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# The Role of Finite Elements in Suction Foundation Design Analysis

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## Abstract

Suction foundations (that is, foundations using piles, skirted compartments, or caisson units installed by or with the aid of suction pressure) are finding increased use in offshore foundations for deep water. Finite element analysis provides a powerful solution technique for solving complex mechanics problems from a fundamental approach without need for many simplifying assumptions. This paper explains the role of finite element analysis in the analysis and design of suction foundations for offshore production and exploration systems.

Suction foundation units have markedly different dimensions and relative geometries than traditional offshore foundation units. Accordingly many of the “ad hoc” assumptions employed in customary offshore foundation design and analysis methods may not be applicable or productive, and more sophisticated design analysis methods can be beneficial. The finite element method both enables freedom from undesired assumptions and provides guidance and justification for proper formulation of simplifying assumptions.

Among the aspects of suction foundation performance that have been investigated via the finite element approach include:

- The significance of interaction between vertical and horizontal components of capacity,
- Effects of separation of the soil from the trailing side of the pile or caisson,
- Sensitivity of foundation performance to skin friction conditions,
- Sensitivity of foundation performance to load point location.

Proper attention to details such as these via finite element analysis of suction foundation designs can help to avoid costly overdesign without incurring undue risk.

## General

The finite element method is experiencing increased use in offshore foundation engineering. This increase is mostly in connection with suction foundations for deep water applications. The most common applications of the method have been to provide insight into foundation design parameter selection through elucidating performance phenomena (e.g. Sparrevik (2002)), to perform parametric studies (e.g. Zdravkovic et al. (2001)) and to provide benchmarks for results of either other calculation methods (e.g., Randolph and House (2002)) or centrifuge testing (e.g. Clukey and Morrison (1993)). Through applications like these, finite element analysis can help to reduce uncertainty in the design process by providing highly accurate solutions to complex foundation problems.

The finite element method is a technique for solution of mathematical problems governed by systems of partial differential equations. It can produce close approximate solutions to problems with highly complex geometries, material behaviors and boundaries which would result in highly complex feildwise variations in the solution variables. The method accomplishes this by subdividing the solution space into many pieces (the finite elements) sufficiently small that the variations in the solution variables can be well approximated within each by very simple functions. Implementation of the method numerically on modern digital computers enables highly accurate solutions with extremely large numbers of small elements. All of the governing equations are then solved on all of the elements, and the elemental solutions are assembled into the solution for the whole, subject to compatibility and continuity requirements.

The method is particularly well suited to problems in solid mechanics because the element formulations are most straightforward when the boundaries of the elements represent material surfaces. In this application, the governing equations are laws of classical mechanics and assumptions of continuum mechanics (including constitutive relations for material behavior), and complete problems are posed by adding to these the specification of material properties, loads and boundary conditions. The method is especially attractive for soil mechanics applications because soils have much more complex material behavior than most other materials, and other available solution methods usually require more restrictive material behavior assumptions. With respect to the true solution to a properly posed boundary value problem in solid mechanics, taken as an ideal, one can generally obtain a finite element solution that is as close to the ideal as is desired, so long as one can work the problem within program capabilities and pay the required attention to minimizing the unavoidable errors.

In modern finite element programs, all of the governing equations are usually solved exactly, with the exception of nonlinear material behavior and equilibrium. Errors associated with approximation of nonlinear material behavior are normally minimized within the program by iteration subject to very strict criteria. The analyst, then, can generally obtain a solution of any desired accuracy by ensuring proper specification of geometry, location and conditions for loads and boundary conditions, material behavior and properties and by minimizing equilibrium errors.

The most fundamental source of equilibrium error in a finite element solution is the fact that equilibrium is enforced only in a weak form - over each element as a whole rather than at every point in the solution space. In a linear analysis, this source of error causes the model to be too stiff; that is, loads will be too high at any particular displacement. In a nonlinear analysis, the results will typically be too strong; e.g., ultimate capacities will be too high. However, in models with disparate redundant load paths, this source of error can result in unrealistically low capacity if the stiffening effect transfers load to a path of inherent weakness. The size of this error depends on the fineness of the mesh and upon the element formulation. For any particular choice of element type, the finer the mesh, the smaller this error. This error can always be reduced by making the mesh finer, particularly in areas of high gradients in the solution, but there are practical limits of cost, schedule and resources. This error can also be reduced, for some problems, by employment of element types that incorporate higher order displacement functions. The analyst can test relative performance of various element types available, choose the most economical adequately performing element and ultimately qualify the mesh fineness by demonstrating insensitivity of results to model change to a mesh that is finer than necessary, either globally or in targeted regions. The type of equilibrium error discussed so far is inherent to the finite element approximation; that is, even an exact solution to the defined finite element problem has this error with respect to the exact solution for the underlying continuum problem. In a linear analysis this inherent equilibrium error is typically the only type of equilibrium error encountered because a linear finite element problem can be solved exactly.

