AC 2009-235: USING COMPUTER MODELING TO INCREASE STUDENT COMPREHENSION OF FOUNDATION BEHAVIOR AND CAPACITY

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USING COMPUTER MODELING TO INCREASE STUDENT COMPREHENSION OF FOUNDATION BEHAVIOR AND CAPACITY

Abstract

Computer modeling in engineering and technology is not only a powerful analytical tool for design, it also has significant potential as an educational tool to help students better visualize and understand the behavior of different elements in engineering systems. Some prior studies have been performed by others where computer simulations were used in an attempt to increase student comprehension of certain concepts in engineering courses. Improvements in learning were observed in some of these investigations, but overall the reported impact and effectiveness of this approach appears to be mixed. Few prior studies have investigated the effect of computer modeling on student comprehension of the behavior and static load capacity of spread footing and pile foundations, which are commonly used in civil engineering to support structures on soil.

The purpose of the study presented in this paper is to evaluate the impact of computer simulations on reinforcing and improving undergraduate students' computational abilities and understanding for spread footing and pile design. The investigation is motivated by the observation that although undergraduate students in civil engineering learn the theories and computational approaches for evaluating the load capacity of these foundation types, they often do not fully appreciate how the foundation interacts with the soil and how load-carrying capacity is developed from that interaction. As a result, they often struggle with calculating the loads that can be supported by spread footings and piles, particularly for non-uniform soil conditions existing in layered soil profiles. In the current study, undergraduate Civil Engineering Technology students in a foundation design course at Rochester Institute of Technology performed analyses of spread footing and pile load capacity using the computer modeling software FLAC, in addition to performing traditional manual calculations based on theory, as part of their homework. FLAC uses a finite difference approach to solve modeling problems. The effectiveness of the FLAC simulations for enhancing and strengthening the students' computational skills and understanding for the load capacity and behavior of these foundations was evaluated by comparing the examination performance of students who used the software with the performance of those from the prior academic year who did not use it. Statistical analysis of the data indicate some improvement in the ability of undergraduate students to manually compute the load-carrying capacity of spread footings and piles in a layered soil profile when they used FLAC modeling in addition to traditional manual computations. The group who used FLAC also gained an appreciation of the importance of the depth factor in the load capacity calculations for footings. In general, students indicated the software helped reinforce their understanding of spread footing and pile foundations. Student feedback also confirmed the importance of providing adequate background on how the software operates. The results of this study show that computer simulations using advanced modeling techniques can be successfully implemented in undergraduate engineering or engineering technology courses to reinforce and improve student comprehension and their manual computational abilities for design of engineering system components, such as foundations supporting structures.

Background and Hypothesis

In civil engineering, students can struggle with clearly understanding the physical behavior of elements in a civil engineering system and relating it to the theory and equations used to design the system. The author has found this to be true in the design of spread footing and pile foundations, particularly in layered soil deposits with more than one soil type. As a result, when students are faced with designing a spread footing or pile in a layered soil deposit, they often have difficulty with correctly applying the appropriate theory and associated design equations.

Previous studies performed by others over the last ten years have shown the potential of using computer simulations to increase student comprehension of engineering systems and designs, particularly in the areas of mechanical and civil engineering. Most of these studies investigated the use of finite element analyses in engineering classes to improve student learning. Cole[1] and Waldorf[2] both indicated that using finite elements in classes to improve student learning can be helpful, but teaching students the basics of how to perform these analyses in a limited amount of time is difficult. Baker et al.[3] used an approach where students were given macros to run finite element analyses, rather than trying to teach them how to set up an analysis. Students in this study indicated that performing the analyses helped them to visualize the problems they solved, but there was no quantitative data collected on changes in student performance. Three different studies were done at the U.S. Air Force Academy by Borchert et al.[4], Bowe et al.[5], and Rhymer et al.[6] where multicolor stress contour diagrams, obtained from finite element analyses of materials under loading, were used in some lecture sections to improve learning. In the first two studies (Borchert et al.[4] and Bowe et al.[5]) no consistent improvement in learning was observed between students who were taught with the finite element results versus those who were not. However, in the last study, where less time was spent explaining the basics of finite element analyses and it was emphasized that there would be finite element related questions on quizzes and exams, there was a noticeable improvement in the quiz and exam performance of students who were taught using the finite element results in comparison to those who were not. Steif and Gallagher[7], who had their undergraduate engineering students use finite element analyses to solve seven mechanics of materials type problems, reported that the students found the finite element analyses slightly to somewhat valuable and doing the analyses improved their understanding little to somewhat.

More recent studies performed by Brown et al.[8] and Brooks et al.[9] showed statistically significant increases in student learning as a result of using finite element analyses. Brown et al.[8] reported mean quiz scores for two groups of students before and after they used a finite element module dealing with stresses in a curved beam. In 2006 the mean quiz scores before and after use of the module were 71.1 and 82.2 percent, respectively; in 2007 the mean quiz scores before and after use of the module were 52.8 and 65.3 percent. Both of the increases in mean quiz scores were statistically significant. Brooks et al.[9] looked at the effect of using a finite element program for pavement analysis on student knowledge about the impacts of geometric conditions, material conditions, and environmental conditions on pavement design. Student knowledge (evaluated on a scale of 0 to 100 percent) about geometric condition impacts on pavement design was 64 percent before and 77 percent after use of the finite element analysis, knowledge about material condition impacts was 61 percent before and 72 percent after, and knowledge about environmental condition impacts was 60 percent before and 67 percent after. All of these changes in student knowledge were reported as being statistically significant and were based on student ratings of their own knowledge.

In the area of foundation design in civil engineering, very few studies have been done using advanced computer modeling to improve student understanding. Lobo-Guerrero and Vallejo[10] discuss examples of how advanced computer modeling based on the discrete element method can be used to illustrate certain behaviors in geotechnical engineering, including spread footings and pile foundations under applied loads. However, they do not report any data showing the effectiveness of this approach for improving student learning.

