Modernize and Upgrade CANDE for Analysis and LRFD Design of Buried Structures

DETAILS

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AUTHORS

Mark Mlynarski; Michael G Katona; Timothy J McGrath; Transportation Research Board

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Modernize and Upgrade CANDE for Analysis and LRFD Design of Buried Structures

Mark Mlynarski
MICHAEL BAKER JR., INC.
Moon Township, PA

Michael G. Katona
CONSULTANT
Gig Harbor, WA

Timothy J. McGrath
SIMPSON, GUMPERTZ & HEGER, INC.
Waltham, MA

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Mark Mlynarski, Project Manager, Michael Baker Jr., Inc., and Michael G. Katona, Ph.D, were the Co-Principal Investigators. The other authors of this report were Timothy J. McGrath, Ph.D., Senior Principal, and Bryan P. Strohman, Engineer of Simpson, Gumpertz & Heger, Inc.

The work was performed under the general supervision of Mr. Mlynarski and Dr. Katona. The software development work at Michael Baker Jr., Inc. was performed under the supervision of Mr. Mlynarski with the assistance of Joseph Ihnat, Software Systems Developer III, and Sabine Boukamp, Civil Associate II. Dr. Katona was responsible for the revisions and enhancements to the CANDE analysis engine. The work performed at Simpson, Gumpertz & Heger, Inc. was under the supervision of Dr. McGrath with the assistance of Mr. Strohman.

FOREWORD

By David B. Beal
Staff Officer
Transportation Research Board

This report documents research performed to develop, modernize, and upgrade CANDE (Culvert ANalysis and DEsign). The new version is called CANDE-2007. The report details the research performed to update the program. CANDE installation files are included on a CD-ROM with this report. The installed program includes integrated help files and 14 tutorial examples. The report and software will be of immediate interest to culvert designers.

First introduced in 1976 under the sponsorship of FHWA, CANDE is a design and analysis tool for all types and sizes of buried structures. CANDE is widely used by state DOTs, industries, consulting firms, and universities in the United States, Canada, Europe, Africa, and Australia. CANDE provides an elastic solution (Level 1), automated finite element mesh generation for common configurations (Level 2), and a user-defined finite element mesh (Level 3).

The earlier version, CANDE-89, operates in a batch-mode environment. Significant changes have occurred in computer technology since the issuance of CANDE-89, such as Windows®-based programming environments. Moreover, recent NCHRP studies have introduced new design criteria and analysis techniques, which have been incorporated into *AASHTO LRFD Bridge Design Specifications*.

The objective of NCHRP Project 15-28 was to modernize and upgrade CANDE-89. The products of this research are CANDE-2007, a user-friendly Windows®-based, buried structure analysis and load and resistance factor design program; a comprehensive user's manual and system manual; and a tutorial. Enhancements over earlier versions include an updated finite element analysis engine and graphical tools for interpreting the CANDE output. The CANDE analysis solver was enhanced to include an automated bandwidth minimizer, an algorithm for predicting large deformations, and LRFD design methodology. In addition to the solver enhancements, an integrated environment was developed to allow input through a menu-driven Windows® interface, a viewer to plot the finite element mesh geometry and results, an output report generator, a graph viewer to review and plot culvert element responses, and a context-sensitive help system.

This research was performed by Michael Baker Jr., Inc. assisted by Michael G. Katona and Simpson, Gumpertz and Heger Inc. The report fully documents the software development effort leading to CANDE-2007.

CONTENTS

SUMMARY

Modernize and Upgrade CANDE for Analysis and Design of Buried Structures

This report highlights the work accomplished under the AASHTO-sponsored project entitled "Modernize and Upgrade CANDE for Analysis and Design of Buried Structures" administered by the National Cooperative Highway Research Program as NCHRP Project 15-28. The research effort has produced a significantly enhanced version of the original CANDE software with many new analysis capabilities, a graphical user interface (GUI), explanatory tutorials demonstrating the various program applications, and a comprehensive context-sensitive help system.

CANDE-2007 is a special purpose finite element program developed for the structural design and analysis of buried culverts. The finite element methodology is based on a two-dimensional (2-D) slice of the culvert installation so that both the culvert structure and soil zones are modeled as a combined soil-structure system subjected to an incremental loading schedule. Buried culverts of any shape, size, and material, including corrugated metal, reinforced concrete, and thermoplastic pipe, may be analyzed and designed to withstand dead weight, incremental soil-layer loading, temporary construction loads, and surface loads, due to vehicular traffic. A particularly unique feature of CANDE's output is the automatic evaluation of the structural performance in terms of safety measures against all failure modes (design criteria) associated with the structural material.

New analysis capabilities include the following:

- Multiple pipe-type analysis and design,
- Large deformation formulation with buckling capacity prediction,
- Load resistance and factor design (LRFD) methodology, and
- Automated bandwidth minimization and several other special utility options.

A new GUI offers the following:

- An integrated windows interface with menu-driven input and error checking,
- Graphical viewing options for the finite element mesh,
- Interactive graphing options for the beam element responses,
- A dynamic report generator, and
- A context-sensitive help system.

The research team, the NCHRP 15-28 panel, and a group of beta-tester volunteers have extensively tested CANDE-2007. The program is judged to be robust, accurate, and the tool-of-choice for culvert analysis and design.

Deliverables from this research project include the CANDE-2007 software program and three stand-alone documents in addition to this report (available as NCHRP CD-ROM 69). The documents are entitled as follows:

- *CANDE-2007 User Manual and Guideline,*
- *CANDE-2007 Solution Methods and Formulations, and*
- *CANDE-2007 Tutorial of Applications.*

Engineers, researchers, and designers from state DOTs, consulting firms, manufacturers, universities, and research institutions are encouraged to use CANDE-2007 for all culvert design and analysis problems. CANDE-2007 is a public-domain program.

CHAPTER 1

Background

CANDE, an acronym derived from Culvert ANalysis and DEsign, is a finite element program developed especially for the structural design, analysis, and evaluation of buried structures including culverts made of corrugated metal, reinforced concrete, and plastic as well as other soil-structure interaction problems such as underground storage facilities and storm water chambers. CANDE was first introduced in 1976 under the sponsorship of the FHWA (*1, 2*). Over the years, FHWA has sponsored upgrades to the program culminating in 1989 with the CANDE-89 program (*3, 4*), which offers the following analytical features:

- Plane strain geometry—a 2-D finite element representation of the soil and structure under quasi-static vehicular loading conditions and based on small deformation theory.
- Incremental construction—the capability to simulate the physical process of placing and compacting soil layers, one lift at a time, below, alongside, and above the culvert as the installation is constructed.
- Interface elements—the ability to simulate the frictional sliding, separation, and re-bonding of two bodies originally in contact. Typically these elements are used between the culvert and soil and between trench soil and in situ soil.
- Soil elements and models—soil elements are high-order continuum elements with a suite of soil models ranging from linear elastic to highly nonlinear. The so-called Duncan and Duncan/Selig soil models are very representative of the nonlinear soil behavior in most culvert installations.
- Beam elements and pipe models—a culvert (or structure) is represented by a connected sequence of short beam-column elements that trace the culvert's periphery. The material models of beam elements distinguish between different pipe types. Each material model includes design criteria, which provide measures of safety against potential modes of failure.

Over the years, CANDE has enjoyed a great deal of popularity in the culvert community including state DOTs, consulting firms, manufacturers, universities, and research institutions in the United States and abroad who have used the program to design culvert installations, understand soil-structure behavior, interpret experimental results, and design new products. The popularity of CANDE is, in part, due to the rigorous adherence to the principle of good mechanics and to the trustworthiness of the program, earned over years of testing (*5*). Equally important to its popularity is the availability of CANDE's source code and documentation of the programming architecture. Accessibility to the source code is an extremely important feature for researchers who often want to test new theories and models as part of their research effort. Often, these research studies lead to new additions to the program that will ultimately become available to the entire culvert community.

CANDE Upgrade—AASHTO

In May 2005, TRB/NCHRP negotiated a contract with Michael Baker Jr., Inc. to modernize and upgrade CANDE-89 under the sponsorship of AASHTO. The project known as the CANDE Upgrade Project, designated as NCHRP Project 15-28, is the funding source for the enhancements that have been incorporated into CANDE-2007 presented in this report.

The CANDE Upgrade Project targeted the following three areas for enhancement:

- Pre- and post-processing with modern computer technology,
- New analysis capabilities and architecture for multiple structures, and
- Update design criteria for all culvert types to include LRFD methodology.

Pre- and Post-Processing

Previous versions of CANDE were in batch-mode input (i.e., ASCII text input file/output file). The input was provided via documented input instructions and an ASCII text editor without dedicated GUI software to aid the user in data preparation. Similarly, output data was written to an ASCII text output file without any post-processing capability to graphically display results.

CANDE-2007 is now equipped with a Windows®-based, menu-driven format for interactive data input and real-time control of data output along with a context-sensitive help system and numerous graphical plotting options.

New Analysis Capabilities

The architecture developed for CANDE-2007 allows the use of multiple pipe groups (previous versions of CANDE permitted a single pipe group), thereby allowing an analysis of several culverts placed side-by-side, or a retrofit design (e.g., a plastic pipe inserted inside a corrugated steel pipe).

In addition to the small deformation theory utilized in the original version of CANDE, CANDE-2007 has been updated to include a Lagrange formulation that provides an accurate and robust algorithm for predicting large deformations along with methodology for predicting buckling capacity at the end of each load step.

CANDE has also been updated to include an automated bandwidth minimizer, thus relieving the user of the requirement of assigning node numbers in a judicious manner to manually reduce the bandwidth of the system matrix.