In a nonlinear analysis, the nonlinear nature of the governing equations usually necessitates an approximation in the solution of the finite element problem itself. The result of this is an equilibrium error associated with an imbalance of residual forces at the nodes. The nodes are the points in solution space at which continuity between elements is enforced, and equilibrium requires a balance of internal and external forces at each and every node. This solution equilibrium error can be minimized by minimizing the increment size in an incremental solution and/or by taking an iterative approach to the achievement of acceptable solution for each increment. Without iteration, the analyst should inspect the errors of this type as reported by the program and either accept them or rerun the analysis with smaller increments. With an iterative solution technique, the user can specify a tolerance on solution error, and the program will iterate until the tolerance is satisfied or end for inability to achieve a satisfactory solution.

With only moderate attention to these solution accuracy details, finite element results may often be achieved with errors of 15% or 20%. Such errors may be acceptable in a situation where there is no important engineering consequence of such levels or when sufficient conservatism can be applied to cover the uncertainty. In critical applications, on the other hand, the errors in finite element analysis results can be reduced to truly insignificant levels through sufficient attention to error minimization.

## Examples

In the following, results are presented from finite element analyses of the foundation performance of suction piles and caissons. Figure 1 shows the typical configuration for the finite element mesh used. Both the pile and caisson cases involved applications as mooring anchors. The only significant distinction between pile and caisson was relative geometry. The ratio of embedded length to diameter was 5-to-1 in the case of the pile and 2-to-1 in the case of the caisson. Using mesh configurations such as shown in figure 1, solution accuracy was explored with both first order and second order element types and with model sizes ranging form approximately 8,000 to over 30,000 degrees of freedom. With relatively uniform element sizes, at least 13,000 degrees of freedom were generally required for achievement of accurate results, but with significant mesh refinement in the areas of high solution gradients, 8,000 degrees of freedom were often sufficient.

Both the pile and the caisson cases were analyzed for soil strength profiles having small but finite strength at the mudline and linear increase of strength with depth representative of common offshore normally consolidated clay sites. Other common characteristics of the analyses for both cases included the following:

- Total stress analyses simulating undrained conditions were performed.
- This soil was modeled as an elastic-plastic material. Analyses were performed both for elastic-perfectly plastic

assumptions and for a work-hardening material with an approximately hyperbolic stress-strain relationship achieving a maximum strength at 7% (axial) strain. A distinctly different maximum shear strength was assigned to each modeled soil layer, according to the prescribed linear strength profile. The plastic yield function used had a Mises criterion in the pi plane. The effects of stress space anisotropy were studied parametrically.

- The soil inside of the pile was modeled, as well as that on the outside. A no-slip condition was taken between the inside surface of the caisson and the adjacent soil. This approximated the condition of the suction above the soil plug being sufficient to prevent slip at the inside caisson surface. Friction assumptions on the outside pile surface were varied from a (frictionless) slip condition to a tied (no slip) condition.
- Analyses were performed both for small deformation and large deformation assumptions. The use of large deformation assumptions enabled correct solutions in regard to large strain effects, large rotation effects and the effects of large displacements, such as load point movement.
- Neither the weight of the soil nor the weight of the caisson was modeled specifically.

The suction pile modeled was a 60-ft long by 12-ft diameter pile in normally consolidated clay conditions common to the Gulf of Mexico. The pile was loaded as a mooring anchor with a load attachment point at a 40-m penetration and at a load elevation angle of 26 degrees. This case was chosen to correspond to the Straw Problem of the Offshore Technology Research Center's 2001 Suction Foundation workshop. Other specific details of the problem were taken from Gilbert and Murff (2001).

This pile problem was solved using two different commercial finite element computer programs. Figure 2 shows load vs. displacement results obtained with Program A. This figure presents comparisons showing the sensitivity of results to mesh size and element selection and to the nature and location of boundary conditions. Results for cases with and without the use of infinite elements at the outside soil boundaries were virtually identical. Very nearly the same results were obtained using an 8,000-degree of freedom mesh of first order elements and a 30,000-degree of freedom mesh of second order elements. The agreement obtained indicates that the smaller mesh is satisfactory in this case.

Figure 3 presents a comparison of results obtained with Program A and Program B for both small deformation and large deformation assumptions. The same mesh and soil properties were used with both programs, but the material behavior convergence tolerances and strategies, the nonlinear solution equilibrium criteria and strategies, the incrementation and the theoretical approaches to incorporating large deformation effects are all entirely different. The remarkable agreement between the solutions from the two programs indicates that these solutions are all highly accurate in regard to material nonlinearity approximation errors, to nonlinear solution equilibrium errors and also to errors due to approximations in the large deformation solution strategies.

