Effective Uses of Finite Element Analysis in Geotechnical Engineering

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Introduction

This paper examines our present capability to effectively use finite element analysis in geotechnical practice. The contents are based on my personal experiences from using finite element analysis for some thirty years to help solve engineering problems. I will use three cases to illustrate how finite element analysis has been of particular benefit.

The discussion in this paper is limited to static loading cases only. Dynamic analysis using finite elements is a whole other world that produces an entirely different set of applications and uses, and about which I seem to know less with each passing year.

I would like to start with some initial comments on my philosophy for doing finite element analysis, which I call "advanced analysis." My guiding rule and perhaps the key point of this paper is, *"Know the answer before you start with a finite element analysis."* To many, especially to clients, this might seem like a ridiculous statement. After all, if I already know the answer, why should I spend more time and resources to do a finite element analysis? Furthermore, how do I find the answer for a complex problem without doing a finite element analysis?

Before answering these questions, let me explain the reason for the rule. Finite element analyses involve quite complicated geometric and mathematical models of simplified reality. Analyses of practical cases usually involve more than one mechanism and multiple materials within the same analysis. It becomes almost impossible to check that the analysis is correct by examining the results of the finite element analysis alone. Seemingly subtle changes in parts of the geometric model or in the details of the material models can sometimes lead to sizeable changes in the computed result. Errors in the model definition within the program input can go undetected. An estimate of what the answer should be serves as a benchmark with which we can evaluate the results of the finite element analysis. Without knowledge of what the answer should be, we have little basis to decide whether the finite element model is a reasonable representation of reality or not. Having a finite element model that looks great on paper is quite possible, yet that model may give calculated displacements that are 0.1 to 10 times those of the actual situation. Knowing what the answer should be gives us a way to review and modify the finite element model so that it better represents reality.

How does one obtain an answer before running a finite element analysis? We use simpler methods and experience. Table 1 shows my attempt to classify levels of analysis. It also shows my general bias that the level of analysis should be matched by an equal level of sophistication in the material parameters used in the analysis. So the answer to the question is that one uses

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simplified and standard analysis methods with experience to obtain an estimate of the answer before undertaking a finite element analysis. This preparatory effort results in one: (a) developing a sense for what the final answer should be, (b) obtaining insight on what parts of the problem are important and should be carefully modeled, and (c) defining the objective(s) for the more advanced finite element analysis.

Table 1: Levels of Analysis

Level	**Analysis Method**	**Material Parameters**
Simplified Analysis	semi-empirical calculations from experience and local correlations	estimated parameters from experience and index tests
Standard Analysis	"standard practice" methods from geotechnical books, codes and local experience	"standard practice" testing such as triaxial, direct shear, field vane, SPT and cone
Advanced Analysis	advanced numerical methods including finite element, finite difference and boundary element	best available from lab and field tests that consider stress path

Why do a finite element analysis, if one must know the answer before starting a finite element analysis? Finite element analysis can remove many simplifications and assumptions used in simpler analyses. Finite element analysis can help refine the answer to obtain a more precise prediction. Finite element analysis can give better insight into the behavior of the problem. Finite element analysis can help look at alternatives in a systematic way. Finite element analysis can help extend a design beyond the envelope of normal practice. Finite element analysis can be particularly useful in analyzing the causes of failures.

The next sections describe three cases where finite element analyses were of considerable value to the outcome. I chose these cases to illustrate the power of finite element analysis in today's engineering practice, and to show that finite element analysis has progressed beyond the position of being a sophisticated tool held by a few academic specialists.

Comparison of Design Alternatives

This case involved the construction of a highway to be placed in a tunnel in the center of a major US city. The final structure was to be a tunnel 90 ft wide with a crown 60 ft below the ground surface. The design called for a 100-ft deep excavation, 100 ft's wide, supported by several levels of massive struts. Major structures with foundations within 50 ft of the excavation existed on both sides of the work. Part of the highway had to pass beneath an existing subway station. The contractor wanted to consider replacing the cut and cover design for the excavation with a tunnel excavation. Tunneling could potentially reduce excavation and spoil and save time and money.

A principal question dealt with the relative impacts on adjacent structures of the two approaches. Would one approach cause more movement of the existing foundations than the other? Finite element analysis of the two approaches provided a way to examine the size and pattern of movements produced by the two approaches. By using the same soil profile and soil parameters, the analysis could focus on which excavation method caused less displacement. The soil profile and typical soil parameters had been previously developed for the original design, so developing the input information for the finite element analysis was straightforward.