Design Criteria and LRFD Methodology

The original CANDE program was based on the concept of working-stress design methodology. Accordingly, the previous versions of CANDE reported safety factors against various modes of failure (design criteria) that have been traditionally associated with the type of culvert being considered. In recent years, AASHTO (*6*) has adopted the reliability-based LRFD methodology. Rather than using safety factors, the LRFD methodology uses load factors and resistance factors to achieve a safe design.

As part of the CANDE Upgrade Project, a complete and compatible set of design criteria, applicable to both working-stress and LRFD methodologies, was identified for the common culvert materials: corrugated metal, reinforced concrete, and thermoplastic pipe. These design criteria are now incorporated in the corresponding pipe subroutines of the CANDE-2007 analysis subsystem. The user now has the option to choose either service load (working-stress evaluation of the design criteria) or factored loading (LRFD evaluation of the design criteria).

Many other improvements have been incorporated into CANDE-2007 that are not mentioned above but are discussed in detail in the *CANDE-2007 User Manual and Guideline* and the *CANDE-2007 Solution Methods and Formulations* documents. It should be noted, however, that all the capabilities and options that existed in the CANDE-89 version have been retained.

CHAPTER 2

Research Approach

The research effort was carried out in three distinct phases: (1) planning, (2) development, and (3) testing and documentation. The planning phase included a literature review, the development of GUI mockups and use cases for the input and output screens, theoretical developments for all new capabilities such as large deformation theory, and interpretation of the AASHTO LRFD specifications to establish mechanistically meaningful design criteria. An interim report documented the planning phase and a proposed work plan was prepared and sent to the NCHRP oversight panel for review. After providing suggestions and guidance, the oversight panel approved the work plan.

Next, the development phase was undertaken to execute the approved work plan. CANDE-2007 was developed using Microsoft Visual Studio 2005 along with Intel FORTRAN 9.1 compiler. CANDE has been tested and may be installed on a personal computer with the following:

- Microsoft Windows XP, service pack 2 or later.
- Microsoft Windows.NET Framework 2.0.

The language used for the development of the GUI was the Microsoft C# programming language. The CANDE analysis engine is written as a separate dynamic link library (DLL) using the Intel FORTRAN 9.1 compiler with a C# shell.

Alpha testing by the research team resulted in improved concepts for the GUI as well as corrections to theoretical developments and coding. The final product of the development phase was the initial version of CANDE-2007 and draft documentation.

The final phase consisted of beta testing and preparing final documentation. Beta testing was first undertaken by the NCHRP oversight panel followed by a group of 35 beta-tester volunteers from the culvert community. Beta testing produced another round of improvements to the CANDE-2007 software and documentation.

The final products are the CANDE-2007 software, both in executable and source form, and three stand-alone documents in addition to this report. Short descriptions of the documents are provided below. Each document is available directly from the CANDE interface in PDF format with the User Manual also available in context-sensitive compiled HTML help format. An abbreviated table of contents for each document is provided in the Appendix of this report.

CANDE-2007 User Manual and Guideline—This document provides a detailed description of all things related to the CANDE-2007 interface (both input and output).

CANDE-2007 Solution Methods and Formulations—This document contains detailed information related to the solution methodology of the CANDE analysis engine. This document is intended for users who seek detailed information on how CANDE performs internal calculations.

CANDE-2007 Tutorial of Applications—This document provides a variety of examples that detail the various features of CANDE-2007 and includes sections on providing input through the CANDE interface and interpreting output results.

CHAPTER 3

Findings and Applications

CANDE-2007 Overview

The results of this research effort enhanced every aspect of the CANDE program and its overall architecture. The CANDE-2007 architecture is best viewed from the perspective of a user stepping through the process of solving a particular soil-culvert problem. To initiate a solution, the user makes several top-level choices that define the character of problem to be solved as illustrated in the flow chart depicted in Figure 1 and discussed in the following paragraphs.

Execution Mode is the choice between design and analysis. The analysis mode defines a particular culvert and soil system in terms of geometry, material properties, and loading conditions and is solved by the chosen solution level. The solution output provides an evaluation of the culvert in terms of its safety for all potential modes of failure associated with the structural material and shape of the culvert. Alternatively, the design execution mode also requires that the culvert shape, materials, and loading conditions be defined exactly as the analysis case. However, the culvert's cross-sectional properties are not defined but, rather, are determined in accordance with the desired level of safety specified by the user. For example, corrugated metal design solutions are given in the required corrugation size and metal thickness while reinforced concrete is given in the required area of reinforcement steel for one or two cages.

Evaluation Methodology is the choice between a working-stress solution and an LRFD solution. A working-stress solution means the applied loads are the actual (or perceived) set of loads acting on the soil-structure system. Evaluation of the culvert's performance under the working stress option is reported in terms of safety factors for each design criterion associated with the selected culvert type. An LRFD solution means the actual-loading schedule is increased by individualized load factors so that the dead loads, earth loads, and live loads may be assigned individual factors as required by the AASHTO LRFD specifications. Evaluation of the culvert's performance under the LRFD option is provided in terms of ratios of factored demand to factored capacities for each design criterion associated with the selected culvert type. The details of the evaluation methodology are provided in the *CANDE-2007 Solution Methods and Formulations* manual available from the tool bar in CANDE-2007.

Solution Level (1, 2, or 3) provides a choice that corresponds to successively increased levels of analytical sophistication, which permits the user to choose a degree of rigor and modeling fidelity commensurate with the details and knowledge of the culvert-soil system under investigation. Level 1 is based on a closed-form elasticity solution (*7*) useful for screening and comparing various circular-shaped culverts in deep burial. Level 2, considered the "work-horse" of CANDE, is applicable to many common culvert shapes including circular, elliptical, box, and arch installations but is limited to center-line symmetry for both loading and geometry. Level 3 is virtually unlimited in modeling the structure shape, soil system, and loading conditions. Level 2 and Level 3 share a common finite element solution methodology and only differ in the manner of input data: automatic versus user defined.

Pipe Groups and Type provides choices for the culvert material(s) to be analyzed or designed. A single "pipe group" is a connected series of beam-column elements composed of one pipe-type material: aluminum, basic, concrete, plastic, or steel. Level 1 and Level 2 culverts are predefined shapes such as round-, box-, and arch-shaped culverts requiring only one pipe group. Level 3 permits up to 30 different pipe groups to define special types of problems. For example, two or more groups may be defined to represent independent structures in the same embankment. Alternatively, several element groups may be joined together to model cell-like structures or composite structures such as a corrugated metal arch roof placed on a reinforced concrete U-shaped base or a plastic pipe placed inside a corrugated steel pipe for rehabilitation.

System Choices refers to a variety of modeling options developed especially for the culvert soil-structure problem.

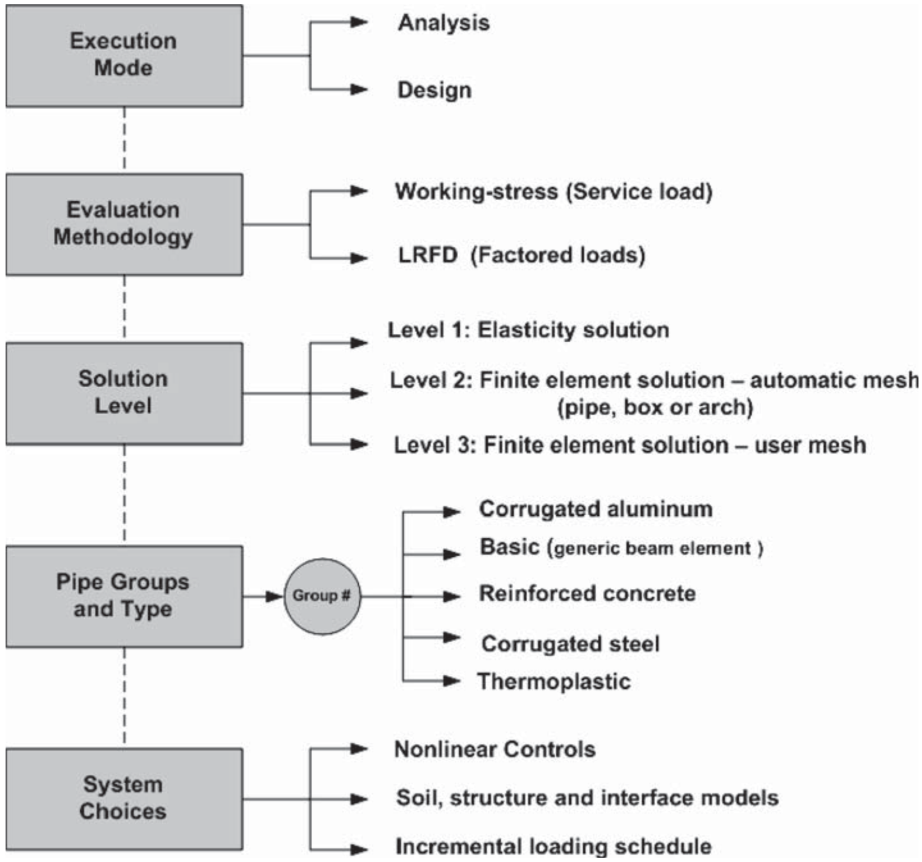


Figure 1. Major options to define the top-level input data for CANDE-2007.

A suite of soil models is available including the popular hyperbolic forms of Duncan and Duncan/Selig as well as the standard linear forms for isotropic elastic, orthotropic elastic, and overburden dependent. Predefined model parameters are provided in the program for simulating crushed rock, sands, silts, and clays under a range of compaction conditions. Another system choice is the interface condition between the soil and culvert or between fill soil and in situ soil. The user may select bonded or a friction interface that permits frictional sliding and separation during the loading schedule. Still, another system choice is the option to include large deformation and buckling analysis. This is particularly useful for investigating large, flexible culverts under heavy loading.