The study presented in this paper looks at the following hypothesis: Advanced computer modeling software can be an effective tool for civil engineering students to check their hand calculations of footing and pile load capacities and its use can reinforce and improve their understanding and manual computational abilities for design of these foundations. It is based on the observations listed below.

- Spread footing and pile foundation design is an important topic in civil engineering.
- Civil engineering students sometimes struggle with understanding spread footing and pile behavior leading to difficulties in calculating the load capacity of these foundations, particularly in layered soil deposits.
- Advanced computer modeling software has been shown to improve student comprehension and performance in other engineering areas, but there is no specific data demonstrating such an improvement for spread footing and pile foundation design.

Details of the study conducted, as well as the results and conclusions, are presented below.

Details of Study

The current study investigating the effectiveness of advanced computer simulations for enhancing and strengthening undergraduate student comprehension and manual computational skills for spread footing and pile load capacities was conducted in the ten-week-long undergraduate Soil Mechanics and Foundations course in the Civil Engineering Technology program at Rochester Institute of Technology. This required course, which is a sequel to Elementary Soil Mechanics, is normally taken in the fourth year of the five year program. To perform the study, student performance was monitored in two different sections of the course taught one year apart due to the fact only one section of the course is taught each year. The first section, which served as the control group that did not use the computer simulations, was taught in Spring 2007 and consisted of 50 students having a mean grade point average of 2.92 (out of 4.0). The second section, which served as the experimental group that used computer simulations, was taught one year later in Spring 2008 and consisted of 43 students having a mean grade point average of 3.00. A two-tailed t-test performed between these mean grade point averages gave a t-value of 0.664 indicating no significant difference between the groups for the probability of 95 percent used.

The instruction that the control and experimental groups received was essentially the same with the exception that the experimental group used computer simulations as part of two homework assignments. Both groups were taught by the same instructor and the lectures, textbook, and other course materials were essentially the same. In addition, both groups completed traditional homework problems requiring manual calculations based on the application of theory and associated formulae. However, for the two homework assignments given on spread footing and pile design the experimental group also performed advanced computer simulations for a few key problems using the software FLAC (Fast Lagrangian Analysis of Continua) and compared the results to their manual computations.

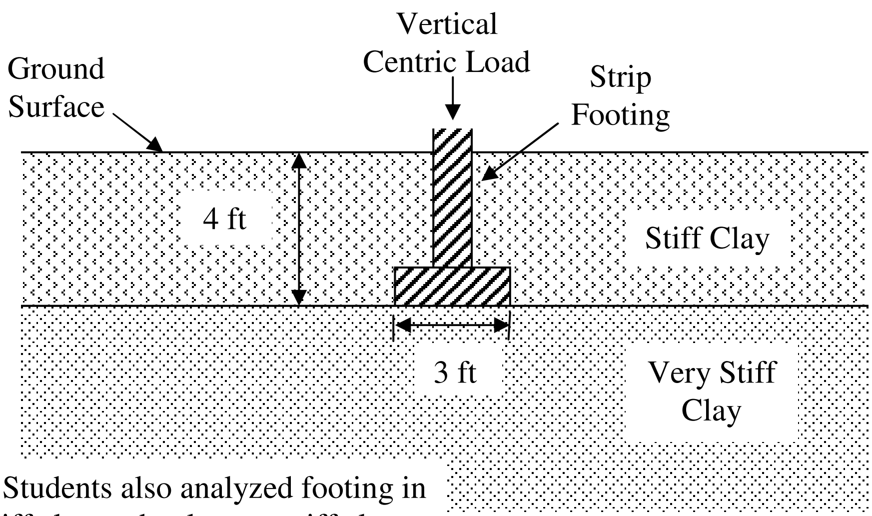
The software FLAC, which was developed by Cundall[11] and Itasca Consulting Group[12] for modeling soil related problems, was selected as the computer modeling software for several reasons. FLAC uses a finite difference solution for solving the equations associated with the system behavior, which is more compatible with the mathematical background of the students in the course, as opposed to the finite element method which uses a unique set of mathematical concepts. In its iterative solution scheme the software also uses the basic equations relating motion, stress-strain, and force, which are all familiar to the students. In addition, FLAC files could be developed by the instructor and provided to the students to execute using some simple commands, thus eliminating the time-consuming process of teaching the students new software.

As stated previously, the goal of introducing the FLAC simulations was to provide students with an effective way of checking their manual calculations of foundation load capacity and, in the process, reinforce and improve their understanding of spread footing and pile performance. To achieve this objective, students in the experimental group used FLAC to simulate the progressive loading of a footing and pile to failure. They then plotted data from each simulation to gain an understanding of the foundation behavior as it is loaded to failure, as well as its behavior at failure. In addition, students in the experimental group compared capacities they obtained from FLAC to their manual computations based on theory. The intent of this comparison was to reinforce the students' confidence when the results agreed and to cause them to investigate discrepancies and correct errors in their understanding and hand calculations when the results did not agree.

To evaluate the effectiveness of FLAC for improving student learning, changes in grades on specific examination questions dealing with spread footing and pile capacities in layered soil deposits were evaluated. Subjective quantitative and qualitative feedback from students was also collected regarding the impacts of the FLAC simulations on improving their understanding of these foundation systems and reinforcing their confidence in manually calculating foundation load capacity. This investigation is unique because no other study has previously been conducted with the same objective.

