Chapter 8

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1. INTRODUCTION

This dissertation describes research involving the finite element program SAGE and deep excavation support systems. This work is summarized in this chapter, and conclusions drawn from the work are discussed. Recommendations for future studies of deep excavation support systems and improvement to the program SAGE are given.

8.2. SUMMARY

In Chapter 2 a comprehensive review of literature on deep excavation support systems was presented. The purpose of the review was to study factors that influence the performance of deep excavations in soil. The publications reviewed indicate that the important factors that influence the performance of deep excavations in soil are:

1. Type of soil and its mechanical behavior
2. Construction method
3. Construction sequencing
4. Initial soil stresses
5. Groundwater conditions
6. Support system
7. Workmanship/quality of construction
8. Temperature
9. Excavation geometry

The role of these factors in the performance of deep excavations is complex. This makes designing excavation support systems and studying deep excavation performance challenging.

In addition, performance data from recent published case histories were compared to the performance data compiled by Goldberg et al. (1976). The recent published case histories showed that diaphragm walls are now used more extensively than any other wall type to support deep excavations. Comparison of recent performance data with that collected by Goldberg et al. showed that the typical maximum wall and ground movements experienced in deep excavations in soft soil conditions has decreased. The benefit is believed to be a result of the increased use of diaphragm walls and tighter control on construction operations.

Another lesson learned from the literature review was that finite element analysis has played an important role in improving the understanding of the performance of deep excavation support systems. The literature review also showed that consolidation is an important consideration when analyzing deep excavations in clays. These observations motivated the implementation of Biot consolidation into the finite element program SAGE. Implementation of the capability for coupled analysis is described in Chapter 3. The Biot consolidation formulation couples pore fluid flow to volumetric deformation in soil. Three example problems involving consolidation were analyzed with SAGE and were presented to verify the implementation of the formulation.

In addition to the implementation of Biot consolidation, other changes were made to SAGE during the course of this research study. These additional changes were described in Chapter 4. The purpose of the changes was to increase the usefulness and flexibilty of the program as a tool for analyzing soil-structure interaction problems like deep excavations. Among the changes described were:

1. Extension of SAGE to axisymmetric conditions.
2. Implementation of an algorithm for reducing cumulative error related to incremental analysis approach.
3. Implementation of piezometric lines, which allow loads due to changes in pore pressure to be modeled in uncoupled analyses.
4. Implementation of a steady state seepage module.
5. Implementation of pinned connections for beam elements.
6. Implementation of the Sekiguchi-Ohta critical state soil model.
7. Creation of pre-consolidation pressure profile lines, which give users of SAGE the ability to specify pre-consolidation pressures for elements using the Modified Cam Clay and Sekiguchi and Ohta models.
8. Addition of a restart analysis capability.

The deep excavation for the Dam Number 2 Hydroelectric Project was presented in Chapter 5. The design and construction of the project, which is an example of the state of the art in deep excavation technology, were described. Structural slurry walls with anchors were used to support the excavation. A summary of the performance data from the extensive instrumentation and monitoring program of the project was also presented. Consolidation of a heavily overconsolidated clay layer beneath the excavation was suggested as the cause of the time-dependent deformations that were observed. A summary of the soil and site conditions for the Dam Number 2 Project were presented in Chapter 6.

Finite element analyses performed with SAGE of the Dam Number 2 excavation were presented in Chapter 7. The analyses presented demonstrate the usefulness SAGE for studying complex soil-structure interaction problems. It was found that modeling consolidation of a thick heavily overconsolidated clay deposit beneath the excavation helped to explain the behavior observed. The analyses, which were performed using the plane strain assumption, agreed well with the observed data, but two discrepancies were noted. One was the difference in the horizontal movement of the toe of the slurry wall predicted by the SAGE analyses and that observed during construction. The second was that the magnitude of the wall movements above the excavation base predicted with the

SAGE analyses were less than the movements recorded during construction. The difference between the complex excavation geometry and the idealized plane strain geometry may be one cause. The interaction between the deadman and anchor systems for the tailrace wall and the powerhouse may be another cause. Creep in the grouted anchors is a third possible cause.

8.3. CONCLUSIONS

The following conclusions are drawn from the work described in this dissertation:

- The implementation of Biot consolidation and the other changes made to SAGE during the course of this research study increase the usefulness of the program as a research and an engineering tool.
- Finite element analysis and instrumentation monitoring of deep excavations are naturally complementary tools for studying deep excavations.
- Diaphragm slurry wall technology plays an important role in the design of many modern deep excavations.
- The time dependent movements observed in the Dam Number 2 excavation can be explained by the process of consolidation in the Jackson Formation.

8.4. RECOMMENDATIONS

Recommendations for further research into deep excavation support systems, and recommendations for future development of SAGE are presented below.

- SAGE should be extended to analyze three-dimensional problems. This would enhance the usefulness of the program. Soil-structure interaction problems with geometry that cannot be modeled satisfactorily with the plane strain assumption could be modeled more accurately.
- The excavation for the Dam Number 2 project could be reanalyzed with a 3-D finite element analysis to investigate the interaction between the tailrace deadman structures and walls with the powerhouse walls.
- The advantages and disadvantages of implementing a frontal solver into SAGE should be investigated. A frontal solver could reduce the computation time required for analyses with large meshes.

- An algorithm should be implemented in SAGE to renumber the global degrees of freedom to minimize the bandwidth and profile of the global stiffness matrix at the beginning of each analysis step. This would facilitate running analyses with large and complex meshes on computers with limited primary storage. Modeling anchors with beams that cross several elements and using pinned connections often result in dramatic increases in bandwidth.

- SAGE should be upgraded to Fortran 90 from FORTRAN 77 in order to take advantage of the features of Fortran 90 such as dynamic memory allocation and whole array operations. Fortran 90 is more compatible with the vision of a structured and modular program that was established when the program was created (Morrison, 1995). Switching to Fortran 90 would also add to the longevity of the program, since FORTRAN 77 is becoming obsolete.