Graphical User Interface

CANDE-2007 provides a GUI that greatly eases the task of creating CANDE input documents and also allows the viewing of the CANDE output results graphically. A companion document, *CANDE-2007 User Manual and Guideline*, describes in detail the input and output capabilities of the GUI that was developed in the course of this research effort. The GUI provides a multiple document interface (MDI) environment where the user can develop and revise input, review graphic information such as mesh geometry and beam-element graph information, quickly navigate the large CANDE output files through the use of an interactive browser, and access context-sensitive help for the whole system. A sample of the interface is shown in Figure 2.

Input Options

The key concept behind the GUI input option is that it ultimately creates a CANDE-2007 input document file that contains the same formatted data stream as that of traditional batch-mode input. The traditional batch-mode method of input requires the user to hand type the CANDE input document via an ASCII text editor in accordance with the written input instructions in the user manual. In contrast, the GUI is much easier to use because each input command is represented by an input menu that is "tailor-made" to conform to the user's previous input choices. Thus, the user does not need to navigate through the entire user manual. Instead, the user just follows the screen input instructions and accesses the context-sensitive help provided by the GUI. The GUI has options to create new CANDE input documents, edit and rerun existing input documents, and import data files from external sources.

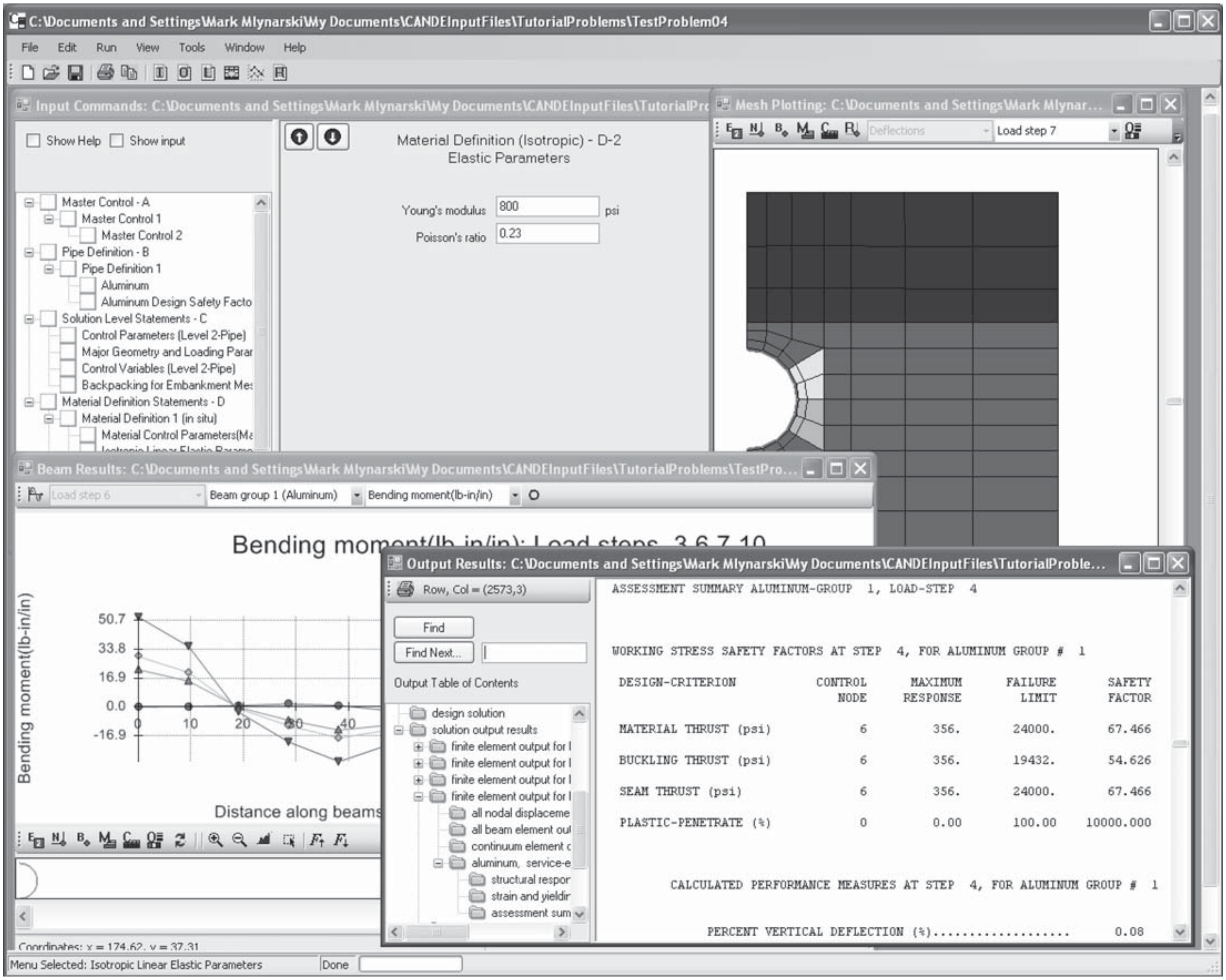


Figure 2. CANDE-2007 multiple document interface.

As an illustration, Figure 3 shows the start-up screen for creating a new CANDE input document using the CANDE Input Wizard. Note that several of the top-level choices previously discussed are shown on this screen with radio-button selections. As a consequence of the user's selections made on this screen, the screens that follow only pertain to the information that is needed for this problem, thereby eliminating up to 80% of the non-relevant input directions in the detailed user manual. Since the *CANDE-2007 User Manual and Guideline* contains more than 180 pages of input instructions, the utility of the GUI input method is readily apparent.

Once the key input parameters are provided, a CANDE input document is generated and the user is provided an input menu browser to navigate and modify the input as necessary. The key features of the input menu browser are detailed in Figure 4.

Output Options

Viewing the CANDE output is controlled by the user via a drop-down menu on the GUI toolbar. The drop-down menu offers five viewing choices consisting of three text files and two interactive graphic tools, which are also accessible from individual icons on the tool bar. Short descriptions of the five choices are provided below.

- **CANDE Output Report.** This is the most comprehensive output file and contains text and tables for all the input selections as well as the complete set of structural response data for each load step. The Output Report has an interactive table of contents that allows the user to quickly locate output data of interest. Most notably the evaluation of the pipe type is given in the last subsection. The output files contain a myriad of information and can be somewhat

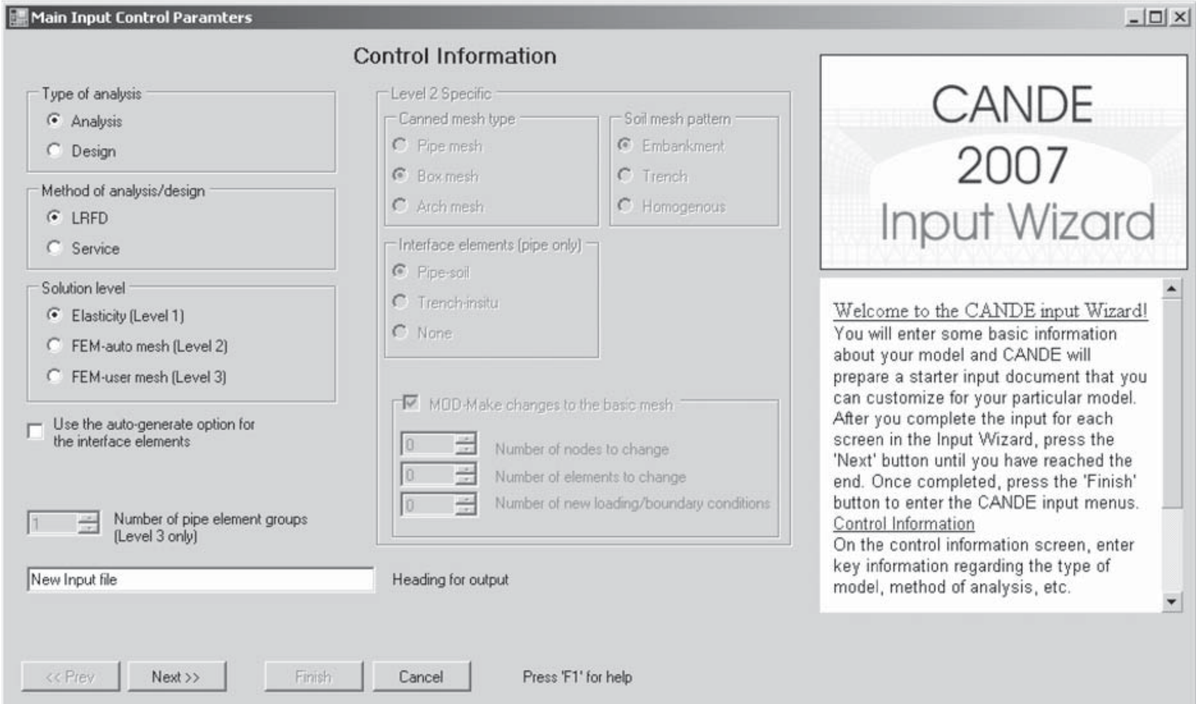


Figure 3. Start-up screen from CANDE Input Wizard.