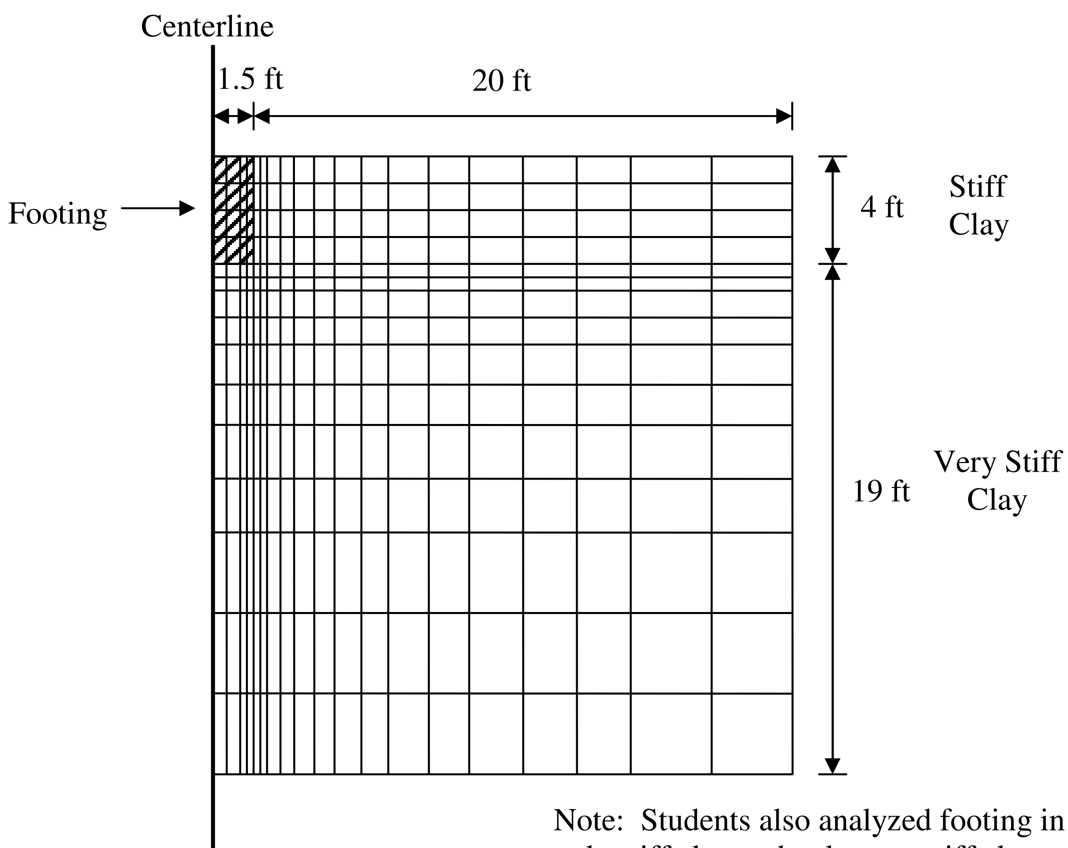
Bearing Capacity of Footing Problem

As part of the Soil Mechanics and Foundations course, students in both the control and experimental groups completed bearing capacity of footing homework problems from the course textbook using traditional manual calculations based on the bearing capacity equation proposed by Terzaghi[13]. The experimental group also analyzed a bearing capacity problem using both manual computations and FLAC. This problem consisted of a 3-foot-wide strip (continuous) footing having a bottom four feet below the ground surface, as shown in the elevation view in Figure 1. The experimental group students manually calculated the ultimate bearing capacity of this footing subjected to a vertical, centric load using the bearing capacity equation, with and



Note: Students also analyzed footing in only stiff clay and only very stiff clay.

Figure 1 – Bearing Capacity of Footing Problem



Note: Students also analyzed footing in only stiff clay and only very stiff clay.

Figure 2 – FLAC Grid for Footing Problem

without a depth factor included, for the following three soil conditions: uniform stiff clay having a cohesion of 1500 pounds per square foot (psf), uniform very stiff clay having a cohesion of 3000 psf, and layered clay consisting of four feet of stiff clay (cohesion of 1500 psf) underlain by very stiff clay (cohesion of 3000 psf). They were also provided with three data files to run FLAC analyses of the strip footing for these same three cases using the FLAC grid shown in Figure 2. Only one-half of the footing and surrounding soil was modeled due to the symmetry of the problem. This approach provided the opportunity to increase the grid density and lateral extent. A Mohr-Coulomb soil model was used in the FLAC analyses, with the strength and material properties listed in Table 1 being input for the two different clays.

A comparison of the ultimate bearing capacities obtained from the manual computations and FLAC analyses is provided in Table 2. The capacities obtained from the bearing capacity equation using a depth factor are much closer to the FLAC results than the capacities from the same equation without the depth factor, as expected. Students in the experimental group compared their hand-calculated capacities to those obtained from FLAC and commented on whether the depth factor should be included when computing bearing capacity of a footing. They also evaluated which soil layer appeared to govern the bearing capacity for the layered clay (stiff over very stiff) case.

Table 1 – Soil Properties Used in FLAC Analysis of Footing

Soil Property	Clay Consistency	
	Stiff	Very Stiff
Cohesion (psf)	1500	3000
Friction angle (degrees)	0	0
Shear modulus (psf)	2.59×10^5	5.17×10^5
Bulk modulus (psf)	25.0×10^5	50.0×10^5
Unit weight (pcf)	125	125

Table 2 – Ultimate Bearing Capacity of Footing from Different Analysis Methods

Analysis Method	Ultimate Bearing Capacity of Footing (psf)		
	Stiff Clay Only	Very Stiff Clay Only	Stiff Clay over Very Stiff Clay
Bearing capacity equation without depth factor	8.19×10^3	15.9×10^3	15.9×10^3
Bearing capacity equation with depth factor	10.3×10^3	20.0×10^3	18.0×10^3
FLAC Simulation	11.3×10^3	21.2×10^3	20.3×10^3

Besides comparing ultimate bearing capacity values, students in the experimental group plotted data generated from the FLAC analyses and evaluated it. One plot they developed, as shown in Figure 3, is the grid displacement vectors representing soil and footing movements as the footing is loaded to failure. The students looked at those displacement vectors and stated whether the pattern agreed with the theory of a bearing capacity failure. In addition, students plotted out the applied bearing pressure versus footing displacement graph shown in Figure 4 and explained how failure of the footing could be identified on that graph.

