Division of Engineering Research on Call Agreement 31796

(Task 2 – Asymmetrical Deformation of Thermoplastic Pipe Analysis)

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for the Ohio Department of Transportation
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and the
United States Department of Transportation
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16. Abstract

This study investigated asymmetric deformation (racking) of installed thermoplastic pipe. ODOT construction records were reviewed to determine the extent of racking noted within Item 611 Conduit Evaluations. Next, a rational method for assessing racking was developed within the framework of the AASHTO LRFD Bridge Design Specifications, Section 12. A spreadsheet was developed to aid in the assessment procedure. The results of the methodology were compared to test cases analyzed using the 2D culvert specific finite element software CANDE. Finally, a one-day course covering the basics of the finite element method was developed and presented to ODOT staff.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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CHAPTER 1: INTRODUCTION

1.1 Scope of Work

The Ohio Department of Transportation (ODOT) wishes to develop a practical method for assessing asymmetrical deformation of installed thermoplastic pipes. ODOT Construction and Material Specifications (CMS) Item 611 requires such asymmetrical deformation (termed "racking") to be evaluated by an independent Registered Engineer.

American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Construction Specifications, Section 30 (2010) refer to Section 12 of the AASHTO LRFD Bridge Design Specifications (2017) for assessment of the structural suitability of installed thermoplastic pipe. However, Section 12 design procedures are all based on deflections less than 5% and are based on uniform deflection. Section 12 does not consider racking in the design method and does not consider deflections in excess of 5%. The assessment is, therefore, left wholly to the independent Registered Engineer.

Assessment of these types of distortion can be assessed using finite element modelling which can estimate the stresses and strains in the pipe wall.

The project goals are to address these deficiencies and offer guidance for the assessment of pipe distortion and racking, and to provide basic training to ODOT personnel on the use of finite element modelling (FEM). The following tasks will be utilized to accomplish these goals.

The project team will make contact with ODOT staff, both in Central Office and in District Offices to identify the types of distress commonly identified during 611 post-construction conduit inspections. In addition, we will draw on our experiences as an independent Registered Engineer and experiences of industry colleagues in identifying common conduit defects.

The project team will develop 2D FEM models using the public domain Culvert Analysis and Design (CANDE) FEM software. The models will be utilized to conduct a parametric study on the performance of distorted thermoplastic pipe.

Based on the results of the parametric study conducted as Task 2, the team will develop a Distortion Assessment Methodology. This will be a practical method for measuring thermoplastic pipe distortion and assessing the structural suitability of the distorted pipe. This will include pipe sizes with nominal diameters of 12 in to 60 in.

A short training procedure will also be developed in order to provide training of the methodology to ODOT personnel.

The project team will develop an introductory training course in the finite element method. The course will not focus on the mathematics behind the method, but rather the practical implementation of the methodology to solve soil-structure interaction problems. The training will discuss soil material models, structural element material models, and interface elements.

The training will discuss both the positive aspects of FEM as well as common pitfalls.

1.2 Outline of the Report

Chapter 2 covers the literature search which aimed at review of current state of the practice in assessing non-symmetric deformation in buried thermoplastic conduits. In addition, a summary of existing ODOT 611 inspection data reviewed are provided in Chapter 2.

Chapter 3 presents the methodology utilized to develop the racking assessment tool as well as the finite element models used to assess the tool.

Chapter 4 discusses the development of the finite element method training session.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

A literature search was conducted to gather literature, specifications, and standards related to the proposed research project's main topic – assessment of asymmetric deformation in thermoplastic pipe. Past and recent publications made in relevant major technical journals and proceedings of conferences and symposia were reviewed to locate technical papers of interest. Some of the target journals and conference publications included:

- TRR (Journal of the Transportation Research Board (TRB))
- American Society of Civil Engineer (ASCE) Journals
- American Society for Testing and Materials (ASTM) Journal
- Proceedings of TRB Annual Meetings
- ASCE Conference Proceedings
- ASTM Symposium Proceedings
- ASTM Specifications

Reports issued on the topic considered in the literature search including:

- Reports Issued by Federal Highway Administration (FHWA), State Departments of Transportation, United States Department of Agriculture (USDA), and Natural Resources Conservation Service (NRCS)
- National Cooperative Highway Research Program (NCHRP) Reports and Syntheses
- Reports issued by research institutions
- Reports issued by pipe manufacturers

The team contacted Plastic Pipes Institute (PPI) member manufacturers and researched the websites of PPI member manufacturers and distributers to collect relevant information.