Also shown on figure 3 is the capacity adjusted form the Workshop solution for this problem. The unfactored Workshop solution (Gilbert and Murff (2001)) was adjusted to eliminate pile and soil weights, take an end bearing capacity factor of 9.0 and assume capacity is primarily limited by axial rather than lateral performance. The level of agreement of the finite element solution limit loads with this calculated capacity is comforting, but it should probably be regarded as a fortuitous result of the combination of the effects of various differences in problem assumptions.

The purpose of the analyses performed for the caisson was to determine expected sensitivity of the caisson performance to the location of the load attachment point and to possible variations in the external skin friction, all for a load elevation angle of 38 degrees. All of the analyses for this study were performed using Program A with a 13,000-degree of freedom mesh, first order elements, infinite elements at the soil outside boundaries and large deformation assumptions.

The results for load vs. displacement performance of the caisson were sensitive to both the anchor point penetration and the assumed friction condition on the caisson's outer surface. The most favorable friction assumption increased capacity by approximately 25%. This modeling assumption is related to the degree of post-installation set-up, a parameter that often cannot be predicted accurately. Capacity was less sensitive to variations in the penetration of the anchor attachment point. With no friction on the caisson outer surface, an anchor point attachment at a penetration 58.5% of the caisson penetration produced the greatest capacity, but anchor point penetrations ranging from 50% to 69% of the caisson penetration produced capacities within 2% of that maximum.

Figures 4 through 7 present plots of plastic strain contours at pullout for the four analyses with various anchor attachment point penetrations, with the slip (no friction) condition on the caisson outer surface. The contour plots are all presented on deformed mesh plots that clearly display the patterns of displacement for both the caisson and the soil. The plastic strain variable contoured in these plots is the magnitude of plastic strain, a scalar invariant of plastic strain that is conjugate to the Mises stress. The value of this plastic strain variable indicates the severity of plastic deformation at any location, and its contour plots show the spatial distribution of the extent of soil yielding. Figure 4 shows the plastic strain contours for the case of the shallowest anchor attachment point penetration (40% of the embedded length). In this case, the axis of the caisson tilts significantly toward the anchor load line, and the greatest soil yielding is concentrated in the weaker soils near the mudline. Figure 5 shows the contours for the case of the anchor attachment point at a penetration of 50% of the embedded length. In this case, there is little caisson tilt, and the soil yielding is distributed rather uniformly along the caisson. Figure 6 shows the plastic strain contours for the case of the 58% anchor attachment point penetration. In this case, the axis of the caisson tilts slightly away from the anchor load line, and the greatest soil yielding is concentrated near the bottom of the caisson. Figure 7 shows the plastic strain contours for the case of the 69% anchor attachment point penetration. In this case, the axis of the caisson tilts significantly away from the anchor load line. The greatest soil yielding in this case is concentrated near the bottom of the caisson, but there is also a region of significant soil yielding near the mudline, where the soil is resisting the reverse direction displacement of the top of the caisson.

The analyses related to figures 4 through 7 did not allow for soil separation from the caisson; however, some of the results indicate that separation could be promoted. Figure 8 shows similar results for a pile case conducted with allowance for separation and with assumptions to promote maximum separation: loading above the pile midpoint and no beneficial effect of deep-water hydrostatic pressure. The results showed minimal separation, and the effect on capacity was entirely negligible. These results indicate that the common practice of allowing for separation effects by disallowing all lateral reaction on the trailing side of the pile (see Gilbert and Murff (2001)) may by overly conservative.

Collectively these results provide an excellent example of the ability of finite element analysis to elucidate the phenomena, which can occur in suction foundation performance.

## Conclusions

In view of the results and discussions presented it this paper, we conclude that the most important role of finite element analysis in the design of suction pile foundations is one of Enlightenment. By this term reference is made not to the popularly recognized Enlightenment of the 18th century (AD) but rather to that of the fourth and fifth century (AD) philosopher, Augustine of Hippo. Augustine was a student of the philosophy of Plato. According to Cornford (1961), Plato had identified a hierarchy of levels for the accessibility of things and inversely related levels of perfection (in terms of clarity, certainty, truth, etc.). In Plato's hierarchy, the lowest level of perfection is associated with images of (physical) objects, which exist at the highest level of accessibility. Next in the hierarchical order are the objects the themselves followed, in turn, by mathematical objects and (ideal) forms. For Plato, the pursuit of higher and higher levels of perfection in states of mind involved progression of observations through each of these levels from imagination (images) to belief (through observation of objects) to thinking (e.g., mathematics) to knowledge (ideal forms). Augustine (399) realized that just as Plato's observations in the visible world needed to be enabled by Illumination, so also the observations in the intelligible world required a corresponding Enlightenment. If we apply this philosophy to the case of (suction) pile performance, the performance of an actual pile is the physical thing in question. Tests (model or field) of pile performance play the role of the images. An idealized problem in classical solid mechanics is the ideal form, and a mathematical problem with requisite assumptions approximating the mechanics problem completes the set.