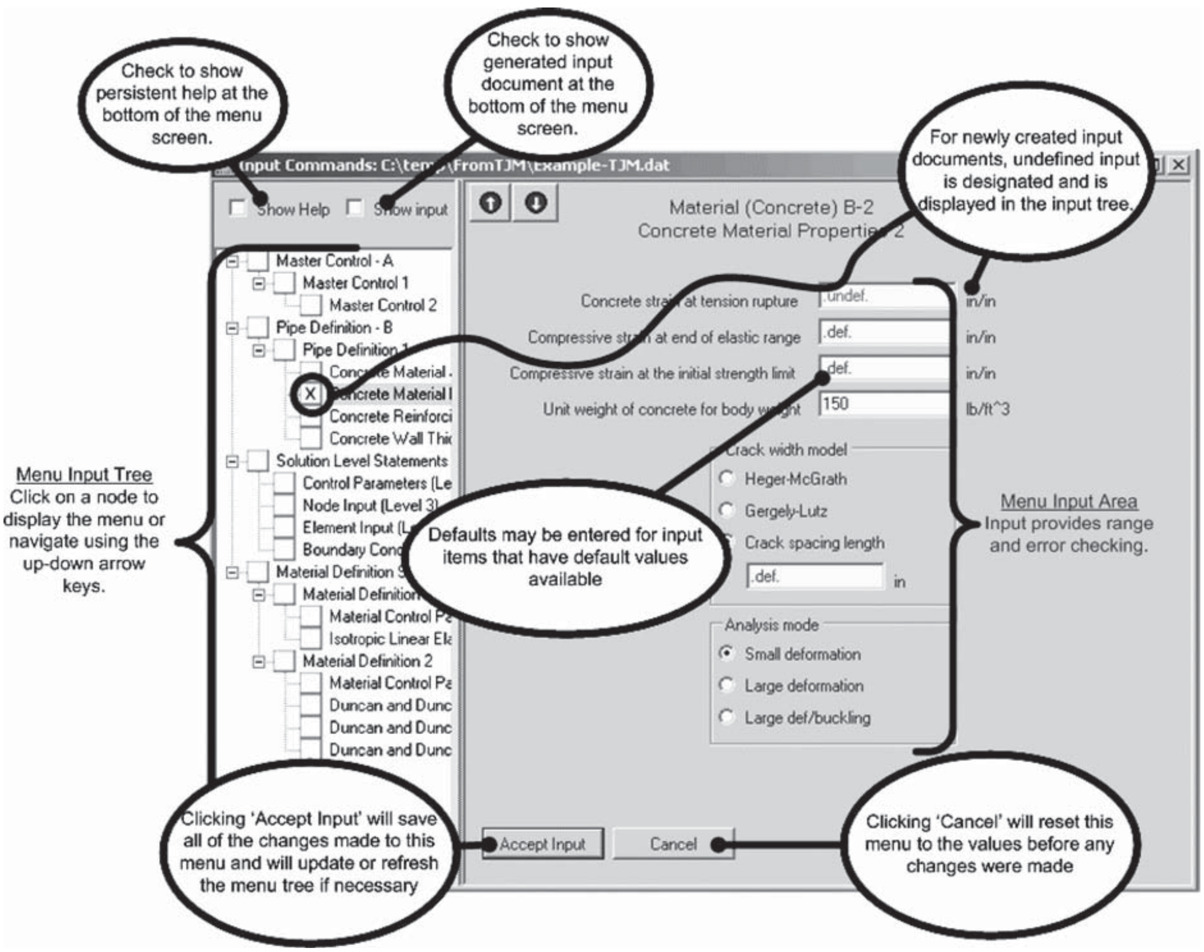


Figure 4. CANDE input menu overview.

cumbersome to navigate in a regular ASCII text editor. To enhance the review of the output report, a topical browser is included as part of CANDE-2007. This browser provides an organized, bookmarked table of contents for the output file that provides quick access to any table in the report (see Figure 5).

- **CANDE Log File.** The log file is a short file that is displayed on the monitor screen during execution. It contains the master input selections along with a history list of each load step analyzed and a trace of iterations required to solve each load step. If the solution is unsuccessful, the log file also provides error messages and, when possible, guidance to correct the error.
- **Mesh Plot.** The mesh plot is an interactive plotting tool for creating and viewing the finite element mesh topology (Levels 2 and 3) including element numbering, nodal connectivity, material zones, construction increments, and boundary conditions. Likewise, the tool is used to create and plot solution output such as deformed shapes and color contours of soil stresses and strains. For an overview of the Mesh Plot options, see Figure 6.
- **Graphs.** This is an interactive plotting tool for creating and viewing the structural response of beam-element groups, (i.e., pipe types). Structural responses are plotted contiguously over the pipe shape for any load step or sets of load steps. Structural responses include moments, thrusts, and shears as well as responses specific to the pipe type such as plastic penetration for corrugated metal and crack depth for reinforced concrete. A local plot of the pipe is also provided (see Figure 7).
- **Results Generator.** This is an interactive text report generator that features user-defined report selection to create dynamic output reports. Options are available for tabularizing soil responses and pipe group responses as a function of load step.

New Analysis Capabilities

In addition to code restructuring, improvements were made in every subroutine of the CANDE Engine, some significant new analytical capabilities were added to CANDE-2007 that did not exist in the previous versions of CANDE. A companion document, *CANDE-2007 Solution Methods and Formulations*, describes in detail the complete derivation of these new capabilities developed in the course of this research effort. Provided is a brief synopsis of the new analysis capabilities.

Multiple Pipe-Type Capability

A new architecture called "multiple pipe-type capability" is embedded in CANDE-2007 that removes the old restriction of limiting the analysis to just one continuous pipe-type

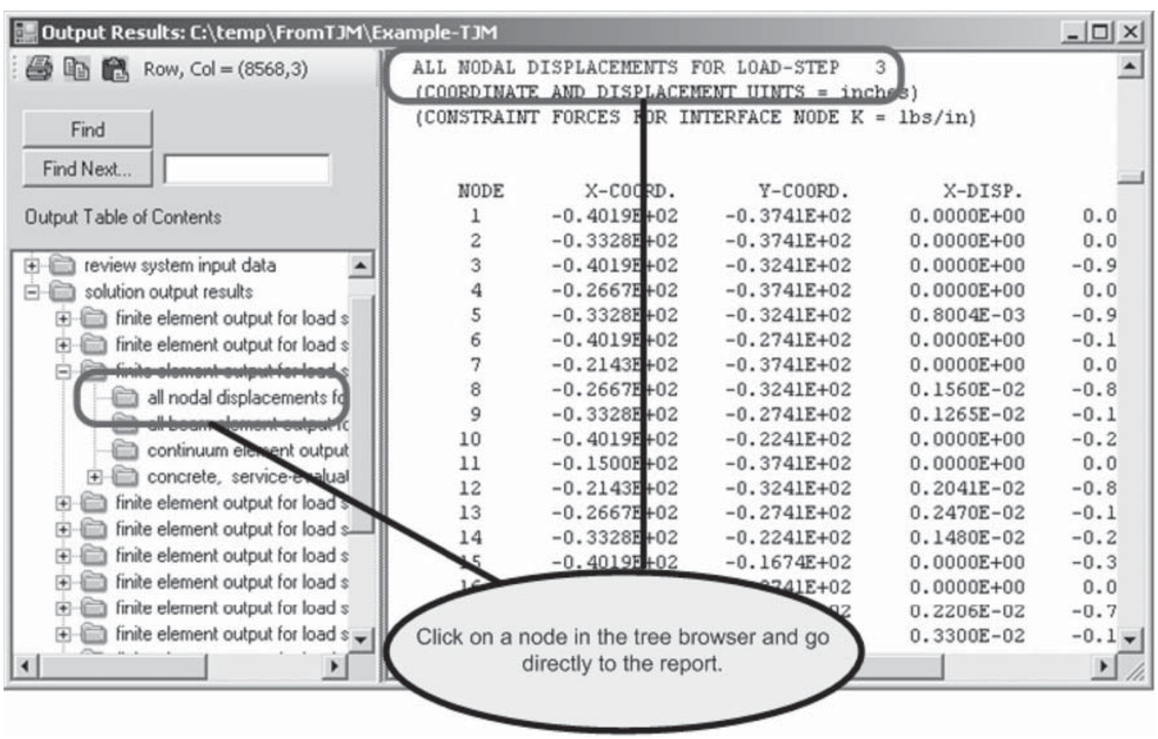


Figure 5. CANDE output viewer.