The results of the literature search produced very little regarding asymmetric deformation. The only germane publication is an article from the Compendium of Papers from the Transportation Research Board 94th Annual Meeting Compendium of Papers entitled "Evaluating Installation Racking in Buried Thermoplastic Conduits" (Domonell, Mailhot, & Beaver, 2015). This paper presents a methodology for assessing the flexural strain resulting from crown racking in buried arch-shaped stormwater chambers. The methodology assumes circumferential strain (thrust strain) remains essentially unchanged from the unracked condition. The method then uses field measurement tools to measure the radius of curvature of the deformed section by measuring the sagitta and chord length of the racked portion of the pipe wall. Finally, the method uses newely developed load combinations that reduce dead load factors because the shape and state of the deformed shape is measured in detail.

CHAPTER 3: DEVELOPMENT OF RACKING ASSESSMENT TOOL

3.1 Assumptions and Limitations of the Methodology

Several simplifying assumptions are made to aid in the development of the racking assessment tool. These factors include:

- The deformed conduit can be reasonably estimated as an ellipse, or as a rotated ellipse.
- The deformed conduit shape is relatively stable.
- Maximum deflections do not exceed 10% to 12%. When deflections exceed this limit, the stability of the conduit ring is in question and global stability cannot be assured.
- The methodology should, insofar as practicable, be consistent with AASHTO LRFD Bridge Design Specifications, Section 12.

3.2 Conduit Mechanical Properties

HDPE pipes exhibit viscoelastic behavior. Viscoelastic materials tend to creep under constant stress and relax under constant strain. Stated otherwise, a conduit under a constant stress will creep (deflect). Whereas, the stress required to maintain a constant strain (deflection) will reduce with time. One interesting result of this viscoelastic response is that the there is an apparent reduction in the modulus with time. This relaxation response and apparent reduction in stiffness can be seen in Figure 1 and Figure 2