Because of it's ability to handle complex details with few restrictive assumptions, the finite element method both allows the consideration of an extremely realistic idealized problem and enables employment of mathematical problems extremely close to the idealized solid mechanics problem. Through these advantages, and through its inherent ability to produce results in forms that graphically elucidate phenomena, the finite element method can provide the Enlightenment necessary for the achievement of very high level of certainty and knowledge in the intelligible world.

Most customary engineering for offshore pile foundations is based on mathematical calculations truthed by checks with empirical data both from successful field experience and from tests of pile performance. Good engineering design always involves the application of a level of conservatism consistent with the level of certainty in the methods and data being applied. In the present connection, this level of certainty is limited by the closeness with which both the empirical situations and the mathematical assumptions can approach the actual pile case. Since currently advocated offshore suction pile foundations are, in both size and function, less closely connected to the relevant empirical data base, the only way that the overall certainty in their foundation engineering can be maintained at a level consistent with customary offshore practice is through the employment of idealizations and mathematical solution methods that reflect reality more closely than do those that have been used traditionally. Finite element analysis can fill this need.

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The analyses ascribed to Program A were preformed with the ABAQUS program from Hibbitt, Karlsson and Sorensen, Inc. The analyses ascribed to Program C were performed with the SAGE CRISP program from SAGE Engineering and the CRISP Consortium, Ltd.

The results presented here for the sensitivity of suction caisson performance to skin friction conditions and to location of the anchor point were developed for use by SAGE Engineering, SA/NV (now Thales Geosolutions (Belgium) SA/NV) in planning a centrifuge test program for the French government's IFREMER in Plouzane. Christophe Jaeck of Thales Geosolutions (Belgium) SA/NV provided useful guidance regarding the productive form of presentation for these results.

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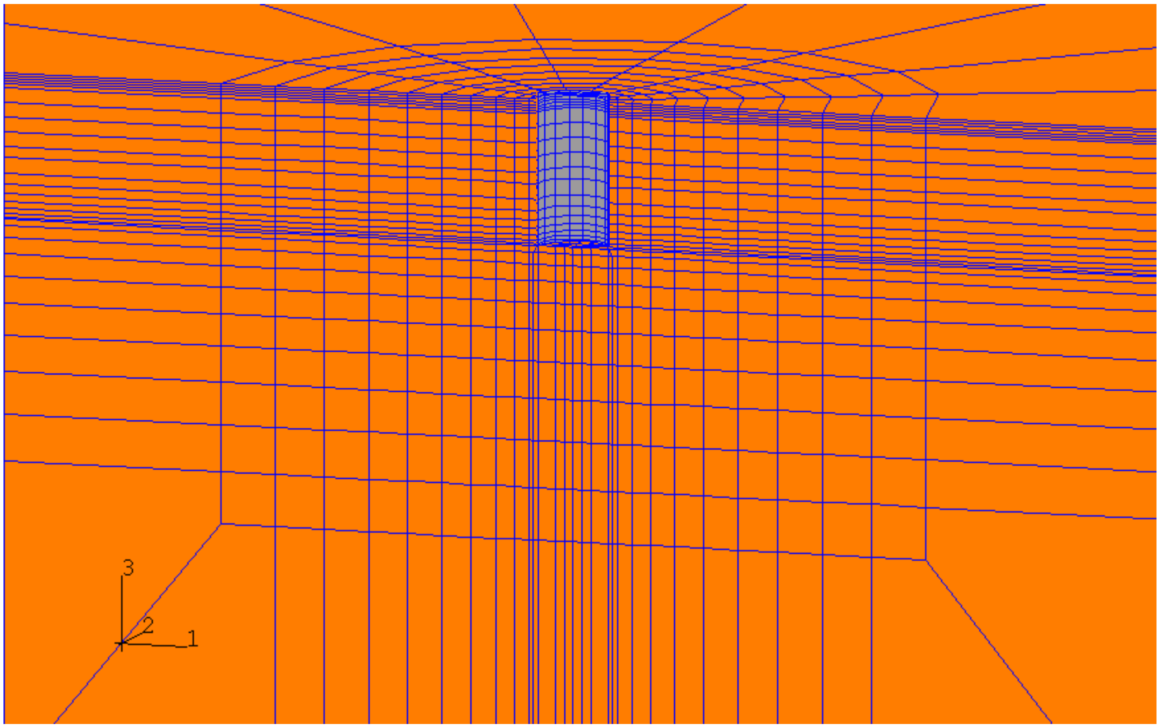


