histories of the application of models in design. The specific areas of modeling currently of interest to the profession include artificial neural networks, micromechanics and microscopic modeling, numerical modeling, reliability, and centrifuge modeling.

ARTIFICIAL NEURAL NETWORKS

Artificial neural networks (ANNs) in engineering are computerized simulations of rapid expert human reasoning. ANNs can arrive at decisions, for example, having incomplete information, or having to select from an apparent overload of sometimes conflicting information. Therefore, use of ANNs can aid engineers who are required to construct facilities without having sufficient knowledge with which to isolate the parameters that determine a specific engineering behavior. ANNs that begin with programmed base logic can be improved by being trained on problem-specific examples. Indeed, one important benefit of ANNs is that they allow engineers to predict engineering behavior on the basis of historical observations, which have proven to be more accurate than statistical methods alone.

The architecture of a simple ANN is a collection of nodes distributed over an input layer, hidden layer(s), and an output layer. The input variables of the problems are situated in the input layer. The output layer contains the output variables or what is being modeled. In statistical terms, the input layer contains the independent variables, and the output layer contains the dependent variable. The nodes between successive layers are connected by links, each carrying a weight that describes quantitatively the strength of that connection, thus denoting the ability of one node to affect the other.

Status in Basic and Applied Engineering Research

At present, the application of ANNs in civil engineering is in its early stages, in part because most learning algorithms in neural computing were rediscovered only a few years ago. However, the successful application of ANNs in other fields of decision-making science and in computer and electrical engineering is expected to lead to increased interest and confidence in their application in civil engineering. The expert judgments that must routinely be made in geotechnical engineering make this an excellent field for the use of ANNs.

Applications in Engineering Practice

ANNs have already been proven to outperform traditional modeling counterparts, such as regression analysis, in solving complex problems. Some of their applications in engineering practice include the following:

- Modeling of the mechanical behavior of geomaterials;
- Development of models that use easily obtained soil parameters, such as liquid limit, plastic limit, specific gravity, void ratio, and grain size distribution, to estimate soil properties that would otherwise require laboratory testing, such as soil-swelling potential, soil-liquefaction potential, in situ soil permeability coefficient, and soil-compaction characteristics;
- Interpretation of geophysical logs for site characterization purposes;
- Prediction of deterioration of pavement structures using simple inputs, such as falling weight deflectometer readings; and
- Development of models that can aid in selecting the most viable maintenance or construction projects.

Directions for Future Research

The following are some important areas for future research in ANNs:

- Coupling the best features of both mechanistic and ANN approaches to create a more efficient hybrid modeling methodology;
- Implementing ANN-based models within other numerical modeling techniques, such as finite element, to analyze engineering boundary value problems; and
- Using ANN technology to build smart systems and structures that can automatically retrain themselves to account for any new changes in their environment.

Obstacles to Fuller Implementation

The primary obstacles to the implementation of ANNs in civil and geotechnical engineering are lack of understanding and skepticism. Most reported ANN-based studies, although successful, have not been applied in practice because engineers have doubts about their use. These obstacles can be overcome by involving practicing engineers in workshops and tutorials focused on ANNs. These meetings should address such topics as key ANN-related issues, explained in simple language and with simple examples; ANN research studies that have been implemented successfully in practice; and the potential benefits of using ANNs as compared with current practice.

MICROMECHANICS AND MICROSCOPIC MODELING

The mechanical response of a soil or rock mass is governed by the interactions between individual particles and between particles and the boundaries. Constitutive modeling, which treats soil as a continuum, has successfully addressed many problems of design and analysis. Problems remain unsolved, however, such as soil liquefaction and the behavior of systems comprised of thin layers, such as pavements. The application of micromechanics to geotechnical engineering involves examining the behavior of individual soil particles under stress, and then using a combination of analytical, phenomenological, computational, experimental, and stochastic techniques to predict the behavior of the entire system.

Status in Basic and Applied Engineering Research

The application of micromechanics and microscopic modeling in geotechnical engineering is still confined to basic research and use by academicians. The current status of the discipline can be best illustrated by the approaches taken to bring the microlevel formulations that are considered to be fundamental—that is, the physics of the problem—to the practical or engineering macrolevel. The most popular approaches are volume averaging, sensitivity analysis, and computer simulation. Of these, computer simulation is the most popular approach used to understand the physics or micromechanics of geotechnical problems. These efforts fall into two broad categories—discrete-element models (DEMs) and discontinuous deformation analysis.

The TRUBAL program (Strack and Cundall, 1978), based on the DEM method, is the most widely used micromechanical model for dry granular material using an explicit finite-difference formulation. In principle, the DEM approach has the capability to simulate large problems, producing an enormous amount of information about granular structure and its behavior. However, simulations of such problems using DEMs are not feasible because of the limitations of conventional serial computers. One logical approach to handling a problem of this nature is to exploit the capability of massively parallel supercomputers.