The impact of the FLAC analyses on reinforcing and improving student comprehension and use of the bearing capacity equation and theory was checked by comparing the performance of the experimental and control groups, who respectively did and did not use the software, on an open-book examination question involving the bearing capacity of a footing in a layered soil deposit similar to the one shown in Figure 1. The experimental group had one question on an one-hour-long exam where they were asked to calculate the ultimate bearing capacity for the footing on the layered soil. The mean percentage (out of 100 percent) score of the group on that question was 93.2. Due to the high percentage achieved on the question, a similar one was not placed on their two-hour-long final examination. The control group had the same type of question placed on an hour-long exam and, due to their relatively poor performance, it appeared again on their two-hour final exam. The percentage achieved by the control group on the hour-long exam question was not available because the exam was returned, but it was lower than the mean of 87.9 percent they achieved on the same basic question on the two-hour final exam.

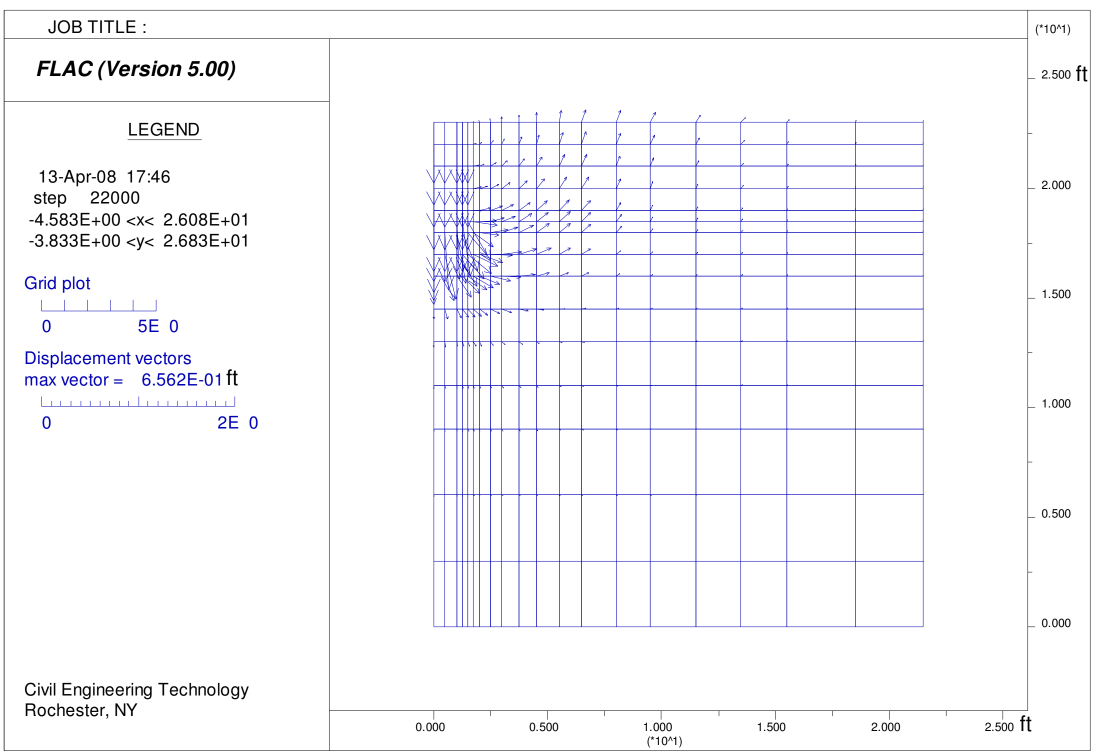


Figure 3 – Grid Displacement Vectors from FLAC

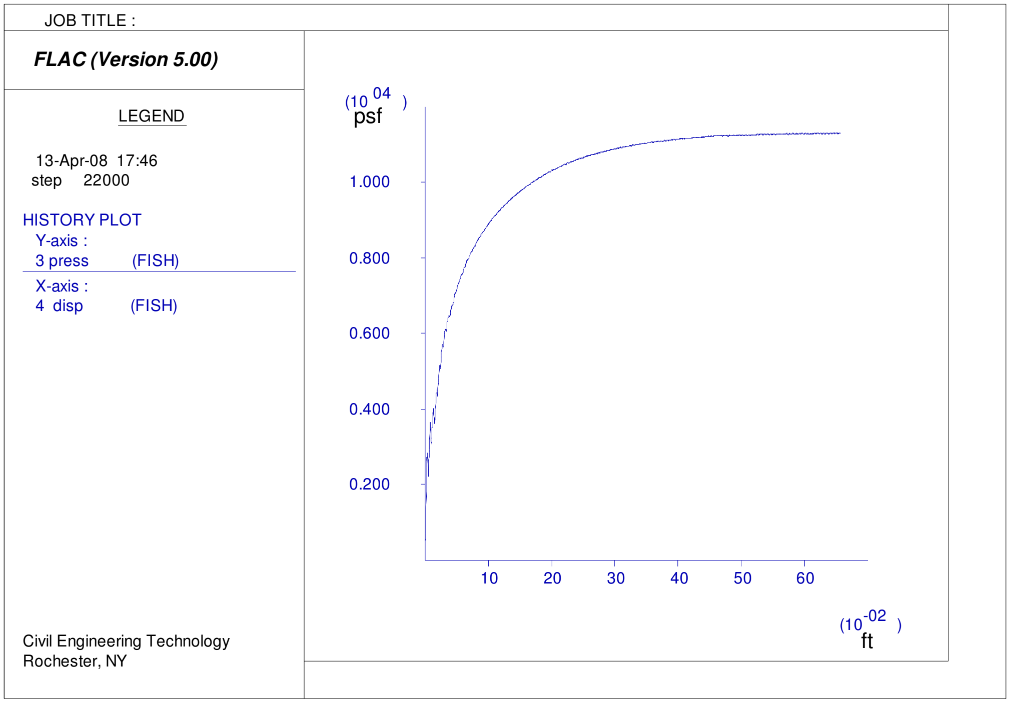


Figure 4 – Footing Bearing Pressure versus Displacement

Two-tailed t-tests performed between the mean question scores of the experimental group on the hour exam and control group on the final exam gave a t-value of 1.636 indicating a significant difference for a probability of 95 percent (minimum value of 1.614 was needed). However, one potential issue with using the t-test for a statistical comparison of this data is the bearing capacity question scores for both groups did not fit a traditional normal distribution due to the high number of students who scored 100 percent on the examination question. Therefore, a Mann-Whitney U test was also performed between the two sets of scores, which both had distributions that were similar in shape. The two-tailed U test did not indicate a significant difference between the experimental and control group scores for a probability of 95 percent.

Given the difference in outcomes from the t- and U-tests and the fact that the statistical evaluation might be impacted by the large number of students with high scores on the exam question, a comparison was made of the percentage of students scoring above certain threshold values. Table 3 presents the percentage of the experimental and control group students who scored 100 percent, over 90 percent, and over 85 percent, respectively, on the bearing capacity

Table 3 – Performance on Bearing Capacity Question for Footing on Layered Soil

Grade Achieved on Question	Percentage of Group	
	Experimental	Control
100%	63	52
90 – 100%	77	58
85 – 100%	88	68

exam question. As seen from the table, the percentages of experimental group students in these respective grade ranges were 11, 19, and 20 percent higher than the control group. Overall, the data indicates the experimental group performed better than the control group.

Other than the use of FLAC, there was one other difference between the bearing capacity of footings homework completed by the experimental and control groups that should be noted. Unlike the experimental group, the control group was not assigned a homework problem for a footing on a layered soil deposit. However, both groups worked on this type of problem in lecture and the detailed solution was then provided and thoroughly reviewed before the footing homework was given. In addition, the performance of the experimental group for the footing question on their hour-long exam was better than that of the control group on their final examination question even though prior to the final exam the control group had already seen that problem on their hour-long exam, the solution to the exam problem was reviewed and posted, and they were informed a similar problem would likely be on the final exam. Therefore a significant part of the improvement in the performance between the experimental and control groups on the bearing capacity exam question appears attributable to the use of the FLAC analyses in conjunction with the traditional manual computations.