Fig. 1 Finite element mesh for suction pile or caisson

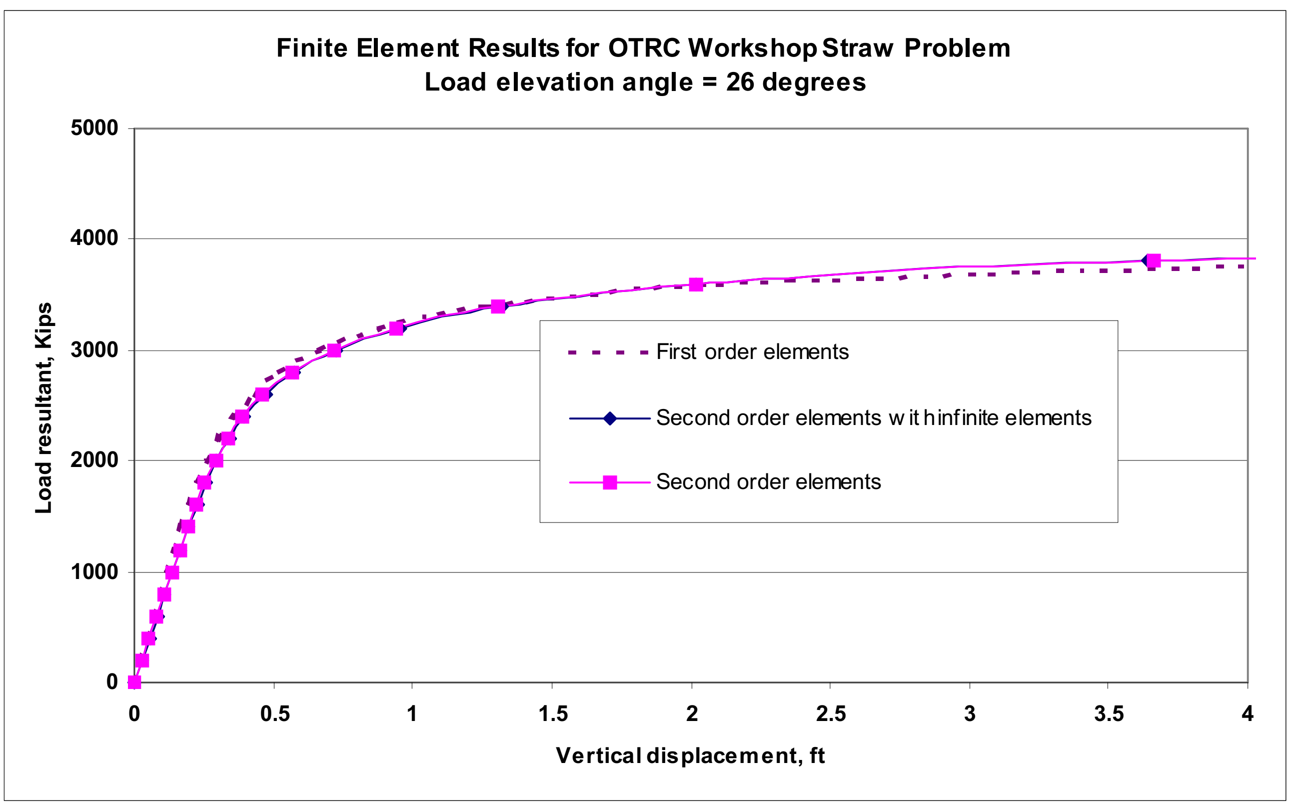


Fig. 2 Program A results for Straw Problem Pile

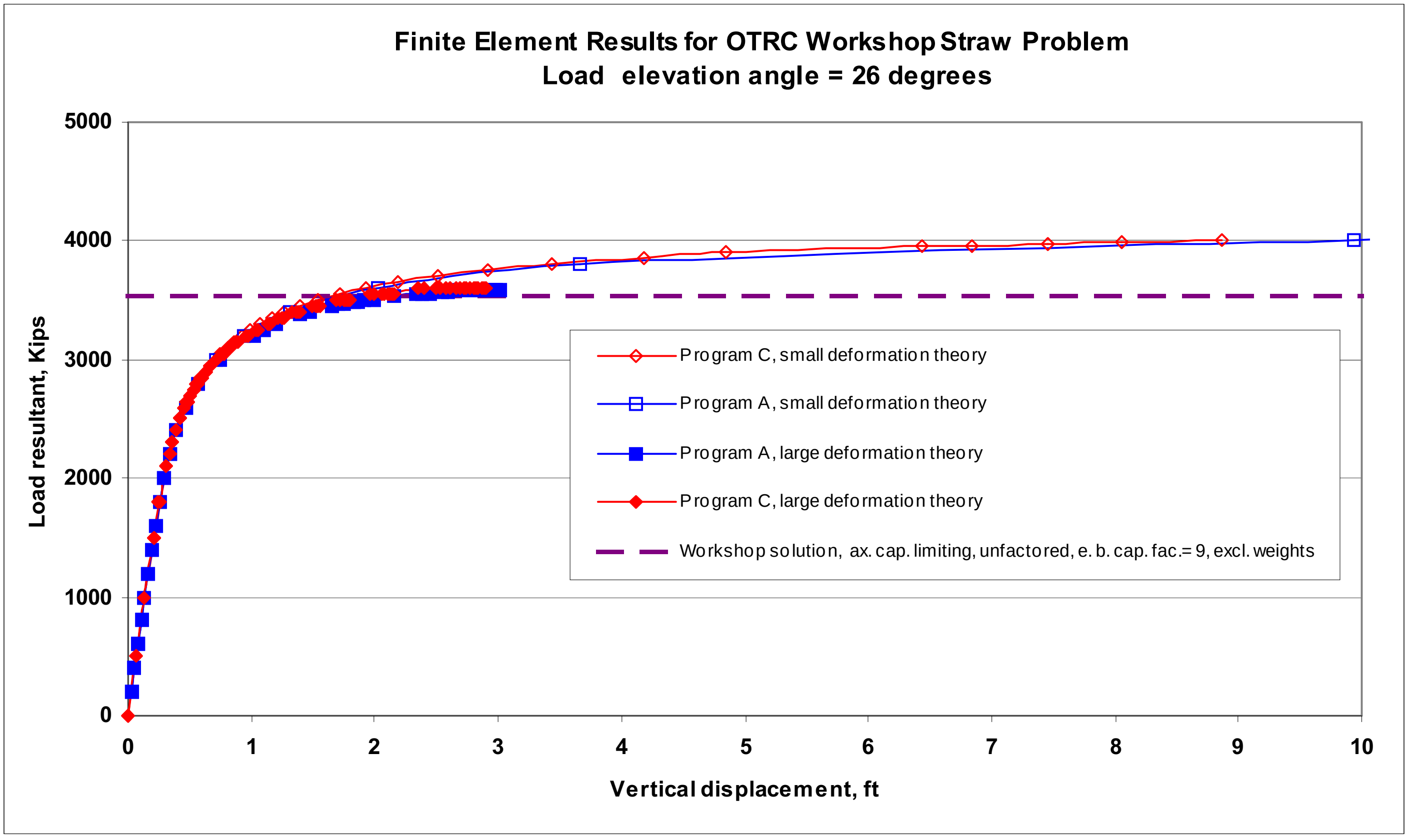