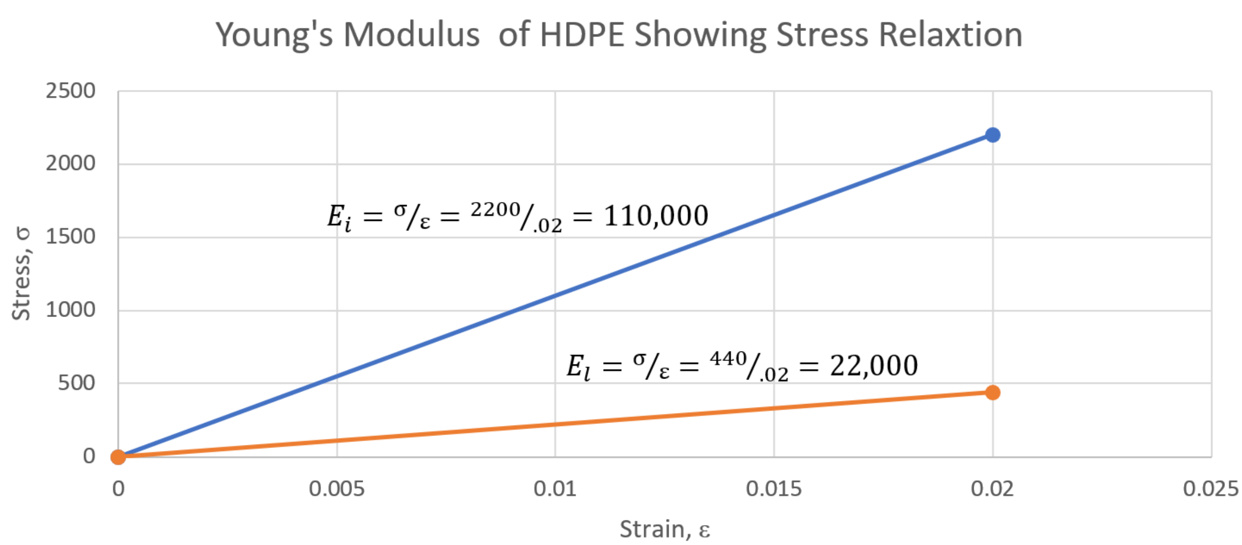

Figure 1 - Modulus of HDPE showing stress relaxation

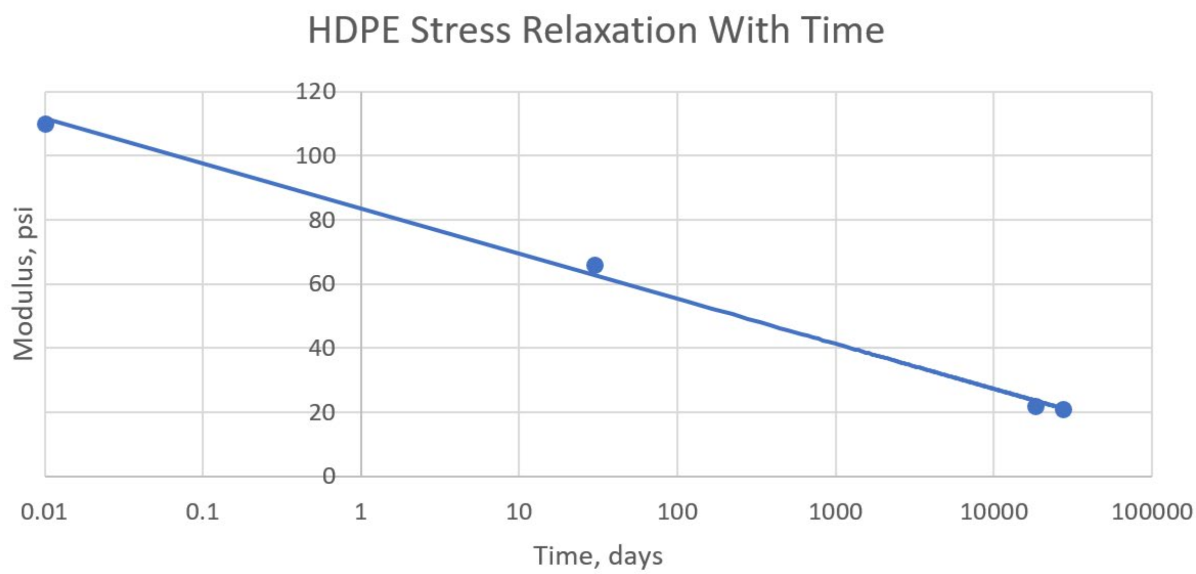

Figure 2 - Apparent reduction in modulus with time

Data from NCHRP Report 870 (2018) on the relaxation of HDPE pipe under constant stress shows that after 30 days there is an apparent reduction of 60 percent in the mechanical properties of HDPE conduit meeting AASHTO M294. A best-fit log-linear equation was calculated using the AASHTO reported initial, 50- and 75-year values for the modulus of 110 ksi, 22 ksi and 21 ksi, along with a 30-day value of 66 ksi (60 percent of 110 ksi). This results in the following equation for determining the modulus as a function of time.

$$E = -6.092 \ln t + 83.419 \quad (1)$$

The flexural strength, f_y, as a function of time was calculated in a similar manner with the following resulting equation.

$$f_y = -0.147 \ln t + 2.3164 \quad (2)$$

3.3 Constrained Soil Modulus Estimation

Assessing the in-situ stiffness of the backfill soil around the installed conduit is a challenge. Non-destructive methods such as a cone penetrometer can be utilized. However, this may be unrealistic for conduits under pavements and can be a cost-prohibitive methodology. Considering the desire to provide a methodology consistent with AASHTO Section 12, it is necessary to determine the secant constrained soil modulus as this is a fundamental variable in the Section 12 design procedure. An equation-based methodology is proposed wherein the secant constrain soil modulus is calculated using the AASHTO modification to the Iowa

Equation for vertical deflection. The AASHTO (2017) equation expands the original Modified Iowa equation to consider both flexural defection and circumferential shortening. The equation is:

$$\Delta = \frac{K_B\left(D_L P_{sp} + C_L P_L\right) D_o}{1000\left(E_p I_p / R^3 + 0.061 M_s\right)} + \varepsilon_{sc} D \tag{3}$$

where:

