Effective Uses of Finite Element Analysis in Geotechnical Engineering

The greater capabilities of computer hardware and finite element software can produce safer, more economical designs as long as there is adequate training on how to perform these analyses.

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The guiding rule for doing finite element analysis is: "Know the answer before you start." To many, especially to clients, this statement might seem ridiculous. After all, if the answer is already known, why should more time and resources be spent to perform a finite element analysis? Furthermore, how can the answer for a complex problem be found without doing a finite element analysis?

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 the results of the finite element analysis can be evaluated. Without knowledge of what the answer should be, there is 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 provides a way to review and modify the finite element model so that it better represents reality.

So, how does one obtain an answer before running a finite element analysis? Simpler

TABLE 1.
Levels of Analysis

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

methods and experience must be used. Table 1 represents an attempt to classify the levels of analysis. The table also shows that the level of analysis should be matched by an equal level of sophistication in the material parameters used in the analysis. Therefore, the answer to the question is that one tempers simplified and standard analysis methods with experience in order to obtain an estimate of the answer before undertaking a finite element analysis. This preparatory effort results in:

- Developing a sense for what the final answer should be;
- Obtaining insight on what parts of the problem are important and should be carefully modeled; and,
- Defining the objective(s) for the more advanced finite element analysis.

Why undertake a finite element analysis if one must know the answer before starting such an analysis? There are a number of answers. 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.

Three cases are presented where finite element analyses were of considerable value to the outcome. These cases were chosen 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 used 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 feet wide with a crown 60 feet below the ground surface. The design called for a 100-foot deep excavation, 100 feet wide, supported by several levels of massive struts. Major structures with foundations within 50 feet 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, as well as 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 each approach. By using the same soil profile and soil parameters, the analysis could focus on which excavation method would cause less

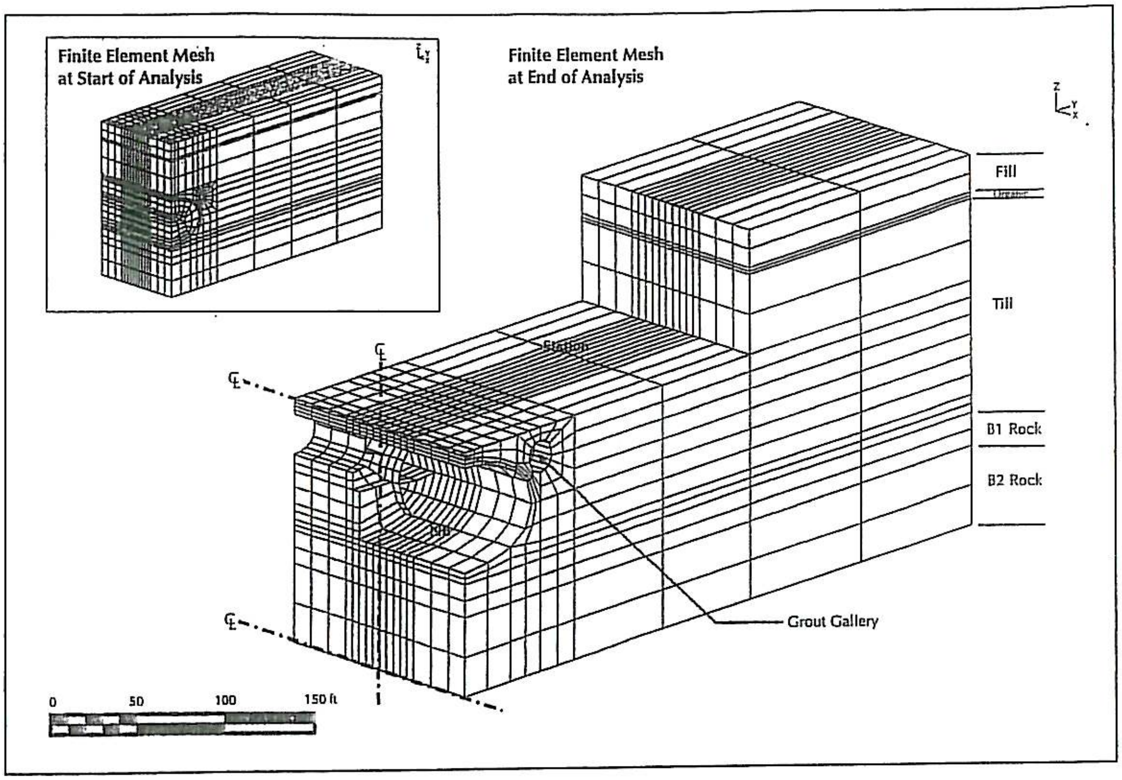

FIGURE 1. Finite element mesh for a tunnel beneath a subway station.