Fig. 3 Program A and Program C results for Straw Problem Pile

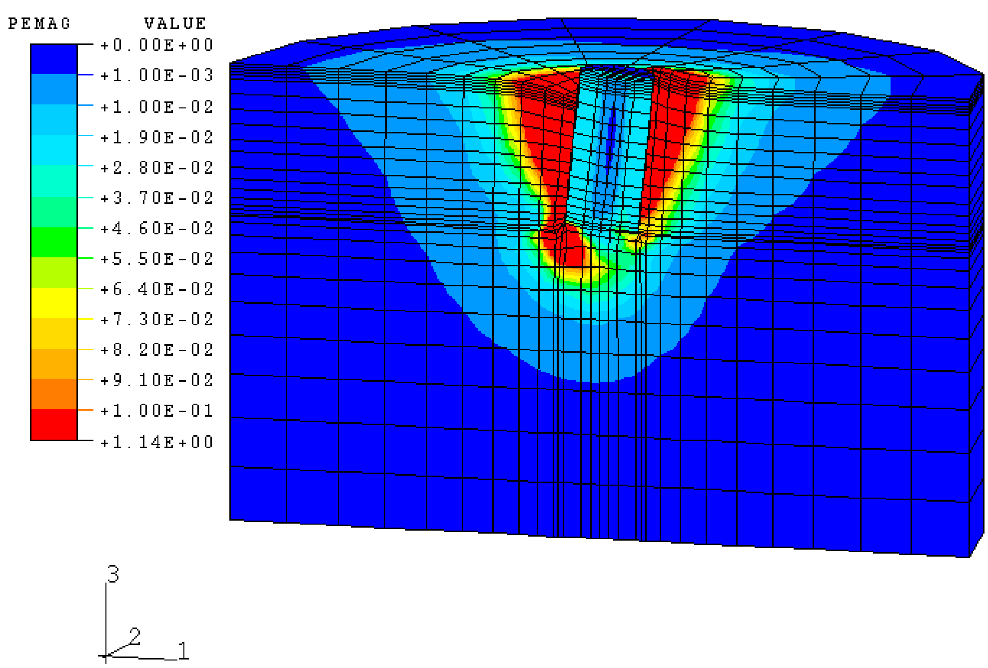


Fig. 4 Plastic strain results, caisson loaded at 40% of penetration

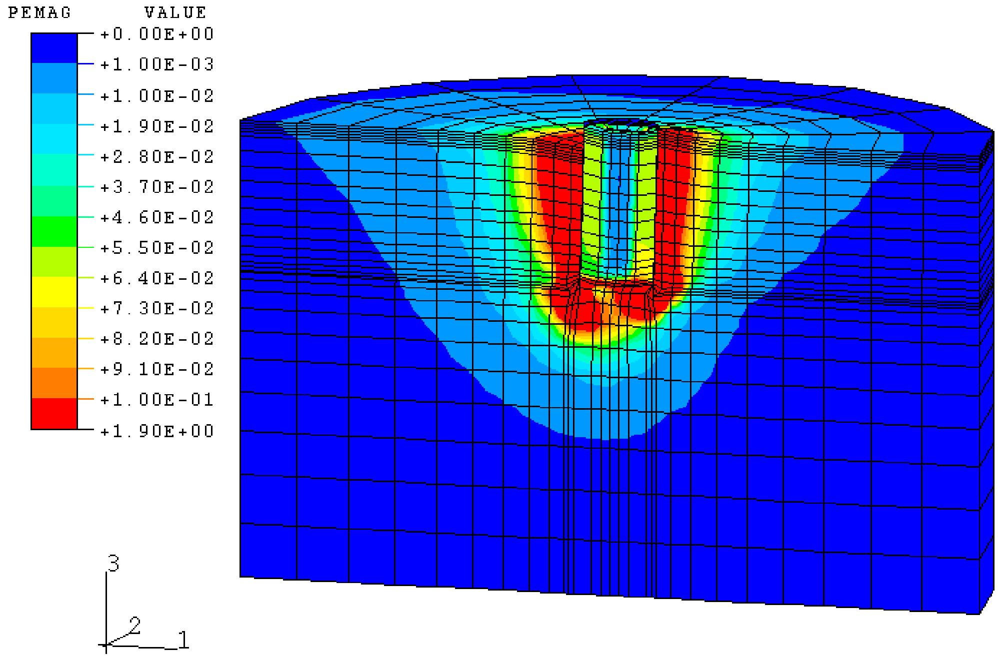