Subjective, quantitative feedback from students in the experimental group on the use of FLAC for the bearing capacity of footing homework is provided in Table 4, where student responses to

Table 4 – Survey Results for FLAC Analysis of Footing

Survey Statement	Number of Students Selecting Likert Rating 1 – 5*					Mean Rating
	1	2	3	4	5	
1. User Instruction's provided clear explanation of FLAC grid being used.	0	0	4	20	3	3.96
2. User Instruction's were clear and easy to follow for running FLAC files.	0	0	4	17	6	4.07
3. Graphics of grid displacements clearly illustrated soil movements around failed footing.	0	2	5	18	2	3.74
4. Graphics improved my visualization of soil movements around failed footing.	0	1	10	15	1	3.59
5. Comparing FLAC and bearing capacity equation results helped me understand importance of depth factor.	0	3	6	14	4	3.70
6. Comparing FLAC and bearing capacity equation results reinforced my use of bearing capacity equation for layered soils.	0	2	6	18	1	3.67
7. Plot of footing bearing pressure vs. displacement helped me understand change in footing displacement rate.	0	1	10	16	0	3.56

*Note: In rating system 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree survey statements are provided. For each statement students were asked to respond using a Likert scale rating of 1 to 5, where 1 is strongly disagree, 2 is disagree, 3 is neutral, 4 is agree, and 5 is strongly agree. Twenty-seven of the 43 students in the class completed the voluntary survey. As seen from the table the mean ratings for statements 1 and 2, regarding the instructions provided about the use of FLAC for the footing problem, are close to 4 indicating students agree that the instructions were clear and easy to follow. Mean ratings of 3.74 and 3.59 obtained for statements 3 and 4, respectively, show that students somewhat agree that the graphics provided by FLAC of soil and footing movements at failure were clear and helpful for visualizing the movements. The mean ratings of about 3.70 for statements 5 and 6 indicate that students somewhat agree that comparing FLAC and their manual calculations was useful for understanding the importance of the depth factor and reinforcing their confidence in regards to manually calculating the ultimate bearing capacity for a footing in layered soil. Plotting the footing bearing pressure versus displacement was somewhat useful in helping students understand footing displacement rates up to failure, based on the mean response of 3.56 to statement 7. Overall, the response of students to the software is on the positive side.

Load Capacity of Pile Problem

Both the experimental and control groups in this study completed pile load capacity homework problems using manual computations based on the static pile capacity equation. These problems included axially-loaded piles installed in uniform and layered soil deposits. The experimental group also analyzed the ultimate axial pile capacity for three additional cases using both hand calculations and FLAC. The three cases involved a 30-foot-long steel pipe pile installed respectively in uniform medium clay having a cohesion of 750 psf, uniform medium-dense sand having a friction angle of 36 degrees, and a layered stratigraphy with 20 feet of medium clay (cohesion of 750 psf) underlain by medium-dense sand (friction angle of 36 degrees), as shown in the elevation view in Figure 5. The pipe pile was 12 inches in diameter and closed at the