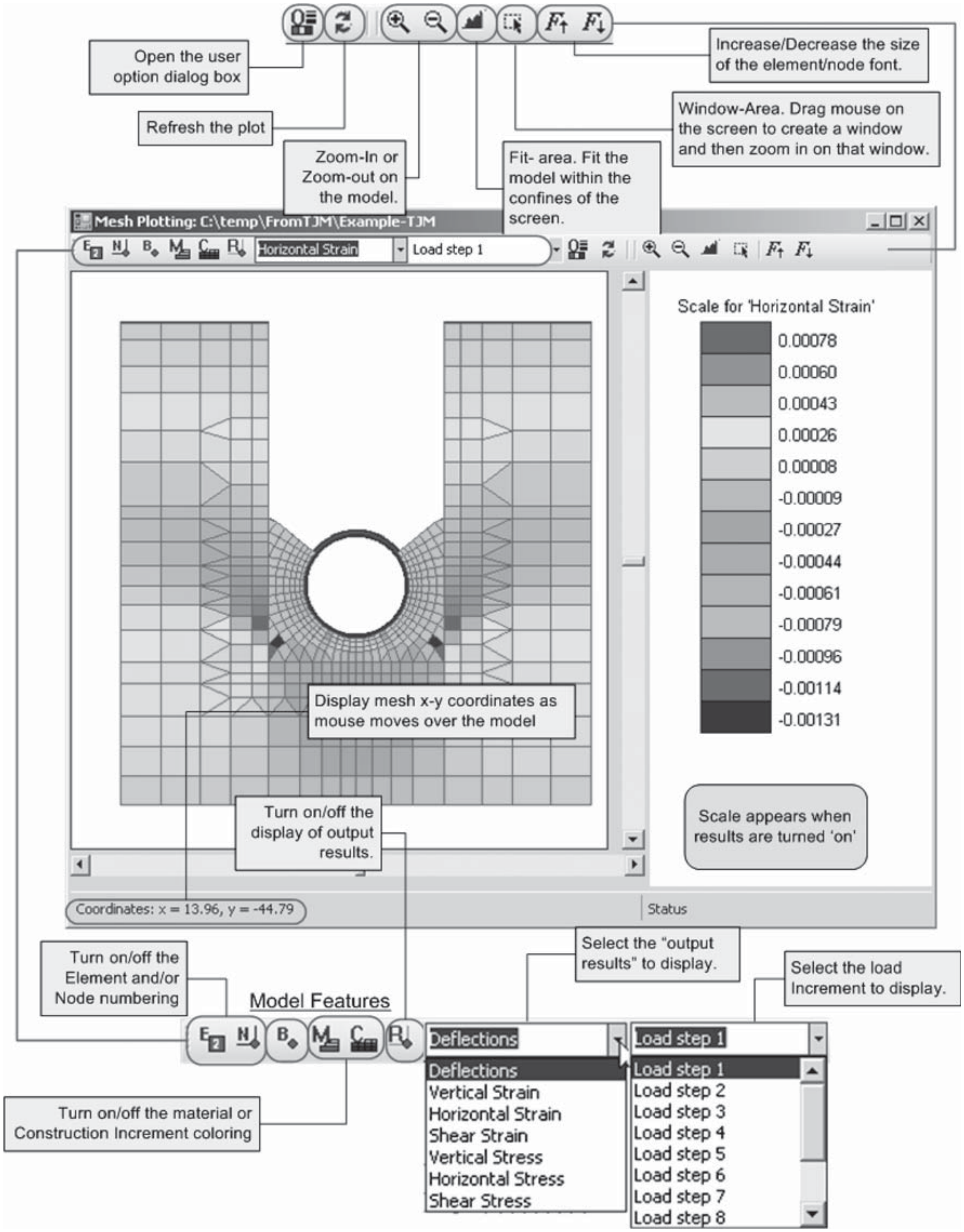


Figure 6. CANDE mesh plot options.

structure. The new strategy allows for multiple element groups rather than just a single group. The connection between element groups is completely arbitrary and can be defined by the user. For example, two groups may be assigned independent node numbers (no nodes in common) so that they become independent structures that only interact through the soil stiffness. Alternatively, element groups may be arbitrarily joined together at common nodes to model cell-like structures or composite structures such as a corrugated metal arch roof placed on a reinforced concrete base. The new architecture provides virtually unlimited modeling capabilities to define any configuration within a 2-D framework. The

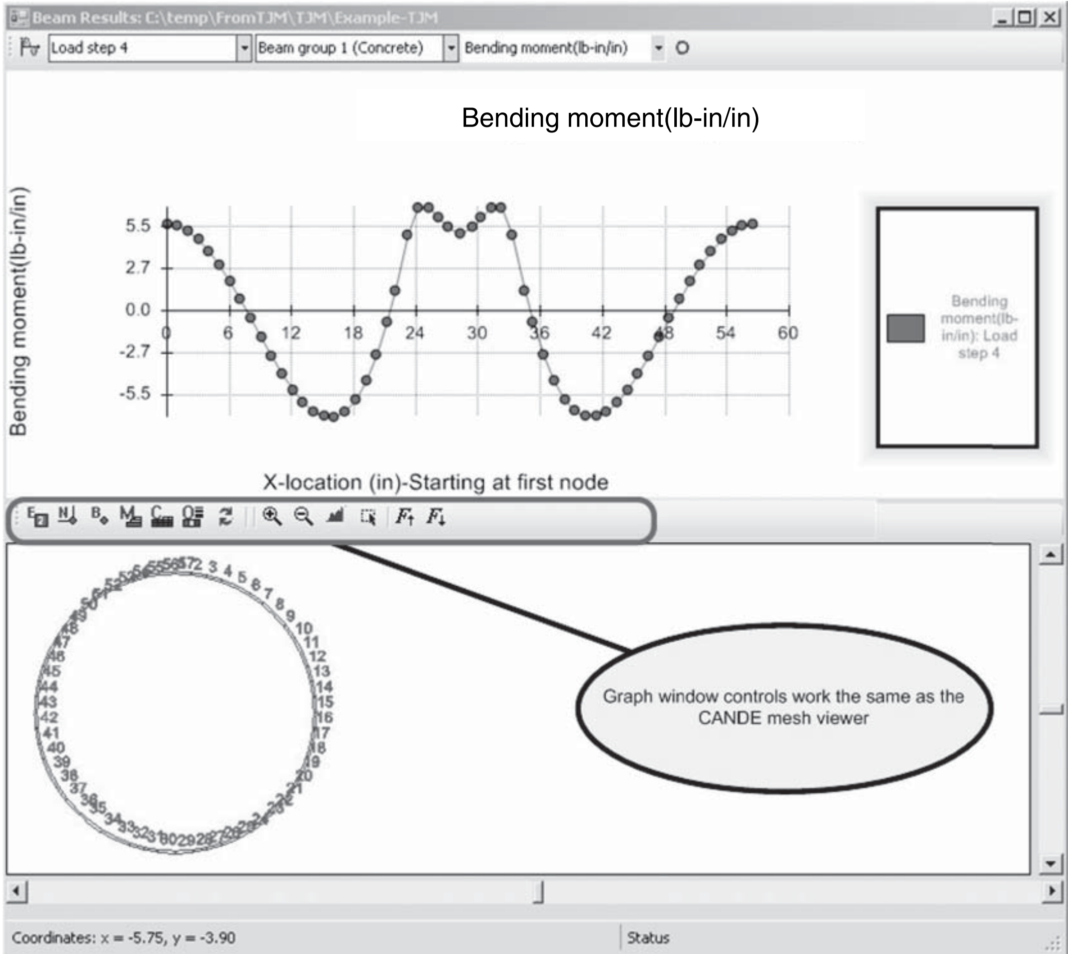


Figure 7. CANDE Graphs window.

implementation of the multiple pipe-type capability is operable in both the analysis and design mode.

Large Deformations and Buckling

The large deformation development is based on the so-called "Updated-Lagrange" methodology, which includes the standard small strain-displacement term plus a nonlinear term related to rotation. This strain-displacement expression accurately represents the beam element's internal strain field due to moderate stretching and large rotations. The word "updated" means that the nodal coordinates of all elements are updated to their displaced position after each load step instead of the original undeformed position being used. Incorporating the nonlinear component of the strain-displacement relationship into a beam-column element results in a new matrix called the geometric stiffness matrix, proportional to current thrust level, and a new load vector called the rotational-stretch vector. This method of analysis produces a nonlinear load-deformation curve wherein the load causing instability may be observed by noting the peak load at which the system fails due to large or unbounded displacements. In order to predict the buckling capacity at the end of each load increment, a linearized buckling prediction methodology is also incorporated into the program based on determining the scalar multiple of the geometric stiffness that renders the determinant of the combined system stiffness matrix to be zero.

Pipe-Type Design Criteria and LRFD Methodology

The design criteria for all pipe types have been extensively revised in accordance with the AASHTO LRFD Specifications *(6)*. The design criteria are equally applicable to either working stress or LRFD design methodologies wherein working stress employs service loads and actual resistance, and LRFD employs factored loads and factored resistance. Listed below are the design criteria for the three major categories of pipe materials with emphasis on the new design criteria developed under this research effort.

- **Corrugated metal.** Corrugated steel and corrugated aluminum have the same design criteria, differing only by the numerical value of design criterion limits such as the yield stress. The strength design criteria include thrust stress limits for material yielding, global buckling, and seam strength. In addition, a new strength criterion is incorporated to warn against full plastic penetration from thrust and bending. Other new additions include revised tables for available steel and aluminum corrugation sizes and updated flexibility factors for handling considerations.
- **Reinforced concrete.** The strength-related design criteria for reinforced concrete include yielding of the reinforcing steel, crushing of concrete, diagonal shear failure (three forms), and radial tension failure of concrete due to tension steel. The theoretical development of the last criterion, which is not well addressed in the AASHTO LRFD Specifications, was developed in the course of this research effort. Similarly, the Heger-McGrath prediction for crack width, a service-related design criterion, is also a product of this research effort.
- **Thermoplastic pipe.** Thermoplastic pipe materials include high-density polyethylene, polyvinylchloride, and polypropylene. All thermoplastic pipe materials have the same general design criteria, differing only in pipe material data and duration of loading. Strength-related design criteria include thrust stress limits for material failure and global buckling, and maximum outer fiber strain limits from thrust and bending. Performance-related criteria include allowable displacements and tensile strain.

Plastic Profile Wall

The previous version of CANDE was limited to smooth walls for all plastic pipes. As part of this research effort, the wall type is extended to include a variety of profile wall sections defined by the length and thickness of subelements that form a repeating profile shape along the length of the pipe. The user-specified subelements include two web elements and four horizontal subelements as shown in Figure 8.

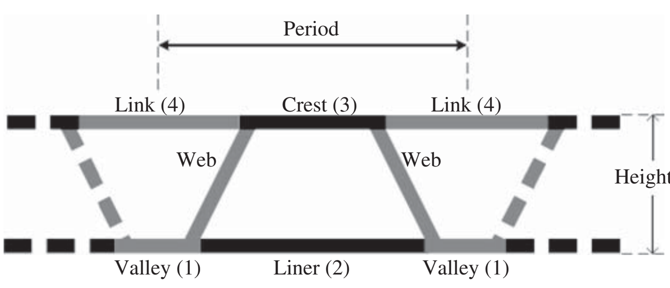


Figure 8. Profile wall with user-defined subelements.