Fig. 5 Plastic strain results, caisson loaded at 50% of penetration

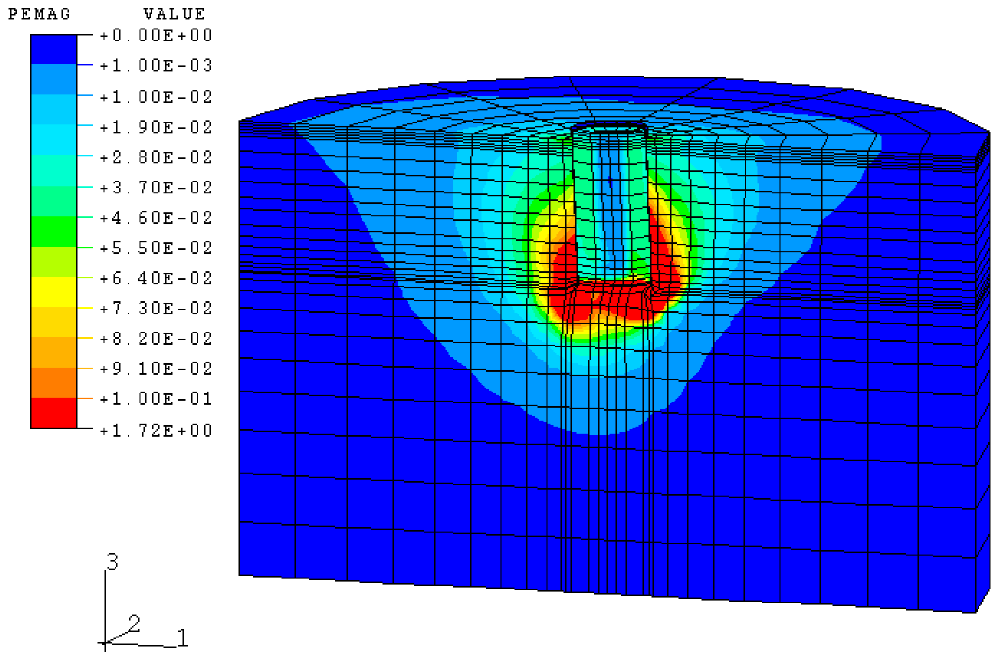


Fig. 6 Plastic strain results, caisson loaded at 58% of penetration

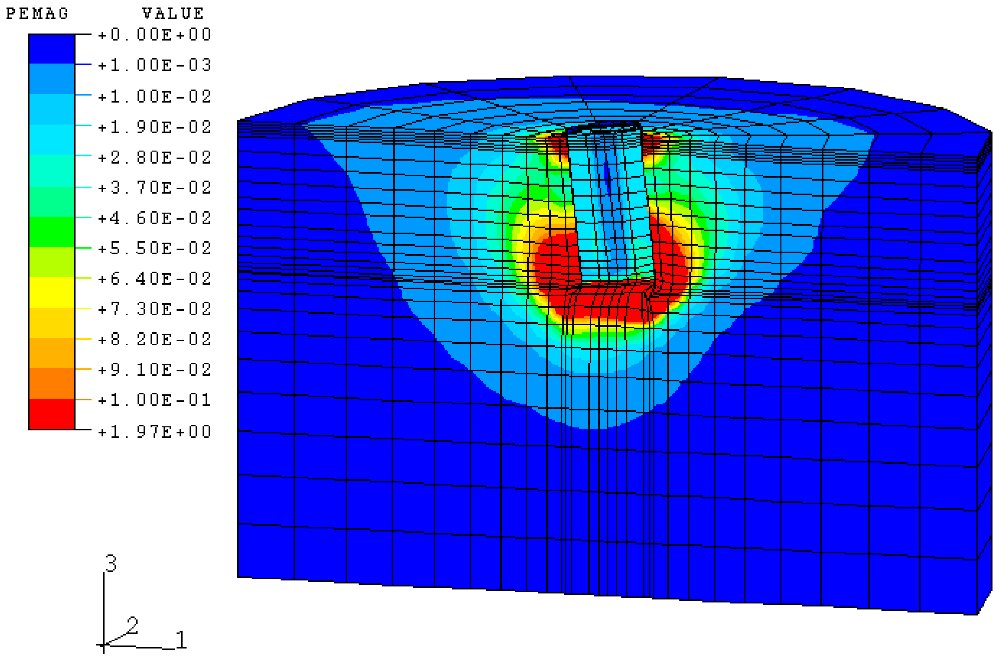