From an analysis perspective, the big challenge of this project was to have the analysis follow the sequence of construction as closely as possible. We knew from experience that the size of movements around carefully designed and constructed supported excavations are as much influenced by the construction details as they are by the material parameters. This requirement meant that considerable effort was required to develop a finite element mesh that could follow the significant steps of the construction. The mesh had to allow the removal of soil in a staged manner, the addition of supporting elements, and the change of ground water level. Additionally, it had to include a realistic representation of the foundations for the existing structures.

Figure 1 shows the typical finite element mesh developed for the tunnel section passing beneath the existing subway station. It shows elements placed into the mesh to model the different soil materials, elements to model a small tunnel to support grouting activities, and elements to simulate construction of the mainline tunnel. The proposed tunneling method involved the use of the New Austrian Tunneling Method (NATM). The finite element model included considerations for the temporary support provided by the shotcrete and lattice girders used in the NATM method. Presence and material properties for these various elements were tracked in sequential steps within the analysis, similar to the steps in the actual construction process. A similarly detailed mesh was developed for the cut and cover method given in the contract design. The actual analysis was done with the finite element program, ADINA.

Figure 2 shows a typical result obtained from this analysis. It shows a section where a high rise building is close to the excavation. The top half shows the cut and cover design method. The bottom half shows the tunneling method, which at this location involves two tunnels, one over the other. The contours show the predicted horizontal displacement resulting from the excavation. The key question being addressed with the finite element analysis is the potential impact of the excavation on the adjacent facilities. Figure 2 shows that the predicted horizontal displacements beneath this building from tunneling are approximately one half of those predicted for cut and cover tunneling. The differential horizontal movement across the base of the foundation is approximately 30% less for tunneling than for cut and cover. The differential horizontal movement across the foundation is important because it stretches the building foundation in tension. Similar reductions occurred for vertical deformations. The finite element results showed that the tunneling method would cause less impact on the building foundation from deformations that the cut and cover method.

In this situation we are using the same method with consistent parameters and assumptions to analyze different cases. This approach can provide considerable confidence that the predicted differences in displacements, strains, forces and stresses are real and reliable. It can also provide an unbiased comparison of the performance benefits of one design over another and show other alternatives that may further improve on the design. In situations like this, having highly refined soil parameters for the analysis may be less important that having the analysis consider the important details of construction sequence and methodologies. Here for example, we had to consider carefully how to model the importance influences of initial slack in the bracing system and loss of ground at the tunnel face.

Extending the design envelope

Geotechnical engineers use design methods that usually envelop past experience. These methods employ considerable conservatism to keep the risk of failure low. Situations frequently occur where one would like to work outside the design envelope to reduce time, save money, or accomplish something not previously tried. Advanced analysis can help us predict performance outside the usual design envelope in which we practice.

In the early 1980's, Washington, D.C. was engaged in a vigorous effort to build a new subway system. The contractor working on the Wheaton Station for the Washington Metropolitan Area Transportation Authority (WMATA) faced a difficult task to complete a complex intersection of inbound and outbound tunnels with a cross over tunnel and an inclined escalator shaft. He proposed changing the design to one using NATM and making major reductions in the thickness of the lining system. Figure 3 shows the original design and the proposed NATM design. NATM had been previously used only once in the United States. WMATA had no design codes or methods with which to assess the integrity of the contractor's proposal. A key question was whether the contractor's proposed liner had sufficient strength to support the excavation and avoid overstressing some rock pillars to be left in place between the tunnels and the escalator.

With the assistance of Prof. Herb Einstein of the Massachusetts Institute of Technology, we made a finite element analysis of the Contractor's proposed design. The actual work was a modeling nightmare. We had somehow to develop a finite element mesh that included all of the complicated three-dimensional intersections of the excavation and the lining system and include bar elements for the rock bolts. We chose a mesh processing program called PATRAN to help create the mesh because it had been quite successful in modeling complex geometries for the aircraft, auto and defense industries. After weeks of effort and with the help of a PATRAN engineer that we employed, we succeeded in getting a mesh together. We used ADINA to do the finite element analysis.

Figure 4 shows the primary result of all of this work. It shows principal stress in the shotcrete liner system at the completion of excavation. The shotcrete provided the initial tunnel support. It would be supplemented with the final cast-in-place liner to provide the long-term tunnel support system. Figure 4 shows that some locations could develop tensile stresses well in excess of the tensile strength of the shotcrete liner. We found no problem with overstressing of the rock pillars and no problems with the final liner system. Based on these analyses and other considerations, the contractor's proposal was modified to increase the tensile strength of the shotcrete liner. The project was successfully completed with savings of millions of dollars accruing to the owner and the contractor. Better water tightness of the final tunnel was achieved as a side benefit.

The finite element analysis help show that the NATM method would work on this project, but more reinforcing steel was required to handle the tensile stresses in the shotcrete. The results of the analysis were a key factor giving the designers and owner the confidence to accept the contractor's Value Engineering proposal. Finite element analysis helped us work outside the normal design parameters for this project. The success at Wheaton Station opened the way for more applications of the NATM technique in the United States.

Failure Analysis

Many failures involve performance outside the working zone encompassed by our design envelopes. Design methods do not tell us what happens at failure. The results of finite element analyses can give insight to likely failure modes, suggest paths that could lead to failure, and help us predict performance up to failure.

This case illustrates the use of finite element analysis to help determine the cause of failure. It involves the wheels on cars used to move concrete forms for a tunnel lining in Chicago. Each car has four wheels that ride on the concrete invert. Each wheel consists of a solid steel hub covered with a 2-inch thick solid polyurethane tire. Less than 2,000 ft into the 50,000 ft job, the tires began to fail. This brought the concreting operation to a halt for several hours while the tire was changed. By 2,500 ft, four tires had failed. The Contractor recognized that he had a serious problem.

We examined the tires and observed that the polyurethane was separating from the steel hub at the bond. However, the visual evidence did not clearly show the cause of the failure. By the time failure was observed, the tire was so badly damaged that the evidence of initial failure was obscured. We discussed the problem with the polyurethane manufacturer who said that properly formulated and molded tires should develop a bond stronger than the material itself. We also noticed that a steel grid work had been added to the steel hub. It consisted of 1/2 inch square bars welded to the circular hub. Two bars were placed around the perimeter of the hub about 2 inches inside the edges. Six bars were placed around the perimeter parallel to the axis of the tire. These bars protruded into the tire and created the potential for concentrating stresses within the polyurethane.

We ran finite element analyses to figure out the stresses in the tire for various loading conditions. We measured the total force delivered to each tire for in-service conditions by placing strain gauges on the wheel struts and taking continuous measurements during a typical pour cycle. The maximum measured force in one tire was 150,000 lb and represented approximately half the total weight of the car. We used this force and analyzed the tire in different configurations with the finite element program, ADINA. With ADINA, we could model the tire as a separate body, then lower it onto a solid surface and load it in steps to the full load. We could then rotate the tire to see what configuration of the steel webs caused the greatest stress concentrations. Figure 5 shows the worst-case condition determined from a two-dimensional analysis, where the tire is considered to have an infinitely long axis.

Figure 5 clearly shows the stress concentrations produced by the steel web. The computed maximum compressive stress was 4,800 psf. This was more than twice the design compressive stress of the polyurethane. A three-dimensional analysis for the same loading conditions showed even worse stress conditions. We also analyzed the tire without the steel webs. Figure 6 shows the result. The maximum compressive stress was reduced to 2,850 lbs, a 40% reduction. This value was still higher than the recommended design value for the polyurethane used in the tire.

Based on our measurements of forces developed in the tires and the stresses in the tire computed from the finite element analysis, we recommended that the webs be removed from the steel hub and a new polyurethane tire be molded onto the hub. The polyurethane manufacturer assured us that sufficient bond strength would develop if proper molding and curing procedures were followed. The contractor remade every tire. We also recommended changes in the carrier hydraulics and operations to reduce the maximum force developed in each tire. The job was completed without a single tire failure, except a couple of tires that were cut by sharp objects. This success reduced the Contractor's potential costs attributable to delays from tire failures by several million dollars.

The results of the finite element analysis played a key role in helping to decide why these tires were failing and showing the benefits of various alternatives. The analyses showed that the webs were greatly overstressing the polyurethane and that removing the webs would reduce those stresses. The analyses also let us look at the tire in different positions to make sure that we were examining the most critical configuration.

Role of Finite Element Analysis in Practice

Until recently, finite element analysis in geotechnical engineering has been limited to special projects where other alternatives were exhausted or unavailable. The analysis required one or more specialists to obtain a useful answer. However, I think this situation is changing.

Powerful microcomputers and easier to use operating systems are making it less costly to do the analyses. The WMATA case I cited consumed more than $50,000 of commercial computer time on a VAX computer. It took more than two months to prepare the finite element model. The equally complex Boston case was run on a microcomputer that cost less than $4,000 to purchase the entire computer. It took about two weeks to prepare the finite element model using the more user-friendly graphical interfaces of Windows NT.