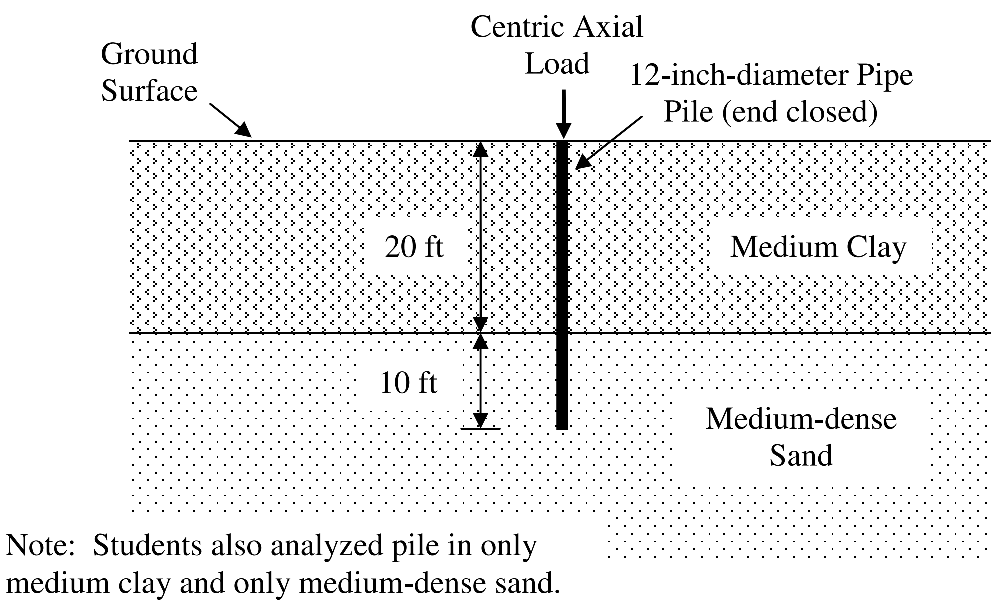
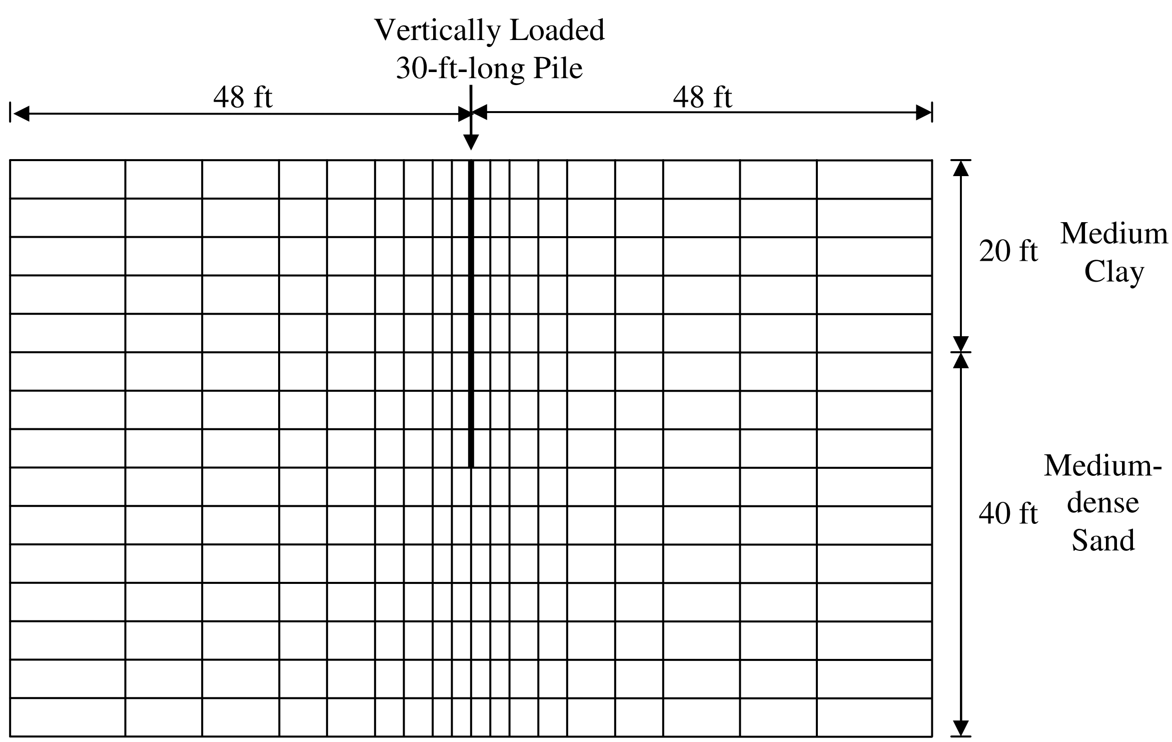


Figure 5 – Load Capacity of Pile Problem

bottom with a plate. When manually calculating the ultimate pile capacity for the three cases using the static pile capacity formula, which includes terms for both skin friction and end bearing capacities, the experimental group students used the alpha factor approach for obtaining the skin friction in clay and were told what friction angle and lateral earth pressure coefficient to use for determining the skin friction in sand. In addition, they were instructed to use the critical depth approach for limiting the end bearing and skin friction capacity in the sand. These analysis approaches were the same ones taught to and used by the control group.

The experimental group students were provided with the data files needed to run FLAC analyses for the three additional pile cases that they analyzed manually. The FLAC grid used in these analyses is shown in Figure 6. Unlike the FLAC analyses of the spread footing, the pile analyses required some pile-capacity-related factors to be input in addition to the material properties of the soil itself. Stiffness factors were input to relate the development of skin friction and end bearing capacity with displacement of the pile. Additionally, limiting values for the skin friction and end bearing capacity were provided to define failure limits. These factors are given in Table 5 and were based on skin friction and end bearing capacities obtained from theory along with the expected pile displacements needed to develop full skin friction and end bearing. Unlike the spread footing analyses, the FLAC analyses for the pile are not completely independent of the



Note: Students also analyzed pile in only medium clay and only medium-dense sand.