Fig. 7 Plastic strain results, caisson loaded at 69% of penetration

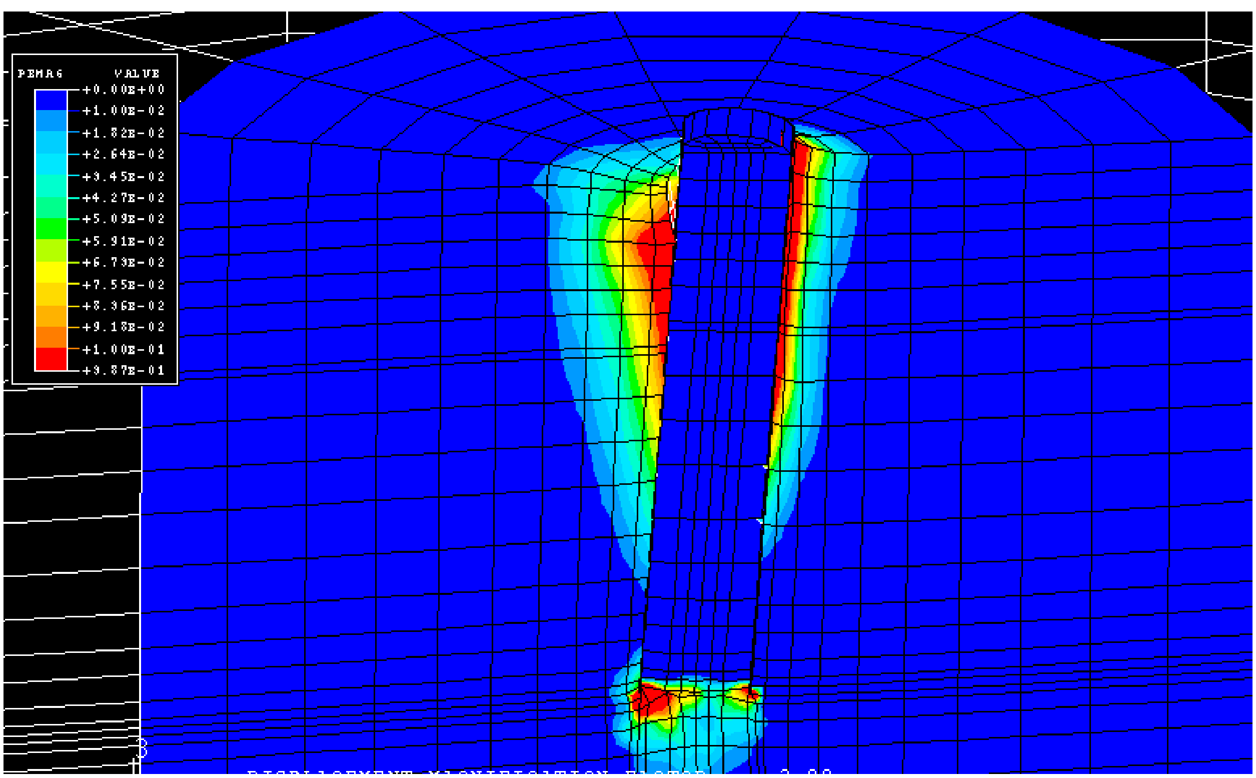


Fig. 8 Plastic strain results, pile loaded above midpoint, with separation