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. Since 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, considerable effort was required to develop a finite element mesh that could follow the significant steps of the construction. The mesh had to allow for the removal of soil in a staged manner, the addition of supporting elements and changes in the groundwater 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, to model a small tunnel to support grouting activities and 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 NATM. 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 involved two

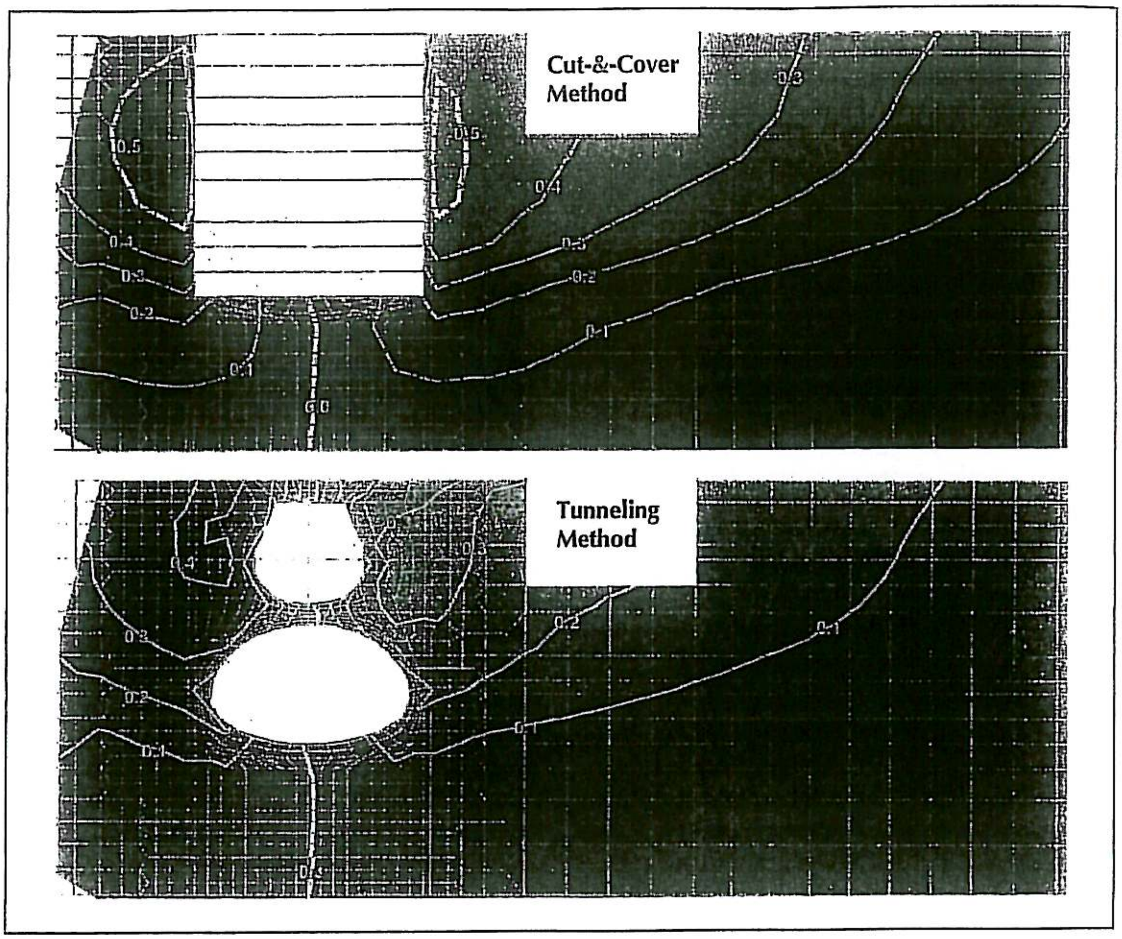

FIGURE 2. Computed horizontal displacements (inches).

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 reveals 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 percent 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 than the cut-and-cover method. The analytical study of the finite element analysis performed did not consider risk factors associated with NATM, such as the availability of skilled laborers in the United States, requirements for close coordination of field measurements and reaction for contingency plans associated with this method, and other factors.

In this situation, the same method, with consistent parameters and assumptions, was used to analyze the 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 present alternatives that may further improve on the design. In these situations, having highly refined soil parameters for the

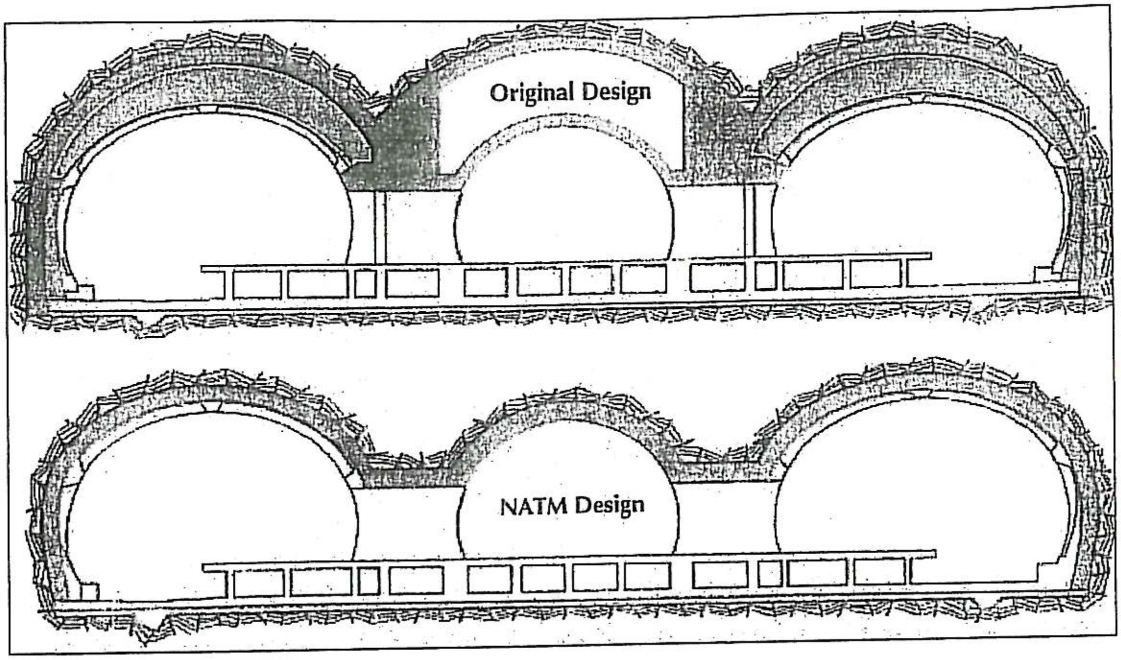

FIGURE 3. Wheaton Station cross sections.

analysis may be less important that having the analysis consider the important details of construction sequence and methodologies. Here, for example, how to model the important influences of initial slack in the bracing system and loss of ground at the tunnel face had to be carefully considered.

Extending the Design Envelope

Geotechnical engineers use design methods that usually encompass 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 predict performance outside the usual design envelope.

In the early 1980s, Washington, DC, 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. The contractor 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 Herb Einstein, of the Massachusetts Institute of Technology, a finite element analysis of the contractor's proposed design was performed. The actual work was a modeling nightmare. A finite element mesh had to be developed that included all of the complicated three-dimensional intersections of the excavation and the lining system and include bar elements for the rock bolts. A mesh processing program called PATRAN was selected to help create the mesh because it had been quite successful in modeling complex geometries for the aircraft, automotive and defense industries. After weeks of effort, and with the help of a PATRAN engineer, a mesh was created. ADINA was then used to do the finite element analysis.