Figure 6 – FLAC Grid for Pile Problem

Table 5 – Soil Properties Used in FLAC Analysis of Pile

Soil Property	Soil Type	
	Medium Clay	Medium-dense Sand
Cohesion (psf)	750	0
Friction angle (degrees)	0	36
Dilation angle (degrees)	0	3
Shear modulus (psf)	1.55×10^5	3.88×10^5
Bulk modulus (psf)	15.0×10^5	8.4×10^5
Unit weight (pcf)	115	115
Skin friction capacity (lbs/ft)	2121	2022*
Skin friction stiffness (psf)	1.70×10^5	1.62×10^5
End bearing capacity (lbs)	5.30×10^3	65.0×10^3
End bearing stiffness (lbs/ft)	6.36×10^5	78.0×10^5

*Note: Skin friction capacity given for sand is for depth of 12 ft and below. Value varies linearly from 0 lbs/ft at 0 ft depth to 2022 lbs/ft at 12 ft depth

manual computations performed by students because the additional factors input in FLAC for the pile were determined from the same equations and theory used for the hand calculations. Nonetheless FLAC analyses of the piles should still provide students with some insight into the behavior of piles subjected to axial load, as well as a means to check their manual computations and reinforce their confidence.

For each pile case that the experimental group students evaluated with FLAC, the pile was loaded until a displacement of 0.96 inches was achieved and the axial load required to produce that displacement was obtained. These results were then used with the results of FLAC analyses for other pile displacements, which were provided to the students, to produce the pile axial load versus settlement curves shown in Figure 7. From the pile load-settlement curves the students determined the ultimate pile capacities from FLAC and compared them to the results of their manual computations, as shown in Table 6. The capacities obtained from FLAC for the pile in sand only and pile in clay over sand are about 20 to 25 percent higher than those obtained from the hand calculations because the end bearing of the pile tip was modeled in FLAC using equivalent skin friction capacity on an extra pile segment added at the bottom. Students were informed to expect this difference in results and that it was possible to improve the modeling of the end bearing in FLAC with a different approach.

Besides comparing the pile capacities from FLAC to their hand calculations, students used FLAC to develop axial load distribution plots showing the axial load capacity developed along different sections of the pile for each of the three cases evaluated. Based on the load-settlement curves in Figure 7 and the plots of load distribution along the pile length for the three cases, students identified the soil layer that provided most of the capacity for the pile in the clay over

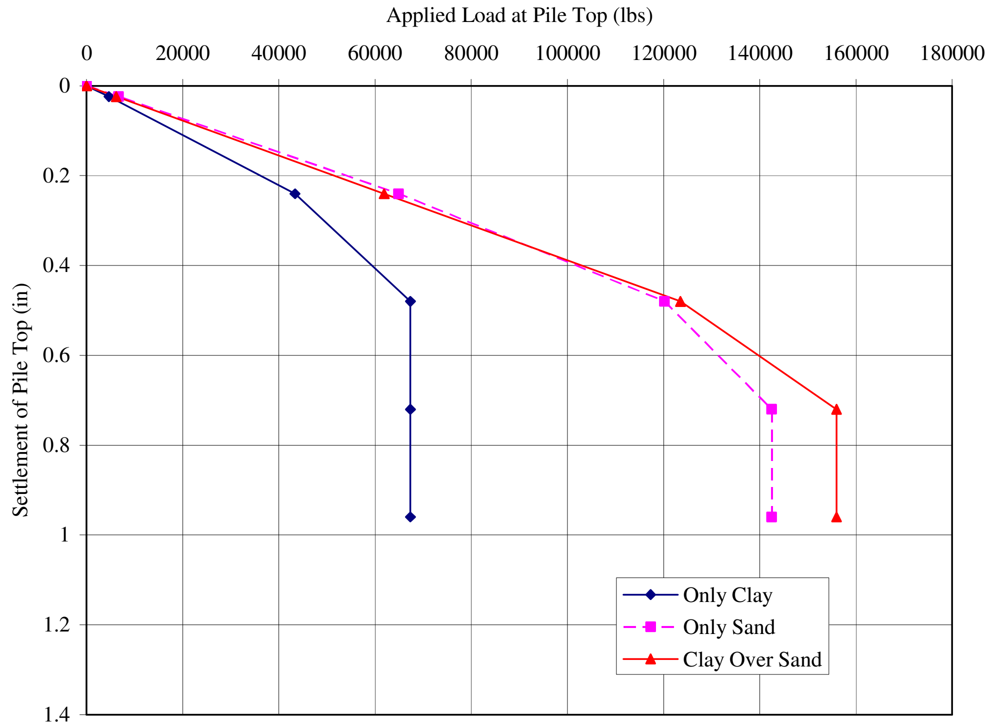


Figure 7 – Pile Load vs. Settlement Curves from FLAC Analyses

Table 6 – Ultimate Axial Pile Capacity from Different Analysis Methods

Analysis Method	Ultimate Axial Pile Capacity (lbs)		
	Medium Clay Only	Medium-dense Sand Only	Medium Clay over Medium-dense Sand
Static pile capacity equation	68.9×10^3	113.5×10^3	127.6×10^3
FLAC simulation	67.4×10^3	142.5×10^3	156.0×10^3

sand case and explained why that layer governed the capacity. As expected for the layered case, the sand governed the pile capacity due to the high end bearing developed in it.

The impact of the FLAC analyses on enhancing and strengthening student comprehension and use of the static pile capacity formula and theory was checked by comparing the performance of the experimental and control groups, who respectively did and did not use the software, on an open-book examination question. The question involved manual computation of the ultimate axial load capacity of a pile in a layered soil deposit similar to the one shown in Figure 5. Both groups were given this type of question on a one-hour-long examination, as well as a similar question on the two-hour final exam. The mean percentage (out of 100 percent) score of the experimental group on the question was 79.7 and 79.8 on the hour-long and final exams, respectively. For the control group the mean score on the hour exam question was not available because their exams were previously returned, but it was lower than the 74.6 percent mean they achieved on the final exam question.