Almost all the typical profiles that are currently manufactured can be represented by a subset of these subelements including ribbed profiles, T-ribbed profiles, unlined corrugations, lined corrugations, and box-like profiles.

The key feature of the Profile wall-type option is that it includes the nonlinear phenomenon of local buckling in accordance with the local buckling equations specified in Section 12 of the AASHTO LRFD Specifications. That is, depending on the level of the compressive strain, some or all of the subelements may experience local buckling, which is simulated by removing a central portion of the subelement's area in proportion to the degree of local buckling. Solutions are iterated until convergence occurs.

Unification of Nonlinear Iteration Schemes

Previous versions of CANDE employed individual iteration counters and strategies for each nonlinear algorithm (i.e., pipe material type, soil models, interface models, and now large-deformation models). CANDE-2007 unifies the iteration schemes of all nonlinear models to be easily controlled by the user by one command. Now, the user may select one iteration limit that governs all nonlinear models (soil, pipes, interfaces, and large deformations). Also, the user now has the option to continue or stop the analysis if the iteration limit is exceeded. In either case, diagnostics of the nonlinear models are printed showing which model(s) did not converge along with a measure of the convergence error.

Bandwidth Minimization

A bandwidth minimizer has been installed in CANDE-2007 that reduces the maximum bandwidth of the system equations characterizing the finite element mesh topology. The motivation for reducing the maximum bandwidth is to reduce computer storage space for the system of equations and to increase the speed of solving large sets of equations. Bandwidth minimization is achieved by strategically renumbering the node numbers that were originally input by the user. Node renumbering is accomplished by swapping node numbers, one pair at a time, starting with the node number with the highest bandwidth and exchanging it with another node number that optimally reduces the maximum bandwidth at the first location while generating a bandwidth at the second location that is less than the original maximum bandwidth. The algorithm (contained in subroutine BMIZER) was developed during this research effort and is unique to the CANDE-2007 program.

In addition to the above new features, many additional modifications have been made to improve the program and ease the burden of user input. For example, a simplified method of defining interface angles is now operational in the program. These and other improvements are discussed in the *CANDE-2007 User Manual and Guideline*.

The FORTRAN code has also been updated from the 1989 code to provide a clearer more structured architecture. The FORTRAN analysis program is now compiled as a DLL that is called directly from the GUI.

Testing and Evaluation

Checking and testing the accuracy and validity of the new capabilities and modifications include comparing CANDE-2007 solutions with older versions of CANDE, closed form solutions, simplified AASHTO solutions, and general purpose finite element programs conducted. This type of testing, called alpha testing, was accomplished by the project team during and after the development phase of each new capability. The results of the alpha-testing phase indicated that the new capabilities were accurate and functioning as planned.

The beta-testing phase, involving CANDE-2007 testers outside the project team, began in May 2007 with the NCHRP project panel serving as the initial beta testers. Subsequently, the beta testing was expanded with 35 beta-tester volunteers from the culvert community over a testing period of 3 months. Beta testers had access to a project website and software to easily record all problems and comments. Of the 35 beta testers and 10 panel members, 16 testers recorded problem reports on the project website. By the end of beta testing, 141 beta incidents were logged on the website. The entire list of beta incidents was reviewed by the project panel at an October 2007 meeting. The vast majority of issues dealt with questions about interpretation of input variables. Accordingly, the *CANDE-2007 User Manual and Guideline* was revised to address these questions. Some comments led to the discovery of bugs in the CANDE-2007 program, which were corrected. Another class of beta-testing comments dealt with desires for future additions to CANDE-2007. These comments will continue to be maintained by the project team for the purposes of building a list of possible future enhancements for the CANDE software.

The beta-testing phase proved to be very effective in uncovering problem areas in the software as well as areas of potential misunderstanding on the part of the user that could be addressed by enhancements to the CANDE documentation. All beta-testing incidents have been addressed and resolved except for those issues that are classified as a future enhancement.

To enhance future regression testing of the software (i.e., comparing a revised version of the software numerically with a previous version), the NCHRP Process 12-50 *(8)* has been incorporated into the CANDE Engine with the new Process 12-50 tags fully documented in the *CANDE-2007 User Manual and Guideline.*

After beta testing was completed and the panel viewed the results, a list of items that were beyond the scope of this research effort was added to a future development list. These items include the following:

1. Element death option to simulate removal of temporary bracing, excavating of soil, or loss of structural elements due to aging and corrosion/abrasion.
2. Reformulating the Duncan and Duncan/Selig soil model into a plasticity-based model to properly simulate unloading.
3. Incorporating shear deformation into structural beam-column elements.
4. Possible incorporation into the AASHTOWare™ suite of products such as Virtis or Opis.
5. Enhanced mesh generation capabilities.
6. Load rating capabilities.

Applications—Tutorials

The applications of the new CANDE-2007 program are best demonstrated with the CANDE tutorial problems. For a complete understanding, the reader is invited to peruse the companion document entitled, *CANDE-2007 Tutorial of Applications*.

List of Tutorial Problems

Listed in Table 1 are the 16 tutorial examples (Note: examples 15 and 16 are only input files and do not include the problem description/narration) that cover all aspects of CANDE-2007 capabilities including multiple structures and retrofit problems.

Illustration of Tutorial

Tutorial examples (Tutorials 1–14) describe the physical nature of the problem to be solved followed by step-by-step input instructions as well as illustrations of graphical solutions and an evaluation of the culvert safety in terms of design criteria. To illustrate the contents of the *CANDE-2007 Tutorial of Applications*, Tutorial Example #4 is highlighted below.

Tutorial Example #4 seeks a design solution for a 60-in. inside diameter corrugated aluminum pipe with 30 ft of fill over the top of the pipe using the Working Stress (service) Design method. The problem is shown schematically in Figure 9. The problem employs Solution Level 2, using an automated finite element pipe mesh for a trench installation

Table 1. Tutorial Example Descriptions.

Problem	Description
1	Level-1, Corrugated Steel Pipe, Design mode (LRFD). Design a 60 in. inside diameter corrugated steel pipe with 30 ft of fill over the top of the pipe using LRFD design. The design will be with Level 1, which is based on the Burns and Richard elasticity solution. The desired result is the corrugation size and thickness.
2	Level-1, Reinforced Concrete Pipe, Design mode (LRFD). Design a 60 in. inside diameter reinforced concrete pipe with 30 ft of fill over the top of the pipe using LRFD design. The design will be with Level 1, which is based on the Burns and Richard elasticity solution. The desired result is the required inner and outer reinforcement.
3	Level-1, HDPE Plastic Pipe, Design mode (LRFD). Design a 36 in. outside diameter smooth wall HDPE plastic pipe with 40 ft of fill over the top of the pipe using LRFD design. The design will be with Level 1, which is based on the Burns and Richard elasticity solution. The desired result is the wall thickness.
4	Level-2, Corrugated Aluminum Pipe, Design mode (Working Stress). Design a 60 in. inside diameter corrugated aluminum pipe with 30 ft of fill over the top of the pipe using Working Stress (service) design. The design will be with Level 2, using an automated finite element pipe mesh for a trench installation having no interface elements. The desired result is the corrugation size and thickness.
5	Level-2, HDPE Plastic Pipe, Analysis mode (Working Stress). Analyze a 36 in. outside diameter smooth wall HDPE plastic pipe with 40 ft of fill over the top of the pipe using Working Stress (service) analysis. The analysis will be with Level 2, using an automated finite element pipe mesh for an embankment installation having no interface elements.
6	Level-2, Reinforced Concrete Arch, Analysis mode (LRFD). Analyze a 237-in. span (90-inch rise) reinforced concrete arch supported on spread footings with 2 ft of fill over the top of the arch, using LRFD analysis. The analysis will be with Level 2, using an automated finite element arch mesh for a trench installation having interface elements. The automated finite element mesh will be modified using Level 2-extended to apply point loads depicting a LRFD design truck at the ground surface above the crown of the arch. Additionally, the live load rating procedure will be demonstrated using CANDE output.
7	Level-2, Reinforced Concrete Box, Analysis mode (LRFD). Analyze a 120 in. x 84 in. reinforced concrete box culvert with standard ASTM steel placement with 2 ft of fill over the top of the culvert using LRFD analysis. The analysis will be with Level 2, using an automated finite element box mesh for an embankment installation.
8	Level-2, Corrugated Steel Pipe, Analysis mode (LRFD). Analyze a 144 in. corrugated steel pipe with 8 slotted joints and 60 ft of fill over the top of the pipe using LRFD analysis. The analysis will be with Level 2, using an automated finite element pipe mesh for an embankment installation having no interface elements. The automated finite element mesh will be modified using Level 2-extended to reduce the thickness of the construction steps above the crown of the pipe.
9	Level-2, Corrugated Steel Long Span, Analysis mode (Working Stress). Analyze a 217-in. span (82-inch rise) 3-segment type corrugated steel long span arch supported on spread footings with 3 ft of fill over the top of the arch, using Working Stress (service) analysis. The analysis will be with Level 2, using an automated finite element arch mesh for a trench installation having interface elements. The automated finite element mesh will be modified using Level 2-extended to apply point loads depicting an LRFD design truck at the ground surface above the crown of the arch.
10	Level-2, Reinforced Concrete Pipe, Design mode (LRFD). Design a 72 in. inside diameter concrete pipe set on gravel bedding with 60 ft of fill over the top of the pipe using LRFD design. The analysis will be with Level 2, using an automated finite element pipe mesh for an embankment installation having a 6 in. layer of soft backpacking soil around the circumference of the pipe and no interface elements. The desired result is the required inner and outer reinforcement.
11	Level-2, Plastic Pipe (Profile), Analysis mode (Working Stress). Analyze a 48 in. inside diameter corrugated plastic (profile) pipe with 40 ft of fill over the top of the pipe using Working Stress (service) analysis. The analysis will be with Level 2, using an automated finite element pipe mesh for a trench installation having interface elements. The automated finite element mesh will be modified using Level 2-extended to change the haunch zones to a user-defined soil material and the thickness of bedding layer to 6 in.