Applications in Engineering Practice

There has as yet been only limited application of micromechanics and microscopic modeling to real-world problems. It is nearly impossible to use these methods if the interactions of all particles, including their shapes, are accounted with the effect of pore fluids in a design problem. This limitation is due mainly to the computational intensity of the approach and the lack of enough computer power. Though many important developments are expected in the near future, it will be a decade before micromechanical models can be used for geotechnical designs.

Directions for Future Research

Fabric anisotropy is a key issue that is overlooked by most macroscopic models. This omission is due mainly to the lack of experimental methods for determining initial and subsequent fabric anisotropy during static or dynamic loads. The application of soil micromechanics using analytical, phenomenological, computational, experimental, and stochastic approaches may provide a means of addressing this issue. For this purpose, long-term yet problem-focused projects would be necessary. At present, it is rather difficult to model real soil behavior because of the lack of analytical and computational tools. A hierarchy of soil models may be needed, starting with the most complex dry granular material that can be handled with currently available analytical and computational tools. The modeling could then be expanded to include pore fluid. Concurrently, an attempt should be made to measure experimentally the micromechanical properties of sand, glass beads, clays, and other materials that are used in microscopic models.

Obstacles to Fuller Implementation

Currently, very few researchers are engaged in this research area. Though many researchers acknowledge that micromechanics is the future of geomechanics, a lack of research support has resulted in few active contributions to this field. This is therefore an area in which there is a substantial need for investment in research.

NUMERICAL MODELING

Mathematical and computational techniques have been developed for design, analysis, and prediction of the behavior of soil and rock, as well as structural elements (such as soil reinforcement, pipes, and foundations) in contact with the soil, when subjected to various internally or externally applied boundary conditions. Models are not meant to be an exact representation of reality, but rather to mimic the essential characteristics of the elements of the prototype as necessary for design or prediction.

Status in Basic and Applied Engineering Research

Numerical modeling is the subject of many basic and applied research efforts in civil engineering. Such efforts often involve the use of finite-difference, finite-element, boundary-element, and discrete-element methods in conjunction with sophisticated nonlinear elastic, elastoplastic, viscoplastic, crystal plasticity, and micromechanical constitutive models. Constitutive models have increased rapidly in sophistication in recent decades.

Applications in Engineering Practice

Traditionally, there have been two distinct branches of modeling in civil engineering. The first, used for stability analyses, is concerned only with failure or critical states without regard to prefailure deformations. The second is concerned exclusively with deformation issues, but based on linear elastic simulation of materials. More recently, a third branch has emerged that involves the use of inelastic constitutive models to simulate prefailure deformations and ultimately failure states.

The use of more sophisticated constitutive models has often met with resistance from practicing engineers. One reason for this resistance is the fear of litigation should a design or construction problem arise. Another reason is that many of the constitutive models developed during the past few decades present a high level of complexity that may not be warranted for many real-world engineering analyses. Finally, many practicing engineers lack a background in continuum mechanics, plasticity theory, and numerical techniques. Consequently, there may be a dependence on a “black box” approach in numerical modeling, an approach that understandably makes engineering companies uneasy.

One area of practice that has frequently used sophisticated numerical modeling techniques is forensic engineering. In cases of litigation, lawyers often bridge the gap between engineering practice and engineering research. Expert witnesses commonly rely on sophisticated computer modeling and powerful computer-based visualization techniques to better present their arguments to a judge or jury.

Directions for Future Research

Both practicing engineers and researchers must continue to seek ways of bridging the gap between the state of the art and the state of practice. Numerical modeling must become a user-friendly field, carried out with “real” engineering in mind. At the same time, practicing engineers must make a greater effort to understand the fundamental aspects of constitutive modeling and numerical techniques so they can feel confident when performing numerical analyses. Computers are as common in engineering today as slide rules and calculators were in the past. Today, commercial computer programs provide the engineer with powerful tools for accomplishing better, safer, and cheaper civil engineering designs. One way to close the research-practice gap is to offer practicing engineers a series of seminars in the proper use of numerical modeling techniques. These seminars should not be restricted to the use of commercially available computer programs, but should also cover the fundamental concepts behind those programs, and details and calibration of each of the constitutive models.

Obstacles to Fuller Implementation

The fear of litigation noted above is the key obstacle to expanded application of numerical modeling in geomechanics. Practicing civil engineers are confronted with this reality daily, and until this obstacle is overcome, significant innovation in this area cannot be expected.

RELIABILITY

Reliability in engineering has been defined as follows (Harr, 1987):

> Reliability is the probability of an object (item or system) performing its required function adequately for a specified period of time under stated conditions…. It is the purpose of reliability-based design to produce an engineered system whose failure would be an event of very low probability. Probabilities of failure are the most significant indexes of reliability. Being objective, they admit directly to comparisons of the risk of failure of different systems or of the components of a single system, and under varying operating conditions. This capability for both traditional and untried scenarios is the very fabric of civil engineering design.

Status in Basic and Applied Engineering Research

Various reliability-related procedures are increasingly being used in applied engineering. These procedures include uncertainty modelling, risk assessment, reliability-based design [including load and resistance factor design (LRFD)], and quality assurance specifications.

Applications in Engineering Practice

Reliability-based procedures are recognized as powerful tools and are used regularly by structural engineers. Various reliability-related procedures are increasingly being employed by geotechnical and pavement engineers. A significant advance in reliability in the pavement community was the incremental addition of reliability in the guidelines of the American Association of State Highway and Transportation Officials. Similarly, the geotechnical (structural) community has benefited from the incorporation of LRFD.

Directions for Future Research

There are two critical but inadequately addressed contributors to decreased reliability. First, a recent study in the state of Washington revealed that the most significant impact on pavement performance was construction variability (Joe Mahoney, University of Washington). Second, spatial variability is almost never addressed in pavement engineering and only occasionally in geotechnical engineering, even though geostatistics, a technique developed by the mining industry to quantify spatial variability, plays a primary role in mining engineering, hydrogeology, and tracing of contaminant flow.

Obstacles to Fuller Implementation

Until a few years ago, a course in probability and statistics or reliability was not common in the standard undergraduate civil engineering curriculum; though the subject has come recently into vogue, it is still not universally required. Fear of unfamiliar statistics remains a primary obstacle to many engineers outside of academia. Consequently, training in reliability is important both at the undergraduate level and for practicing engineers in government and industry.

CENTRIFUGE MODELING

Centrifuge modeling is a technique for simulating the mechanical response of full-scale geotechnical structures in reduced-scale physical models. Analogues to this technique include flume testing in hydraulic engineering and wind tunnel testing in structural engineering. To achieve mechanical similitude in geotechnical models, it is necessary to replicate the materials' effective stress state. For example, if a model is made at 1/100 scale, it should be tested under an acceleration 100 times earth's gravity. The principles, scaling laws, limitations, and some applications of centrifuge modelling are described elsewhere (*1*,*2*).

Status in Basic and Applied Engineering Research

Centrifuge modeling is a mature technology for basic research. In the past 30 years, the field has benefited from advances in electronics, miniature instrumentation, and computers. A recent survey by the Japanese Geotechnical Society shows a fourfold increase in the number of centrifuge-related journals and a tenfold increase in the number of active Japanese centrifuge centers in the last decade. Likewise, an increasing number of industry-related centrifuge modeling programs are now being undertaken in centrifuge centers in North America and elsewhere.

Applications in Engineering Practice

Engineering applications of centrifuge modeling are increasing for site-specific studies, calibration of numerical models, and understanding of various mechanisms. Examples include bridge pier foundation behavior on sedimentary rock for Northumberland Strait Crossing in Canada (*3*); strengthening of first-generation piled jacket foundation on calcareous sands in Bass Straits, Australia (*2*); seismic design of Pier 400 at the Port of Los Angeles (*2*); flow liquefaction in loose sands in Canada (*4*); optimum road-widening strategies on soft soils (*5*); soil-pile-superstructure interaction in liquefiable sand (*6*); behavior of plumb and battered pile groups in sand (*6*); and stability of sand foundations during earthquakes (*4*). The latter four applications are also leading to rational design procedures, for example, in foundation design (French code Fascicule 62), lateral pile behavior in calcareous sand (*2*), and the extension of design procedures for large drag anchors in clay for floating production systems (*2*). These three examples highlight the benefit of centrifuge modeling in understanding complex foundation interactions (such as footings near slope crests), unusual soil conditions, and novel foundation systems, respectively.

Directions for Future Research

There should be a continued increase in applied engineering research in centrifuge modeling. New applications should continue to be developed in, for example, code calibration, environmental engineering (*3*; see also http://www.lcpc.fr/~necer/necerwww.htm), marine engineering, engineering for cold regions, and other civil engineering disciplines. More complex boundary value interaction problems, novel foundation systems, and unusual soil conditions need to be addressed. The trend toward increased use of natural instead of artificial soil can be expected to continue. The lack of knowledge of similitude conditions and scaling factors and means of mitigating the limitations associated with the technique need to be addressed. Growth in the acquisition of smaller, "desk-top" centrifuges for teaching and parametric studies and in shared access to larger national centrifuge centers can be anticipated. The future should see the development of more intelligent systems, including on-board actuators (such as robots); optical measurement methods (such as use of lasers and field displacement mapping); and direct interaction among external collaborators via, for example, the Internet.

Obstacles to Fuller Implementation

The main obstacles to wider adoption of centrifuge modeling in practice are lack of awareness on the part of users and modelers and economics. The standardization of experimental procedures and techniques, leading eventually to quality assurance, should result in greater application of centrifuge modeling techniques. The practitioner and the modeler must be educated about centrifuge modeling and the practitioner's needs, respectively. Only major projects can support dedicated centrifuge modeling programs, but routine designs can significantly benefit from the techniques. Collaborative, jointly funded programs should therefore be undertaken by industry consortia and funding agencies to develop more rational and cost-effective designs, especially for novel conditions.

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