A two-tailed t-test performed between the mean scores of the experimental and control groups on the final exam question gave a t-value of 1.544, which does not indicate a significant difference for a probability of 95 percent (minimum value of 1.614 was needed). The difference in the scores is significant for a probability of 90 percent, which has a minimum required t-value of 1.292. Since the mean question score on the hour exam for the control group was likely lower than the final exam, it is possible that there was a significant difference between the control and experimental groups on the pile capacity question given on the hour exam, even when using a probability of 95 percent.

Another useful comparison for showing the impact of FLAC on student learning regarding pile capacity in a layered soil deposit is the percentage of students who scored above certain threshold values on the final exam question. Table 7 presents the percentage of the experimental and control group students who scored 100 percent, over 90 percent, and over 80 percent, respectively, on the question. A slightly larger percentage of the control group scored 100 percent on the question in comparison to the experimental group. However, the percentage of experimental group students who scored over 90 percent and 80 percent were respectively 8 and 14 percent higher than the control group. Overall, the data indicates the experimental group students who used FLAC in conjunction with manual computations performed better than the control group.

Subjective, quantitative feedback from students in the experimental group on the use of FLAC for the pile capacity homework was obtained through a survey similar to the one given for the spread footing homework. A summary of student responses to survey statements using a Likert scale rating of 1 to 5 is provided in Table 8. Thirteen of the 43 students in the class completed the voluntary survey. Mean ratings of 3.54 and 3.69 for statements 1 and 2 indicate some agreement among students that the instructions provided clearly explained the FLAC grid and were clear and easy to follow. Likewise, the mean ratings of 3.42 to 3.54 for statements 3 through 6 indicate students somewhat agreed that plotting FLAC results and comparing them

Table 7 – Performance on Pile Capacity Question for Pile in Layered Soil

Grade Achieved on Question	Percentage of Group	
	Experimental	Control
100%	5	8
90 – 100%	30	22
80 – 100%	56	42

Table 8 – Survey Results for FLAC Analysis of Pile

Survey Statement	Number of Students Selecting Likert Rating 1 – 5*					Mean Rating
	1	2	3	4	5	
1. User Instruction's provided clear explanation of FLAC grid being used.	0	2	2	9	0	3.54
2. User Instruction's were clear and easy to follow for running FLAC files.	0	1	2	10	0	3.69
3. Plotting the pile axial load vs. settlement results from FLAC analyses helped me better understand load-settlement behavior.	0	1	5.5	6.5	0	3.42
4. Comparing FLAC results to my static pile capacity calculations for uniform soil made me more confident in my calculations.	0	1	4	8	0	3.54
5. Comparing FLAC results to my static pile capacity calculations for layered soil made me more confident in my calculations.	0	1	5	7	0	3.46
6. Comparing FLAC results for a pile in only clay, only sand, and clay over sand helped me understand the impact of layering on pile capacity.	0	0	7	6	0	3.46

*Note: In rating system 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree.

to manual pile capacity calculations was helpful for their understanding and confidence in relation to pile capacity determination and behavior.

The ratings given in Table 8 regarding using FLAC to learn about pile capacity are slightly lower than the ratings given in Table 4 for using FLAC to learn about bearing capacity of a spread footing. The lower rating for piles may be partly related to the 25 percent discrepancy between the pile capacities obtained from FLAC versus manual computations and could indicate the need to improve the way end bearing was modeled in FLAC. The difference in the ratings may also show the need to improve the plots and data from FLAC that are reviewed and evaluated by the students for the pile problems. Overall, the student ratings still indicate a somewhat positive response regarding the use of FLAC for learning about pile capacity and behavior.

Student Comments on FLAC

The surveys given to students regarding their use of FLAC for spread footing and pile analyses solicited written comments regarding things that they liked or did not like about using the software. Comments received regarding things that students liked about FLAC included:

- It was easy to use and the directions provided were easy to follow;
- Modeling, visuals, and graphics in the program were useful; and
- It provided a basis for checking manual calculations.

Things that some students didn't like included:

- Plots did not have clear labeling;
- It was difficult to understand what the program was doing and why;
- Program was not user friendly and was DOS based; and
- Not enough explanation was provided regarding the program.

One lesson learned from these comments is the need to spend sufficient time explaining the computer software before it is used. Due to time constraints roughly five to ten minutes of explanation was provided to students in lecture about using FLAC for the spread footing analysis, and then another five to ten minutes for the pile analysis. Even though a detailed written explanation of FLAC was provided to students for review before they used it, an additional ten minutes of lecture time spent explaining each case, as well as reinforcing the basic concepts behind the program, would help students better understand what the program does.

Conclusions

The results of this study support the hypothesis that FLAC computer simulations are an effective means for civil engineering students to check their hand calculations of spread footing and pile load capacities and this use strengthens and enhances their understanding of footing and pile behavior and improves their ability to correctly calculate the load-carrying capacity of these foundations, particularly in layered soil deposits. Although the gains in computational abilities and comprehension appear to be modest, improvements in the use of the software could result in additional gains.

Overall, student response to the use of FLAC is somewhat positive. An increase in positive responses of students to the software might be achieved by improving the manner in which it is presented and used. When selecting and using more advanced software, such as FLAC, in an undergraduate civil engineering course, the factors listed below should be considered and addressed, if possible.

- Students need to understand the basics of how the software functions even if the purpose is not to make them proficient users of the program.
- High-end user interfaces and graphics are expected in software by today's student and this expectation should be met when possible.
- It is important to schedule sufficient class time to review basic background information about the software with students because they may not necessarily read the written information provided to them.

Results from this study support the idea that advanced computer modeling tools, such as FLAC, can reinforce and improve students' understanding and manual computational abilities for design of engineering system components.

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