Table 1. (Continued).

Problem	Description
12	Level-3, Reinforced Concrete Box, Analysis mode (LRFD). Analyze a 120 in. x 84 in. reinforced concrete box culvert with standard ASTM steel placement with 2 ft of fill over the top of the culvert using LRFD analysis. The analysis will be with Level 3, using a user-generated finite element mesh for an embankment installation. This problem analyzes the reinforced concrete box culvert from Tutorial Problem 7, which was performed using a Level 2 analysis.
13	Level-3, Corrugated Steel Long Span, Analysis mode (Working Stress). Analyze a 217-in. span (82-inch rise) 3-segment type corrugated steel long span arch setting on concrete footings with 3 ft of fill over the top of the arch using Working Stress (service) analysis. The analysis will be with Level 3, using an imported finite element arch mesh in XML format from Tutorial Problem 9 for a trench installation having interface elements. This problem analyzes the corrugated steel long span arch from Problem 9, which was performed using a Level 2 analysis.
14	Level-3, Reinforced Concrete and Corrugated Aluminum Arch, Analysis mode (Working Stress). Analyze a two-material structure composed of a reinforced concrete U-shaped base with 15-ft span and 5-ft rise supporting a pin connected, corrugated aluminum arch-shaped roof with 13 ft of fill over the top of the arch. The analysis will be with Level 3, using an imported finite element mesh in XML format.
15	Level-3, Multiple Plastic Arches, Analysis mode (LRFD). Analyze three corrugated plastic arches with 42 in. span and 27 in. rise placed side by side with 8.5 in. spacing between the legs (storm water retention chambers) with 2 ft of soil over the top of the arches. The analysis will be with Level 3, using a user-generated finite element mesh for a trench installation. The desired analysis result is to evaluate LRFD local and global buckling. (INPUT FILE ONLY)
16	Level-3, Corrugated Steel Pipe Retrofitted with Plastic Pipe Liner, Analysis mode (Working Stress). Analyze a 48 in. corrugated steel pipe with an eroded invert and retrofitted with a profile plastic pipe with 5 ft of fill over the top of the pipe. The analysis will be with Level 3, using a user-generated finite element mesh for a trench installation. (INPUT FILE ONLY)

without interface elements. The desired results are the corrugation profile and sheet thickness and a final evaluation.

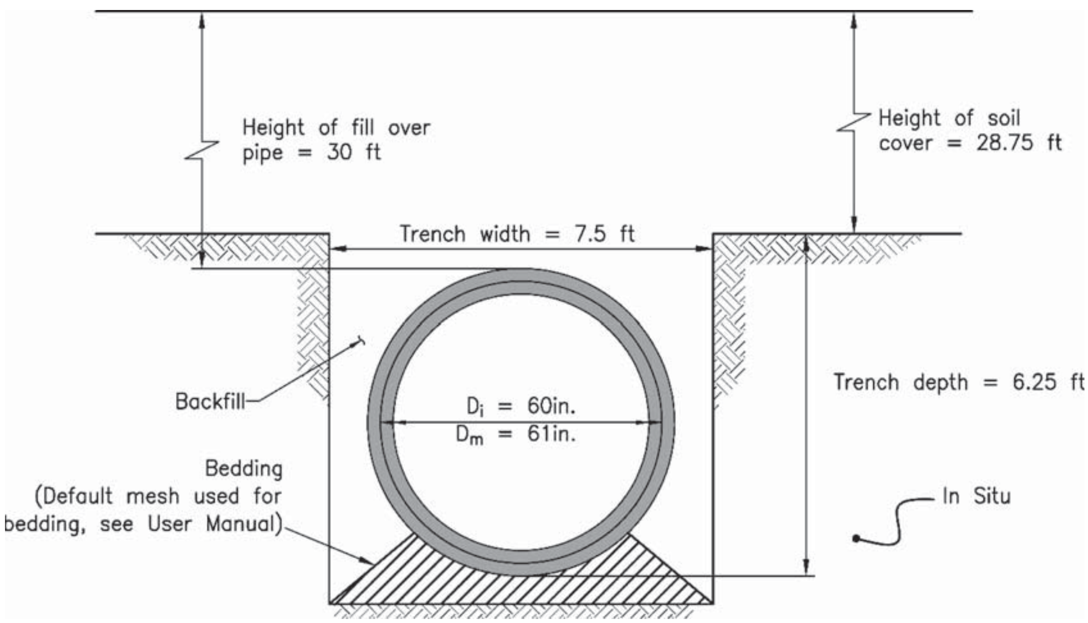
The tutorial leads the user through 10 GUI-input screens that convey the above physical information into a complete CANDE input document. After executing the input file, CANDE generates the symmetric mesh shown in Figure 10 wherein the shaded/numbered layers of soil are construction increments. The initial configuration, shown shaded with a numeric "1" in each box , includes the in situ soil bedding, and culvert. Next, three layers of trench fill soil are placed to the top of the trench (designated with load step numbers 2-4), followed by one larger layer of overfill (load step 5) to a fill height of 1.5 diameters above the crown. The remaining overfill soil loading is placed in five load steps using equivalent overburden pressure loading.

The design solution, taken directly from the CANDE output report, is shown in Figure 11, wherein three design-iteration cycles were required to determine the required thrust area, moment of inertia, and section modulus to sustain the soil loading with the desired safety factors. Using the required section properties, CANDE searches through the corrugation tables for aluminum culverts and lists the least weight design solution for each corrugation size.

From the list of acceptable corrugation sizes, CANDE selects the corrugation with a combined minimum thrust area and moment of inertia for a final analysis and evaluation. In this example, the selected corrugation profile is 2-2/3 in. (period) by 1/2 in. (height) with a metal thickness of 0.135 in.

After performing another analysis cycle, the CANDE Output report provides a final evaluation of the selected corrugation as shown in Figure 12. All safety factors meet or exceed the user-specified requirements. Excess safety occurs because the available manufactured section properties exceed the minimum required section properties.

This example, as do all the tutorial examples, demonstrates how CANDE-2007 differs from general purpose finite element programs. That is, CANDE sorts through all the mechanistic responses of deformations, stresses, strains, thrust, moments, and shears and summarizes the pipe performance in terms of safety factors or demand-to-capacity ratios.



Soil Zone	Type of Soil	Young's Modulus (psi)	Poisson's Ratio	Soil Density (lb/ft^3)
In situ	Hard clay	6,000	0.35	120
Bedding	Compacted sand	2,600	0.19	120
Backfill in trench	Compacted sand	2,600	0.19	120
Overfill above trench	Lightly compacted silt	800	0.23	120

Figure 9. Illustration of Tutorial Example #4 with soil zone properties.

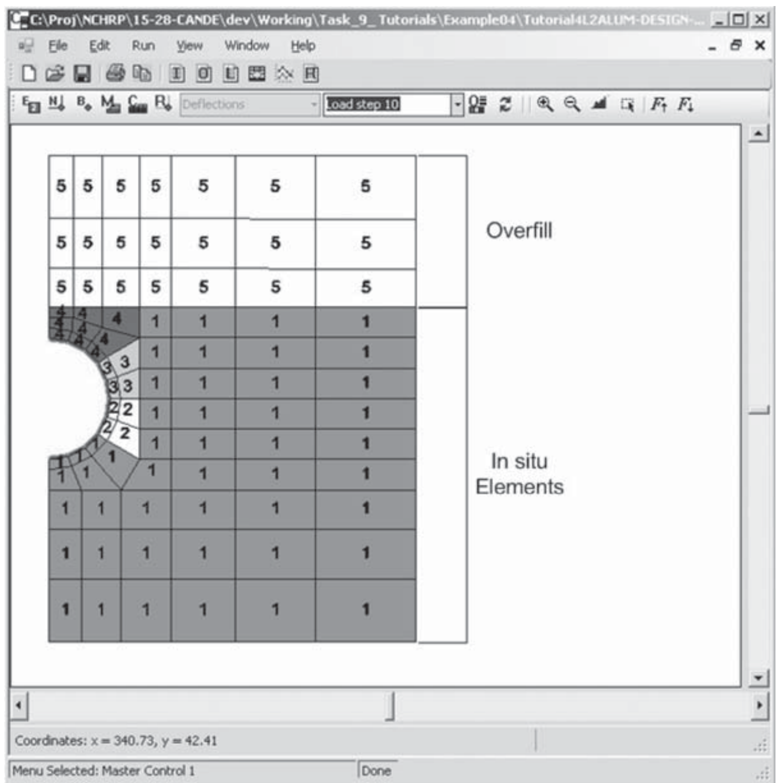


Figure 10. Soil construction increments for Tutorial Example #4 from GUI.

