The Role of Finite Element Methods in Geotechnical Engineering

Greater computational power and higher accuracy software have led to wider acceptance of finite element analyses within the profession of geotechnical engineering over the past two decades.

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While the use of finite element analyses is so ubiquitous in many branches of engineering, and even though geotechnical engineers were prominent among the early developers of finite element methods,[1,2] there is considerable skepticism about their usefulness and reliability in solving practical geotechnical problems. One can contrast this situation with their almost universal acceptance in structural engineering design. Cautious use of sophisticated numerical analyses is certainly warranted in geotechnical practice given the spatial variability and complex properties of geomaterials (soils and rocks) and the limited site characterization data available in most projects. Furthermore, there is often extensive experience with simplified empirical methods that appear to provide an adequate basis for safe design.

Apart from these general constraints, the technology of finite element analyses has matured during the last 20 to 25 years, and it has become readily available through advances in user-friendly interfaces and powerful personal computers (PCs). During the 1970s, university research groups carried out much of the development and application of prototype finite element codes (local examples at the Massachusetts Institute of Technology [MIT] included FEAST for stress analyses, FEDAR for steady flow and CONSOL for uncoupled consolidation). Programs originally written for card reader input devices have achieved remarkable durability and have formed the kernels of numerous programs that are still used in practice today. However, the user community today is very different and can be broadly sub-divided into two groups:

- The first are experienced engineers who are familiar with their design problems, who recognize limitations in finite element codes and adjust the use and interpretation of these numerical analyses accordingly.
- The second are junior engineers, who are primary users of the much more powerful second-generation finite element software. They are highly literate in current computer technology, but tend to have very limited knowledge of the underlying formulation and numerical approximations used in finite element methods (these are not topics that are routinely covered in graduate courses in geotechnical engineering) or conversely of soil/rock properties and behavior (topics that are often unfamiliar to students with strong mechanics backgrounds).

Successful application of finite element analyses in geotechnical engineering requires a clear understanding of the design problem/ parameters to be solved (based on sound knowledge of the geological context, soil/rock mechanics, groundwater hydrology, etc.) *and* an understanding of the capabilities and limitations of finite element modeling techniques.

Current Program Capabilities

There is some excellent software available for performing finite element analyses of geotechnical engineering problems. One can distinguish three main classes of software:

- Very big, general-purpose finite element codes that include subroutines specifically for geotechnical applications (constitutive models for soils, etc.). Examples include ABAQUS, ADINA and ANSYS. Among these programs, ABAQUS was one of the first to include capabilities for modeling coupled flow and deformation in soils (*i.e.*, capability for modeling effective stress behavior with partial drainage of pore water), and it was the first general-purpose program to include critical state models of soil behavior such as Modified Cam Clay (MCC).[3] Despite these features, the complexity of the program represents a formidable challenge to the user, requiring a long learning curve (several months of training) and an extensive background in mechanics. The difficulties associated with input and output controls can be made more manageable through separate pre- and post-processor programs.
- General-purpose, geotechnical finite element programs are a more recent and welcome development and have been specifically designed for the geotechnical engineering community. Examples include CRISP, FLAC and PLAXIS. (FLAC is actually a finite difference program. Although this formulation entails different numerical and discretization issues, the scope and objectives of the program are consistent with other finite element programs in this class.) These programs were developed for the PC user, and have benefited from the enormous advances in PC software and hardware capabilities, including very convenient features (such as vastly improved operating system graphical interfaces, etc.). The programs are general purpose in the sense that they can tackle a full range of geotechnical applications ranging from foundations (shallow and deep), to earth structures, to excavations and tunnels. These programs also are able to solve problems involving coupled deformation and flow. They typically incorporate nonlinear constitutive laws such as simple cap models (such as MCC, etc.) and variants of the hyperbolic Duncan-Chang shear stress-strain relations.[4]
- Finite element software for specialized or more advanced geotechnical applications (such as ground amplification of earthquake base motions, liquefaction analyses or advanced constitutive modeling) is still being developed primarily within the domain of university research groups.

From a user's perspective, some of the most important advances in finite element programs (especially those such as CRISP, FLAC and PLAXIS) are linked to the automation of previously time-consuming (and technically difficult) tasks such as mesh generation and load stepping schemes for nonlinear analyses. These programs have greatly improved efficiency and have brought complex, nonlinear analyses within the reach of most practicing geotechnical engineers.

Automation of load-stepping is a very important topic since it shifts the control of solution accuracy from the user to the program itself. For example, programs such as ABAQUS and PLAXIS have default parameters governing the accuracy (error tolerance) within their nonlinear equation solvers (both of these codes use iterative Newton-Raphson solvers that are unconditionally stable). Although users can override some of these parameters, the clear intention is to guarantee solution accuracy to the user and, hence, provide a reliable black-box solving capability for use in design practice. Built-in components of the finite element codes are usually well written and robust.

However, several of the current programs have adopted an open architecture that enables plug-in type modules (subroutines or functions) to be added by the user (examples include FISH functions within FLAC, and UMAT subroutines in ABAQUS). These features are particularly attractive to researchers or advanced users of the codes. However, they represent a major liability in geotechnical practice, where poorly documented or minimally tested subroutines can be used within an otherwise sound code. Recent experience suggests that this type of code customization is quite commonplace but is often marketed under the original product label. Geotechnical practitioners should either require much higher standards for documenting custom features and benchmarking the analyses, or adopt programs with a closed architecture and accept the limitations imposed within these codes.

One should recognize the intrinsic complexity of finite element programs used in geotechnical engineering. The analysis of elastic materials or steady flow in porous media represents a much simpler class of problem than those related to nonlinear soil behavior, transient and coupled flow-deformation, etc. This difference may explain the long time lag between the establishment of finite element capabilities for solving very complex dynamic problems of interactions between three-dimensional structures and elastic soils (*e.g.*, SASSI[5]) or massive groundwater simulations (*e.g.*, MODFLOW[6]), compared to nonlinear effective stress in geotechnical engineering (or contaminant transport models in geoenvironmental engineering).

Although many of the available finite element programs are capable of performing calculations for three-dimensional geometries, the vast majority of applications in geotechnical practice to date have focused on two-dimensional (usually plane strain) conditions. This emphasis is especially true when considering nonlinear soil behavior and/or coupled flow-deformation problems. This situation is about to change. The current generation of PCs have achieved computational speeds that make three-dimensional analyses practical, while sophisticated pre- and post-processing programs (such as PATRAN, IDEAS and FEMAP) have greatly simplified finite element model construction and interpretation. However, one should not underestimate the difficulty of performing numerically accurate nonlinear analyses of three-dimensional problems (*cf.* automated time-stepping algorithms in two dimensions), given the fact that the complexities of constitutive behavior and the representation of spatial distributions of soils are important topics that require further research.

Some Limitations

Finite element analyses provide a powerful tool that can be used in a variety of different modes ranging from simulation (understanding mechanisms of behavior, effects of individual parameters, etc.) to prediction (usually in calculations of deformations, flow or stability) and design (especially structural design, comparison of construction schemes, etc.). However, in all cases, the user needs to pay careful attention to potential limitations in the geotechnical engineering context. Many of these limitations can be traced to three sources:

- Complexity of ground conditions or inadequate site characterization;
- Complexity of geomaterial behavior or inadequate data for appropriate constitutive models; and,

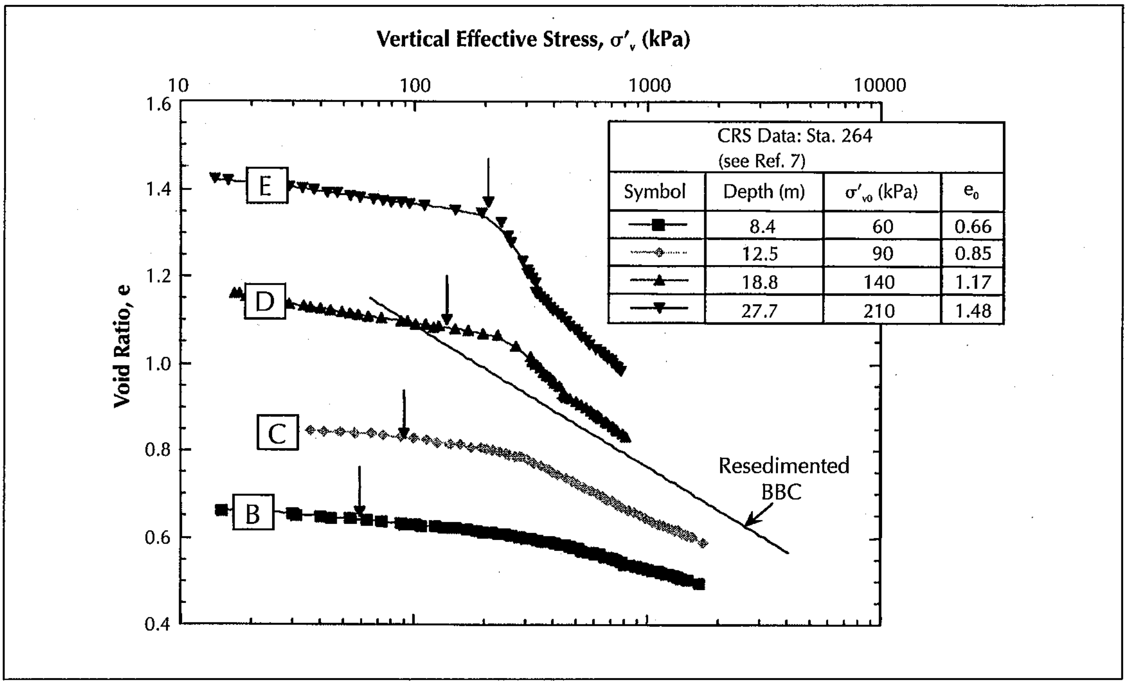

FIGURE 1. One-dimensional compression behavior of a clay.

- Complexity of construction processes that are difficult to represent in finite element models.

Complexity of Ground Conditions or Inadequate Site Characterization. All finite element models are built on simplified models of stratigraphy and/or geological units. Good site characterization data are essential for locating critical/weak soil layers, continuity of drainage horizons, boundary characteristics (usually rock-soil interfaces and rock mass characteristics), and so on. However, spatial variability (*e.g.*, complex layering of alluvial sediments) and macroscopic fabric features (*e.g.*, fissuring of overconsolidated clays masses, voids in karst topography) can represent a formidable challenge. These issues lie outside the spectrum of conventional problems and may either invalidate use of finite element analyses or require stochastic or other specialized modeling techniques (joint elements, etc.) that are best handled by specialists. Jointed rock masses represent perhaps the most extreme case, where the continuum behavior of the intact rock material plays a secondary role to the mechanical and hydraulic properties of the joint system(s).

Complexity of Geomaterial Behavior or Inadequate Data for Appropriate Constitutive Models. There is no doubt that soils exhibit complex material behavior. Even a well studied material such as Boston Blue Clay exhibits features such as undrained strength anisotropy, nonlinear stiffness even at shear strain levels below 10^{-3} percent, stress history and compressibility parameters that vary widely.

For example, Figure 1 shows four one-dimensional compression tests on specimens from different depths within a deep clay layer (from a site north of Boston) — note that specimen E is from the deepest part of the profile. This specimen has the highest in-situ void ratio, and is more sensitive than overlying material with very high compressibility for loading beyond the pre-consolidation pressure (σ'_p).

The diversity of natural soils and rocks as well as other constructed geomaterials (compacted fills, soil-cement mixes) are the basis for the continued existence of geotechnical engineering as a specialty within civil or environmental engineering. While the engineering properties of some materials can be measured through procedures of sampling and laboratory testing, other materials are sufficiently non-homogeneous or difficult to sample that mass parameters must be estimated by other (usually much cruder) field tests. The net effect is that finite element analyses are often based on very crude constitutive models. The majority of analyses assume linear, elastic deformation properties, while shear strength is characterized by a linear Mohr-Coulomb failure envelope. Even relatively modest advances such as the nonlinear Hoek-Brown failure criterion for rock masses are used comparatively rarely.[8] Most of the current finite element programs include a version of the hyperbolic shear stress-strain law originally introduced by Duncan and Chang.[4] This law has the abiding virtue that it can represent shear behavior for a wide range of materials. MCC remains the most widely used effective stress model and is useful primarily for soft clays.[3]

There remains an important role for the application of more advanced constitutive models,[9,10] especially if more reliable predictions of performance are required (*e.g.*, effects of excavation-induced ground deformations on adjacent structures). However, the additional complexity of these models must be balanced by an equal attention to improved site characterization and measurement of soil properties.