A selection of new and upgraded finite element programs are becoming available that are more comprehensive in their capabilities, more robust in their operation and easier to use. These programs make the finite element portion of the analysis transparent to the user. The user defines the geometric model and the material properties without any consideration given to the details of finite element analysis. Many programs automatically create the finite element mesh and apply boundary conditions through a graphical interface. The output is presented as contours or shaded zones of equal stress or displacement.

Whereas previous generations of programs required up to several days to create, correct and refine a finite element model, these new programs reduce the effort to a few hours at most. I used to budget a minimum of one week to set up and run a finite element analysis for seepage or displacement. I would budget another week to run various cases and study the results. With these newer programs, I typically budget one day to set up the problem and one day to run various cases and study the results. Of course difficult problems, problems where we have no experience, and problems where we are using a new program for the first time can take much longer to set up and to interpret the results.

Another great advantage of some new programs is that they can do different analyses with the same input information. The user can define the geometry and material parameters once, then continue to do a flow analysis, a consolidation analysis, a deformation analysis, and a stability analysis. Previously, each analysis would require a different program, each with its own finite element mesh and material input requirements. This ability can save considerable analysis time and permit these various performance modes to be combined in complex problems.

Some new programs include a variety of elements that permit one to analyze geotechnical problems with structural members, geotextiles and slip interfaces. They provide a much improved analysis of the discontinuities produced by the different properties of these materials. These programs should help us do a much better job analyzing soil-structure interaction.

Finally, most Windows-based programs include improved graphical options for displaying the results of the analysis. These options let the analyst examine large quantities of output quickly and efficiently. They help use present results in ways that nonspecialist can understand.

Conclusions

It has been more than thirty years since the first use of the finite element method in geotechnical practice. We are finally beyond the development stage of this technology. As practicing engineers, we can now focus on using the tool rather than fussing with the mechanics of doing the analysis.

Powerful microcomputers, easy-to-use interfaces, better software, and more experienced engineers are making it cost-effective to use finite element analysis on more routine work. Using a finite element program to analyze many geotechnical problems in a few hours from start to finish is now possible for experienced users. This optimistic statement assumes that the geometry is known and relatively simple, the material parameters are defined, and the analyst is very familiar with the software being used.

I expect the use of finite element analysis in day-to-day geotechnical practice will increase considerably over the next few years. This is due to the presence of tremendous computing power on most engineers' desks, the availability of reliable finite element software that most engineers can learn to use, and the increasing computer literacy of our young geotechnical engineers.

This widespread capability does cause me some concerns. I grow concerned when I see analysts with inadequate geotechnical knowledge using finite element programs to solve complex geotechnical problems. A strong understanding of effective stress principles and of soil behavior is essential to anyone doing finite element analysis of geotechnical problems for design.

I am also concerned with the number of instances where I see inexperienced persons consuming project resources trying to do finite element analyses without coming to a useful answer. These analytical failures give finite element analysis a bad name. While I already said that it is possible to obtain an answer with finite element analysis in a few hours, some geotechnical problems can become quite complex. Getting an appropriate model can become quite involved. Evaluating and interpreting the output can be intellectually demanding and time consuming. Any team working on a complex problem and using finite element analysis should have at least one person on the team who is well versed and experienced in the finite element tools being proposed for the project.

I also note a trend for people to be impressed with nice looking graphics, though the information in those graphics may not make sense or address the key issues of the project. Impressive graphics can be prepared from meaningless information. I think we will become ever more professionally challenged trying to figure out which of these impressive graphics make sense and help us advance the project.

As the finite element tools become more sophisticated and easier to use, the emphasis is decreasing on how to do the analysis and focusing more on obtaining meaningful input information. To coopt a phrase from our recent political history to suggest the future of finite element analysis in geotechnical engineering, "It's the input, stupid."

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Biography
W. Allen Marr is founder and Chief Executive Officer of GEOCOMP Corporation and of GeoTesting Express, Inc., headquartered in Boxborough, MA. He received his Ph. D. in Geotechnical Engineering from M.I.T., where he also taught for 10 years. He has provided consulting services for analysis and materials testing on a variety of projects nationally and internationally, including the Oosterschelde Storm Surge Barrier in the Netherlands; the Kawasaki Refinery in Japan; the LAGOVEN Refinery in Venezuela; the Central Artery/Tunnel Project in Boston; transit tunnels in Boston, Chicago, Los Angeles and San Juan; the Woodrow Wilson Replacement Bridge in Washington, D.C.; and many earthen dams. He has written more than forty papers in geotechnical engineering, one of which won the ASCE Wellington Prize. He is a Fellow in ASCE, an active member of ASTM, and a member of the Editorial Board for *Geotechnical Testing*.

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