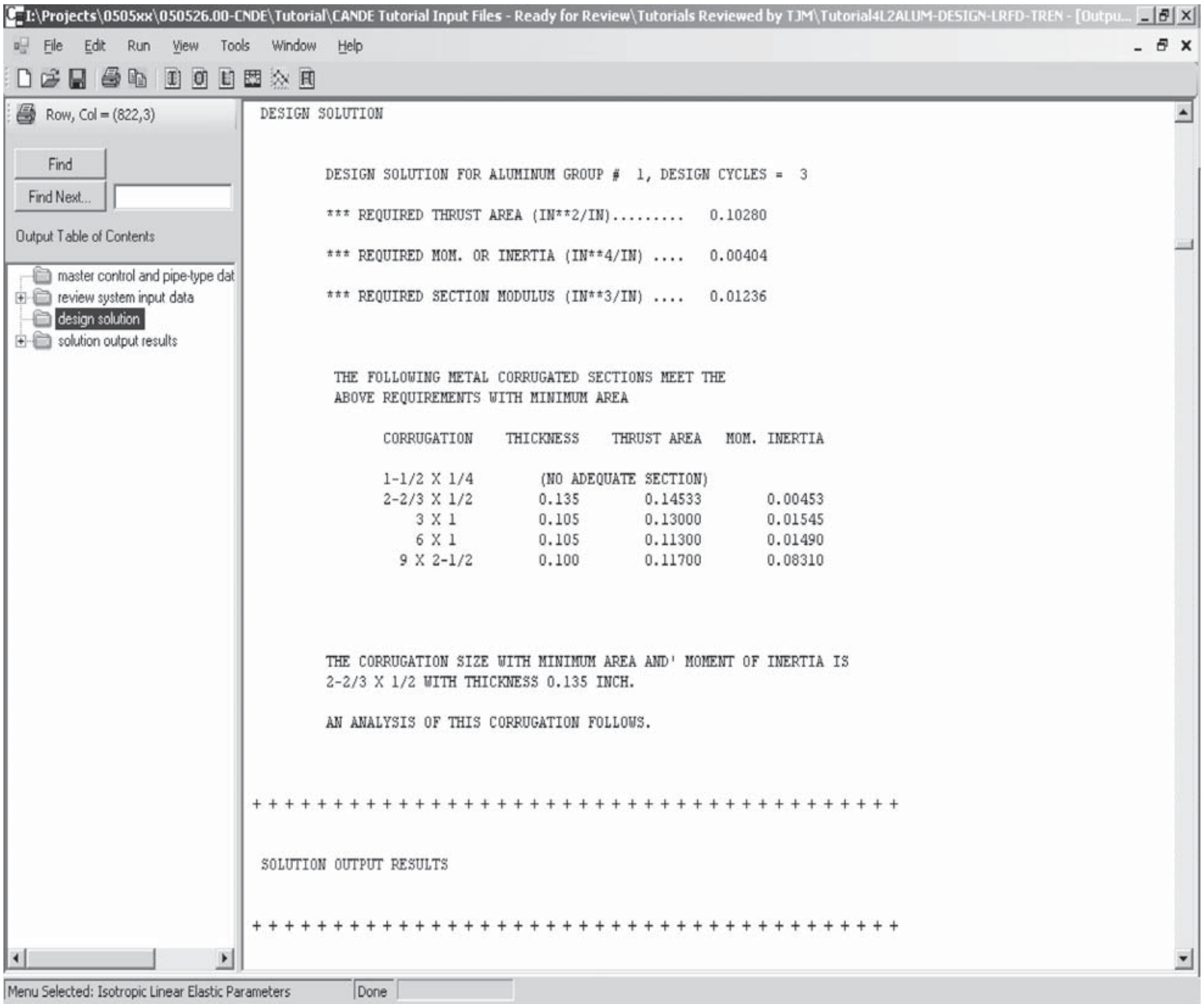


Figure 11. Design solutions for Tutorial Example #4.

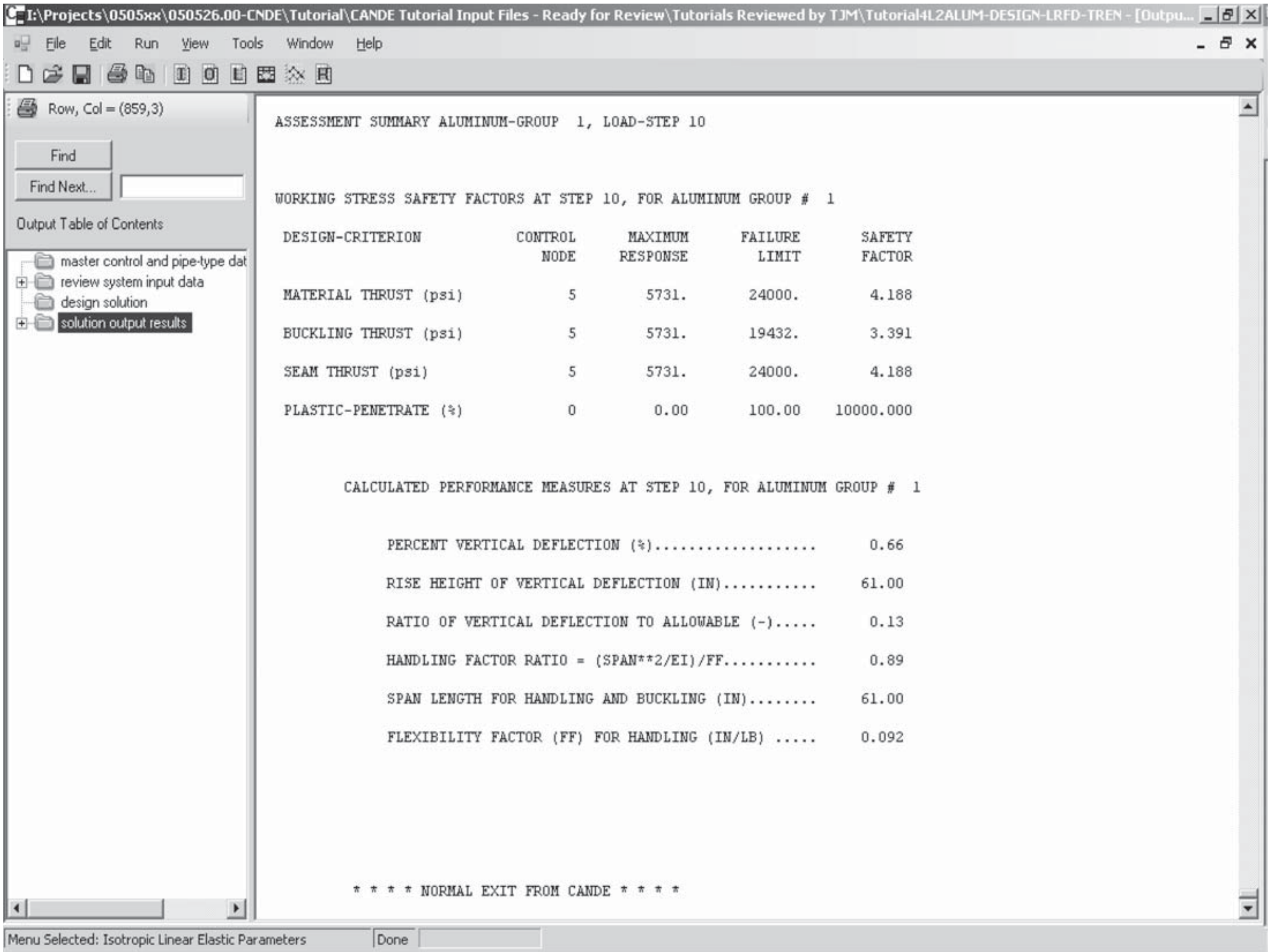


Figure 12. Final evaluation of selected design.

CHAPTER 4

Conclusions and Recommendations

Assessment

Every objective for the new CANDE capabilities and user-friendly GUI options has been met or exceeded. Of course, the user community will make the final judgment on the utility of CANDE-2007 after it is released into the public domain. Since the older versions of CANDE have been extensively used during the last 30 years to design highway culverts and other soil-interaction structures, it is reasonable to expect that engineers will continue to use CANDE in its newest version. In particular, when engineers are confronted with specialized installations that do not lend themselves to simplified or routine design methods, it is anticipated that CANDE-2007 will be the tool of choice. Moreover, because of the new user-friendly interface and the new LRFD design methodology, the CANDE usage may expand to include more routine culvert designs.

Future Research

As with any successful computer program, future upgrades and enhancements are a continuing process. Based on the comments of beta testers and survey results, the next recommended set of new capabilities to be incorporated into CANDE-2007 include the following:

1. Element death option to simulate removal of temporary bracing, excavating of soil, or loss of structural elements due to aging and corrosion/abrasion.
2. Reformulating the Duncan and Duncan/Selig soil model into a plasticity-based model to properly simulate unloading.
3. Incorporating shear deformation into structural beam-column elements.
4. Possible incorporation into the AASHTOWare™ suite of products such as Virtis or Opis.
5. Enhanced mesh generation capabilities.
6. Load rating capabilities.

As in the past, it is quite likely that some researchers will undertake incorporating one or more of the above capabilities into CANDE-2007 using their own research funds. This is an advantage of public domain software, like CANDE, wherein the entire user community contributes to future developments.

Implementation

It is recommended that AASHTO pursue all avenues of technology transfer for the CANDE software, not only its in-house methodology for software transfer and maintenance.

In summary, the researchers are confident that the new CANDE-2007 program is the best available tool for culvert design and analysis. Further, the researchers believe CANDE will continue to be the tool-of-choice well into the future provided that CANDE's successful attributes are maintained. These attributes include formulations that are based on sound principles of soil-structure interaction and a well-documented source code to allow other researchers to develop and test new theories and concepts in soil-structure interaction.

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APPENDIX

Table of Contents to Companion Documents

Three companion documents are associated with this report:

- *CANDE-2007 User Manual and Guideline,*
- *CANDE-2007 Solution Methods and Formulations*, and
- *CANDE-2007 Tutorial of Applications.*

The full documents are included with the CANDE-2007 software and are accessible from the GUI toolbar. The abbreviated table of contents of each document is shown on the following pages at the chapter level.

CANDE-2007 User Manual and Guideline—Abbreviated Table of Contents

CANDE-2007 Solution Methods and Formulations—Abbreviated Table of Contents

CANDE-2007 Tutorial of Applications—Abbreviated Table of Contents

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation