APPENDIX A: GEOTECHNICAL ANALYSIS BY THE FINITE ELEMENT METHOD

Chapter 1
Introduction

1-1. Background

a. *Purpose*. The purpose of this engineering technical letter (ETL) is to provide guidance to engineers who are unfamiliar with the finite element method, but who are interested in understanding its potential for use in geotechnical engineering. The emphasis is on practical applications. The objective is to provide a basis for understanding what can be learned from finite element analyses, what skills are required for its application, and what resources in terms of time, effort, and cost are involved.

b. *Use of finite element method*. Use of the finite element method for geotechnical engineering began in 1966, when Clough and Woodward used it to determine stresses and movements in embankments, and Reyes and Deer described its application to analysis of underground openings in rock. Many research studies and practical applications have taken place in the intervening 30 years. During this period, considerable advances have been made in theory and practice, and the cost of computers has diminished to a small fraction of the cost 30 years ago. This report emphasizes the practical lessons learned in the past 30 years, that together define the current state of practice with regard to finite element analyses.

c. *Emphasis*. The theory of the finite element method is not covered in this report. Instead, emphasis is placed on the types of geotechnical problems to which the method has been applied and the options available to engineers who wish to use it for analysis of their problems.

1-2. Types of Problems

a. *Sequence of real events*. Almost all geotechnical finite element analyses are performed in steps that simulate a sequence of real events, such as the successive stages of excavation of a braced or unbraced cut, or placement of fill on an embankment. Performing the analyses in steps has two important advantages for geotechnical problems:

(1) The geometry can be changed from one step to the next to simulate excavation or fill placement, by removing elements or adding elements to the mesh.

(2) The properties of the soil can be changed from one step to the next to simulate the changes in behavior that result from changes in the stresses within the soil mass.

b. *Types of problems*. The finite element method has been applied to a wide variety of geotechnical engineering problems where stresses, movements, pore pressures, and groundwater flow were of interest. The types of problems analyzed include:

- Anchored walls used to stabilize landslides
- Building foundations
- Cellular cofferdams
- Embankment dams
- Excavation bracing systems
- Long-span flexible culverts
- Offshore structures
- Plastic concrete seepage cutoff walls
- Reinforced embankments
- Reinforced slopes
- Retaining walls
- Seepage through earth masses
- Slurry trench seepage barriers
- Tunnels
- U-frame locks
- Unbraced excavations

This list is representative, but not exhaustive. It is clear that the finite element method can be used to calculate stresses, movements, and groundwater flow in virtually any conditions that arises in geotechnical engineering practice. Limitations on the use of the method usually stem from limitations on resources to define problems and to perform analyses, rather than inherent limitations of the method itself.

1-3. What Can Be Learned from Finite Element Analyses?

a. *Analysis by finite element methods*. For analysis by the finite element method, the region to be analyzed is divided into a number of elements connected at their common nodal points. A finite element mesh used in the seismic analysis of the Mormon Island Dam of the Folsom Reservoir Project is shown in Figure 1. This mesh contains a total of 297 elements and 332 nodal points. By means of the finite element method, it is possible to calculate the complete state of stress in each element and the horizontal and vertical movements of each nodal point at each stage in the analysis. The analyses thus provides a very detailed picture of stresses, strains, and movements within the region analyzed. This information has been used to evaluate several aspects of behavior, including:

- Earth pressures within earth masses and on retaining structures
- Earthquake response of embankments and foundations
- Local failure in slopes, embankments, and foundations
- Pore pressures and seepage quantities in steady and nonsteady flow conditions
- Pore pressures induced by loading under undrained conditions
- Potential for cracking in embankment dams
- Potential for hydraulic fracturing in embankment dams
- Potential for hydraulic separation between concrete and soil
- Settlements and horizontal movements

b. Comparing results. The finite element method complements field instrumentation studies very well because each stage in the analysis represents an actual condition during or following construction. By comparing the results of the finite element analyses with measured behavior, the accuracy of the analyses can be assessed. If the calculated values are close enough to the measured values to give confidence in the analytical results, the analyses can be used to infer information about aspects of the behavior that are not shown directly by the instrumentation. Finite element analyses thus extend the value of instrumentation studies by filling out the picture of behavior that can be derived from the field measurements. Finite element analyses have also proved very useful for planning instrumentation studies by showing where instruments can be located to best advantage. In addition, the process of comparing calculated and measured results fits very well into the use of the observational method, which offers one of the most reliable approaches for unusual and difficult problems.