Complexity of Construction Processes That Are Difficult to Represent in Finite Element Models. It is well recognized that there are many construction activities that can cause "disturbance" (*i.e.*, deformations, changes in stresses and soil properties) of the surrounding ground. Examples include the installation of piles, support walls (ranging from driven sheet piles to excavated diaphragm wall panels), tieback anchors (often with multiple grout sequences), as well as grouting or other soil-mixing techniques of ground modification. In some cases (such as the driving of piles in soft clay), these disturbance effects dominate the subsequent pile response to applied loads (due to the generation of excess pore pressures during installation, subsequent dissipation and setup of effective stresses and modification of soil properties close to the shaft) and cannot be ignored in a finite element model. In other cases (such as diaphragm wall installation), the effects on soil stresses and properties are more subtle, and may legitimately be ignored in a finite element analysis (several research groups are currently investigating this topic), although the resulting ground movements may represent a significant fraction of the movements caused by excavation.[11]

Despite these limitations, there is no doubt that finite element analyses can be applied successfully to a wide range of practical problems. Indeed, it is perhaps surprising that they have had relatively modest impact on design methods. This situation seems to reflect other, more general aspects of geotechnical engineering practice.

For example, one should ask why certain empirical methods of design are so widely accepted and/or slow to evolve? One good example is the use of apparent pressure diagrams to design struts for braced excavations. Apparent pressure diagrams were originally derived from measurements of strut loads obtained during construction of subways in Berlin and New York in the 1930s. The current design envelopes (see Figure 2) have evolved using data from projects in several other cities (Chicago, Oslo, London, Washington, etc.). Although the underlying database is substantial, there are many factors that are not explicitly considered in the design charts, such as bending stiffness of the wall (very few of the case studies used high stiffness diaphragm and secant pile walls), levels of strut pre-stress, effects of dewatering, construction sequence, and so forth, while soil profile appears only through the designated ground classification (clay, sand, etc.). For design situations where the bracing system is a temporary structure, there are considerable incentives to reduce the number of struts. Finite element analyses offer an attractive alternative method of design that can handle site-specific ground conditions, proposed construction sequences, and so on, and were first applied for this purpose by Goldberg *et al.*[13] (In this application, the predictions can even be calibrated through observational approaches.) Many subsequent studies have shown the advantages of using finite element analyses for designing strut loads. However, geotechnical consultants most frequently use apparent earth pressure envelopes to design strut loads.

A second general observation is that the geotechnical profession undervalues the impor-

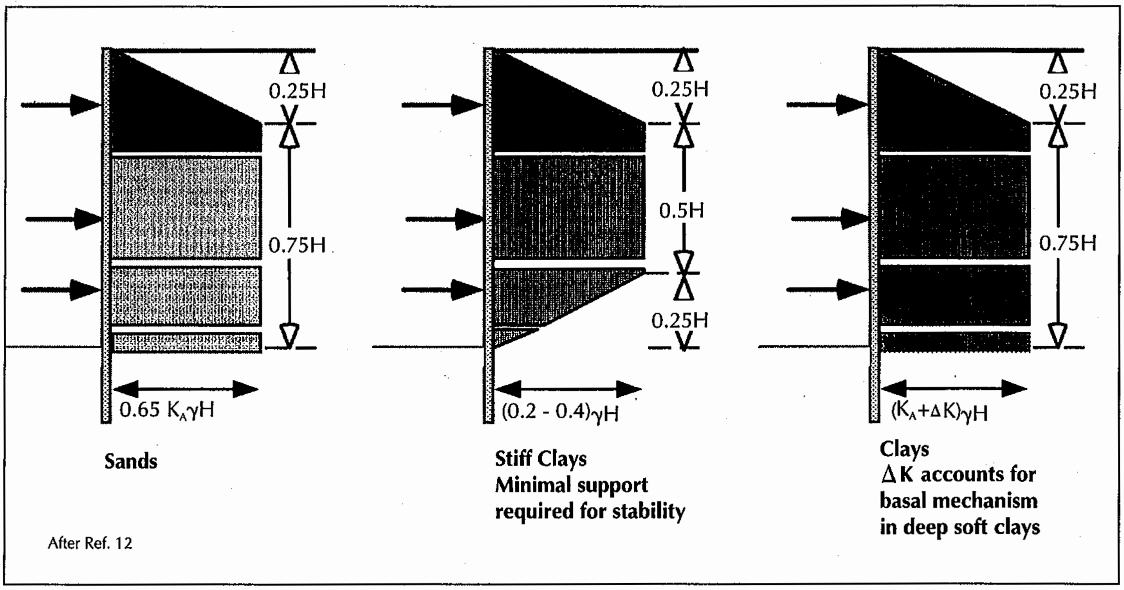

FIGURE 2. Apparent earth pressure design charts.

tance of careful measurements of soil properties (especially laboratory tests — even on high-quality samples). For example, the one-dimensional compression data shown in Figure 1 indicate important variations in clay compressibility with depth (and stress level) within a single clay profile. This type of behavior is only rarely taken into account in simple one-dimensional settlement calculations (where constant values of the compression ratios CR, RR are widely assumed), and even more infrequently in finite element analyses. Similarly, there is a tendency in finite element analyses to rely on published correlations for estimating stiffness parameters, even in projects where laboratory triaxial tests have been performed as part of the site investigation program.

Future Needs

The availability of high-quality software and the massive increase in available computational power guarantee the increased usage of finite element analyses in geotechnical engineering. An assessment of current program capabilities and limitations can lead to the formulation of a number of actions that should be taken in order to achieve wider acceptance of these methods.

In the short term, the profession needs to adopt procedures for benchmarking the programs currently used in practice. This step is particularly important since it provides a way to check that users are achieving numerical accuracy in their nonlinear finite element calculations. It is also essential for validating any non-standard components (constitutive laws, interface elements, etc.) for programs with an open architecture. The benchmarking could include:

- Calculations of standard example problems where complete input parameters for the finite element model are specified (foundations, excavations, etc.) — checking numerical accuracy only;
- Problems where input data are provided but parameter selection for the finite element model is left to the user — checking the modeling approach; or,
- Evaluation of predictive capabilities using case-study data from real projects or controlled experiments.

Wider acceptance of finite element analyses for design will depend, in large part, on the validation of predictive capabilities through the publication of well documented case studies.

The long-term development of finite element analyses will require progress in three main directions:

- Improvements in the measurement, interpretation and representation of material properties in finite element analyses. Many advanced constitutive models have already been presented in the research literature.[14] Some of these models will undoubtedly appear in commercially available finite element software, while others will be used as plug-ins (customized features). However, further research is definitely required to address some specific aspects of behavior that remain poorly understood (*e.g.*, the time-dependent behavior of clays, the behavior of partially saturated natural soils and compacted clays, frozen soils, etc.), and to define properties for certain classes of material (*e.g.*, residual soils, soilcrete, etc.).
- Integration of finite element analyses with statistical and probabilistic techniques is inevitable given the large uncertainties that exist in geotechnical projects (geological anomalies, spatial distributions of soils and their engineering properties, etc.) and should be encouraged. There has already been much work on the development of statistical and probabilistic methods for use in site characterization (*e.g.*, exploration strategies[15]), reliability-based design (*e.g.*, first-order second moment methods combined with limit equilibrium analyses of slope stability[16]), and stochastic finite element analyses that consider random and spatially correlated soil properties[17] and address complex problems such as liquefaction potential.[18] Finite element methods have also been used in conjunction with formal back-analysis techniques (*e.g.*, optimized estimation of soil properties from field measurements of ground movements[19]). Despite these advances, there is currently little application of these techniques in geotechnical engineering practice. This lack of use reflects conceptual difficulties associated with non-deterministic methods of analysis and also the need to demonstrate practical benefits in design.
- Substantial and sustained educational efforts are needed to train geotechnical engineers in the most effective use of finite element analyses. This process is already occurring in the form of professional short courses related to the recent spread of commercial geotechnical finite element programs. However, there is also need for adequate training in finite element methods in most geotechnical graduate degree programs (in the United States). This training requires providing both background (theoretical basis and techniques of numerical analyses) and application knowledge (modeling nonlinear soil behavior, parameter selection, etc.). This situation will certainly change now that high-quality (user-friendly and robust) software is available.

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