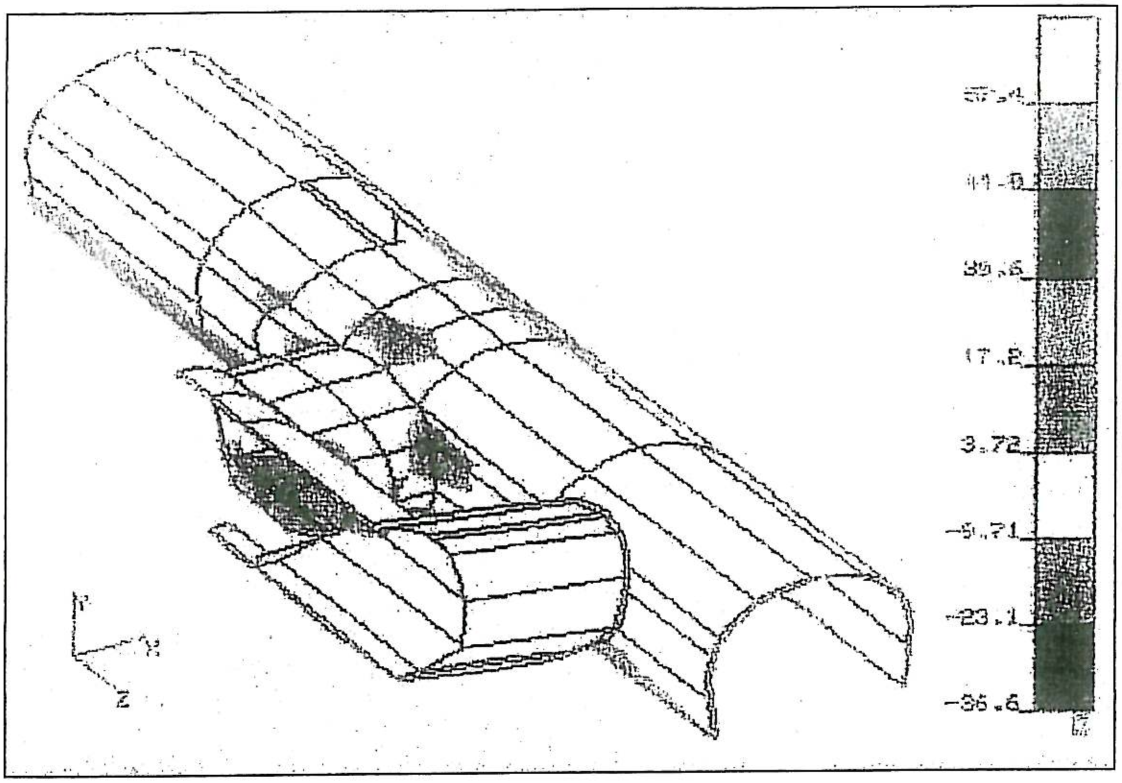

FIGURE 4. Tensile stresses in a shotcrete liner (ksi).

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 long-term tunnel support system. Figure 4 indicates that some locations could develop tensile stresses well in excess of the tensile strength of the shotcrete liner. However, no problem with overstressing of the rock pillars and no problems with the final liner system were found. 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 a 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 helped show that NATM 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 key in giving the designers and the owner the confidence to accept the contractor's value engineering proposal. Finite element analysis helped the project participants work outside the normal design parameters. 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 design envelopes. Design methods do not reveal 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 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 had four wheels that rode on the concrete invert. Each wheel consisted of a solid steel hub covered with a 2-inch thick solid polyurethane tire. Less than 2,000 feet into the

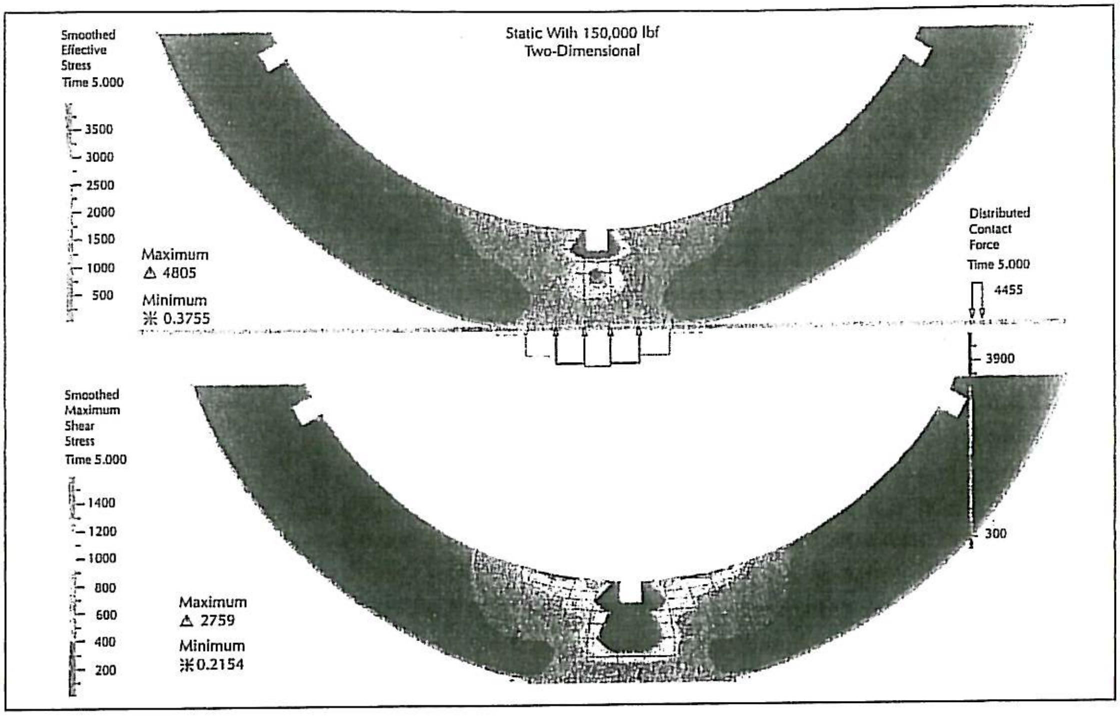

FIGURE 5. Stresses in a solid tire with webs (psi).

50,000-foot job, the tires began to fail. This failure brought the concreting operation to a halt for several hours while a tire was changed. By 2,500 feet, four tires had failed. The contractor recognized that there was a serious problem.

The tires were examined and it was 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. The polyurethane manufacturer informed the contractor that properly formulated and molded tires should develop a bond stronger than the material itself. However, it was noticed that steel gridwork had been added to the steel hub. The grid consisted of 0.5-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.

Finite element analyses were conducted to figure out the stresses in the tire for various loading conditions. The total force delivered to each tire for in-service conditions was measured 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 pounds and represented approximately half the total weight of the car. This force was used to analyze the tire in different configurations with the finite element program ADINA. With ADINA, the tire could be modeled as a separate body, then lowered onto a solid surface and loaded in steps to the full load. The tire could then be rotated 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 stress was more than twice the design compressive stress of the polyurethane. A

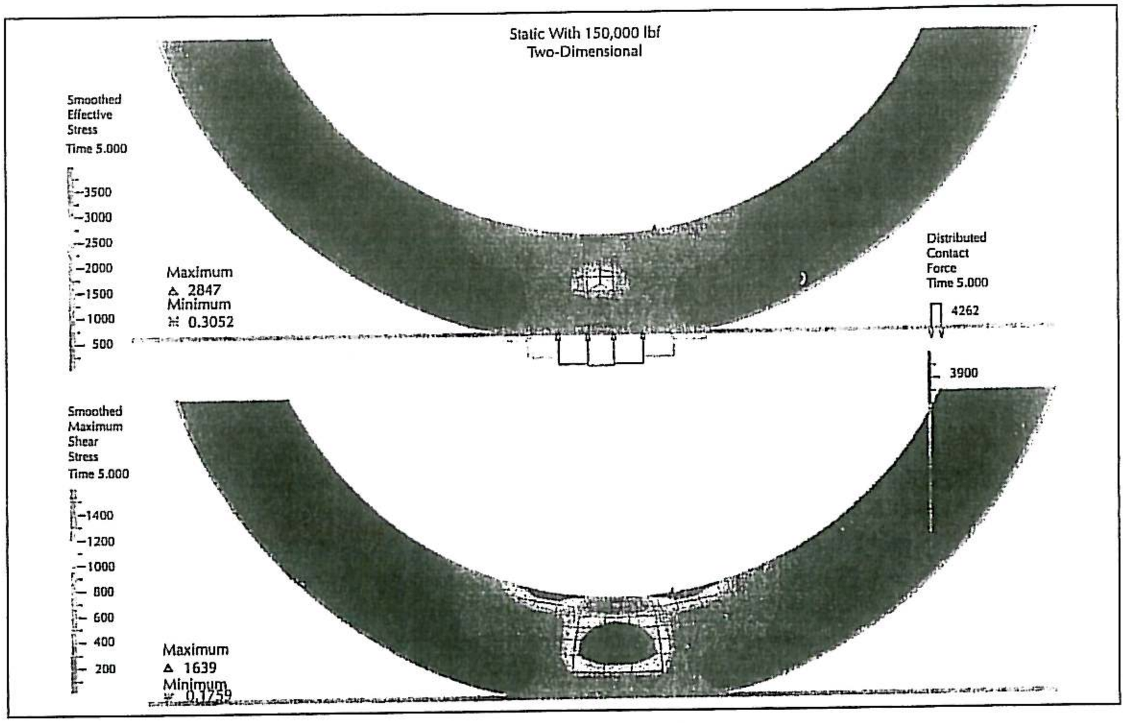

FIGURE 6. Stresses in a tire with webs removed (psi).

three-dimensional analysis for the same loading conditions revealed even worse stress conditions. The tire was also analyzed without the steel webs. Figure 6 presents the result. The maximum compressive stress was reduced to 2,850 psf, a 40 percent reduction. This value was still higher than the recommended design value for the polyurethane.

Based on measurements of the forces developed in the tires and the stresses in the tire computed from the finite element analysis, it was recommended that the webs be removed from the steel hub and a new polyurethane tire be molded onto the hub. The polyurethane manufacturer assured the design consultant that sufficient bond strength would develop if proper molding and curing procedures were followed. The contractor rebuilt every tire. Changes in the carrier hydraulics and operations to reduce the maximum force developed in each tire were also recommended. With the "new" tires, the only other tire failures on this project were 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 key roles in helping to decide why these tires were failing and in showing the benefits of various alternatives. The analyses indicated that the webs were greatly overstressing the polyurethane and that removing the webs would reduce those stresses. The analyses also permitted looking at the tire in different positions to ensure that the most critical configuration was being examined.

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. This situation, however, is changing.

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

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. In the past, a minimum of one week usually would be budgeted to set up and run a finite element analysis for seepage or displacement. Another week would have to be scheduled to run various cases and study the results. With these newer programs, the problem typically can be set up in one day, with another day to run the various cases and study the results. Of course, difficult problems, problems where there is no prior experience and problems where a program is being used for the first time can take much longer to set up and to interpret the results.

Another great advantage of some of the new programs is that they can perform 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 provide the means to do a much better job analyzing soil-structure interaction.

Finally, most new graphical-user-interface-based programs include improved options for displaying the results of the analysis. These options let the analyst examine large quantities of output quickly and efficiently, as well as let the analyst present the results in ways that non-specialists can understand.

Conclusions

It has been more than thirty years since the first use of the finite element method in geotechnical practice. The development stage of this technology has been left far behind. Practicing engineers 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.

The use of finite element analysis in day-to-day geotechnical practice will increase considerably over the next few years. This greater use 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 young geotechnical engineers.

This widespread capability does cause some concerns. Analysts with inadequate geotechnical knowledge should not use 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.

There is also the problem of 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 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.

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

As 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 co-opt a phrase from recent political history to suggest the future of finite element analysis in geotechnical engineering: "It's the input, stupid."

NOTE — *This article is based on a presentation at a technical session entitled, "What Has the Finite Element Method Done for (or to) Geotechnical Engineering?" held at the ASCE National Convention in Boston in October 1998.*

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