1-4. Information Required for Finite Element Analyses

a. Nonlinear stress strain behavior. Almost all geotechnical finite element analyses represent the nonlinear stress-strain behavior of the soil, because this is almost always a significant factor. To model nonlinear behavior, it is necessary to estimate:

- The initial stresses (before construction)
- The strength and nonlinear stress-strain behavior of the soils
- The sequence of construction operations of other loading conditions to be represented by the analysis

b. Stresses in the soil. These three things are needed because the stress-strain behavior of soil depends on the stresses in the soil. The higher the confining pressure, the stiffer the soil (all else being equal), and the higher the deviator stress, the less stiff the soil (all else being equal). Also, since the soil is inelastic, the strains and displacements that occur depend on the sequence of changes in load as well as the load magnitudes. Despite the complexities of soil behavior, the data required for a finite element analysis can be obtained from a more detailed study of the same type tests as those required for conventional settlement or stability analysis.

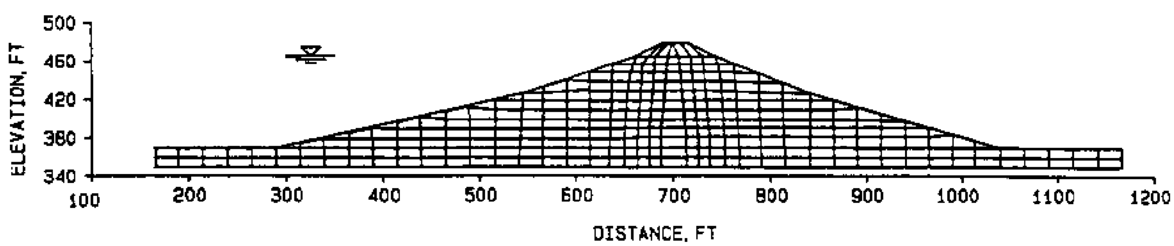

Figure 1. Finite element mesh for Mormon Island Dam

c. *Parameters*. The parameters required for most of the soil stress-strain models that are used in finite element analyses can be determined from the results of conventional soil laboratory tests, such as triaxial tests or direct shear tests used in combination with consolidation tests. The results of in situ tests (SPT, CPT, or PMT) can be used, together with data for similar soils, to estimate stress-strain parameters when results of tests on undisturbed tests are not available.

1-5. Skills Required for Geotechnical Finite Element Analyses

By far the most important skill required for geotechnical finite element analyses is a firm understanding of the geotechnical engineering aspects of the problem being analyzed, most particularly the physical behavior of soils and rocks. It is also necessary to understand the principles of mechanics and numerical analyses that form the basis for the finite element method. An engineer with a solid background in geotechnical engineering and mechanics can become effective in using the finite element method within a few weeks or months. The time required to become skilled in using the method is shortened considerably by the opportunity to work with and learn from an engineer who has already achieved mastery of the method. When weeks or months to learn to apply the method are not available or affordable, the alternative is to engage an engineer who is already an expert with this method. The examples summarized in subsequent sections of this report include suggestions for further study and for possible sources of expert assistance that may be of use in either case.

1-6. Required Effort and Cost

a. *Minimum time and effort*. The amounts of effort and time required for finite element analyses vary over a wide range, depending on the purpose of the analysis and the complexity of the problem analyzed. An example of the minimum time and effort would be a simple analysis performed to estimate possible settlements within an embankment during construction. If the geometry of the embankment was simple, if the foundation was rock or firm soil that would not contribute to settlements, if the anticipated constructions sequence was simple, and if the properties of the embankment materials could be estimated using available data for similar soils, a geotechnical engineer experienced in performing finite element analyses might be able to develop the mesh, select the soil parameter values, perform the analysis, and summarize the results in 1 or 2 days. Computer costs would be negligible, because this type of analysis could be performed readily on a 486 computer.

b. *Dynamic analyses*. If the conditions analyzed or the objectives of the analysis are more complex, considerably more time may be required to perform finite element analyses. Among the most time-consuming analyses are dynamic analyses of earthquake response, analyses of consolidation that model elasto-plastic soil stress-strain behavior, and three-dimensional (3-D) analyses. An example of a very complex series of analyses are the 3-D analyses performed to estimate the movements, earth pressures, and pore pressures in New Melones Dam, California. These analyses (which had a research component because they were unprecedented at the time) required a total of about 4,000 hours of effort. About one-fourth of this time was needed to evaluate the stress-strain characteristics needed for analyses, which used both hyperbolic and Cam Clay properties.

c. *Costs*. Costs of finite element analyses have decreased in the past few years because the cost of computers has decreased so dramatically. New computer programs are now available that use graphical preprocessors and postprocessors to reduce the amount of time required to prepare input, to interpret, and to plot output.

1-7. Finite Element Codes Used on Corps' Projects

a. *Corps of Engineers' experience*. The Corps of Engineers has extensive experience in the use of the finite element method for the analysis of geotechnical projects. A list of the most commonly used codes is provided in Chapter 5. Chapter 5 also includes an extensive bibliography that can be used to obtain further information on the finite element method.