Δ = Total deflection

D_L = Deflection lag factor

K_B = Bedding coefficient, typically 0.10

P_{sp} = Soil prism pressure

C_L = Live load coefficient

P_L = Live load pressure

D_o = Outside diameter of the conduit

E_p = Modulus of the conduit material

I_p = Moment of inertia of the conduit material

R = Centroidal radius of the conduit

D = Centroidal diameter of the conduit

M_s = Secant constrained soil modulus

ε_{sc} = Service compressive strain given as:

$$\varepsilon_{sc} = \frac{T_s}{1000\left(A_{eff} E_p\right)} \tag{4}$$

where:

T_s = Service compressive thrust

A_{eff} = Effective area of conduit wall

It is noted that service thrust is also a function of the secant constrained soil modulus which adds considerable complexity to the derivation of secant constrained soil modulus from the field measured deflection thus, an iterative solution procedure is recommended. It is also noted that the deflection lag factor is an empirical factor used to estimate the long-term settlement of the soil surrounding the conduit which results in additional long-term conduit deflection. Because the actual field measured deflection is utilized in Equation (3), the deflection lag factor is set to unity.

As the conduit deformations exceed 7%, there is a rapid decline in the calculated constrained soil modulus to values well below what practical experience dictates as being realistic minimum values. Because of this, a minimum constrained soil modulus is set equivalent to the range of values presented for silty soils at 85 percent standard proctor density. These values are provided in Table 12.12.3.5-1 of AASHTO Section 12. The silty soil type selection as a lower bound is somewhat arbitrary and is based solely on the experience of the authors.

3.4 Flexural Strain

AASHTO provides an empirical approach for calculating maximum flexural strain at the outer fiber of a profile-wall conduit. The equation is given as:

$$\varepsilon_f = \gamma_{EV} D_f \left(\frac{c}{R}\right)\left(\frac{\Delta_f}{D}\right) \quad (5)$$

where:

ε_f = factored flexural strain

γ_{EV} = load factor for earth and dead load pressure

Δ_f = Vertical deflection due to flexural

R = Centroidal radius of the conduit

D = Centroidal diameter of the conduit

D_f = Shape factor provided in AASHTO Section 12 Table 12.12.3.10.2b-1

c = Distance from profile centroid to innermost or outermost fiber

A simplified method of computing flexural strain can be determined from the deformed shape of the pipe and the change in radius of the conduit wall. Two methods for determining the change in radius are presented. The first is by assuming the deformed conduit is in the shape of an ellipse. For this methodology the changed radius is calculated as:

$$R_s = \frac{b^2}{a} \quad (6)$$

$$R_c = \frac{a^2}{b} \quad (7)$$

where:

R_s = radius of the conduit springline

R_c = radius of the conduit cro7wn

a = ½ of the semimajor axis (see Figure 3)

b = ½ of the semiminor axis (see Figure 3)

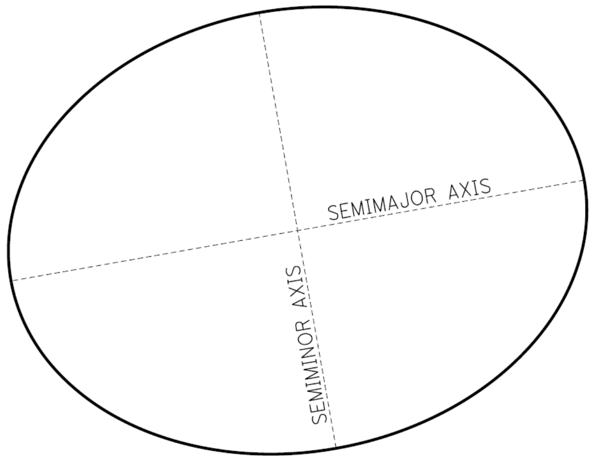

Figure 3 - Ellipse nomenclature

The second method uses the measured sagitta and chord length of the deformed shape to calculate the change in radius. See Figure 4 for a representation of the measurement methodology. For this methodology the changed radius is calculated as:

$$R_d = \frac{L^2}{8e} + \frac{e}{2} \tag{8}$$

where:

R_d = Changed radius of the conduit

L = Common chord length

e = sagitta length

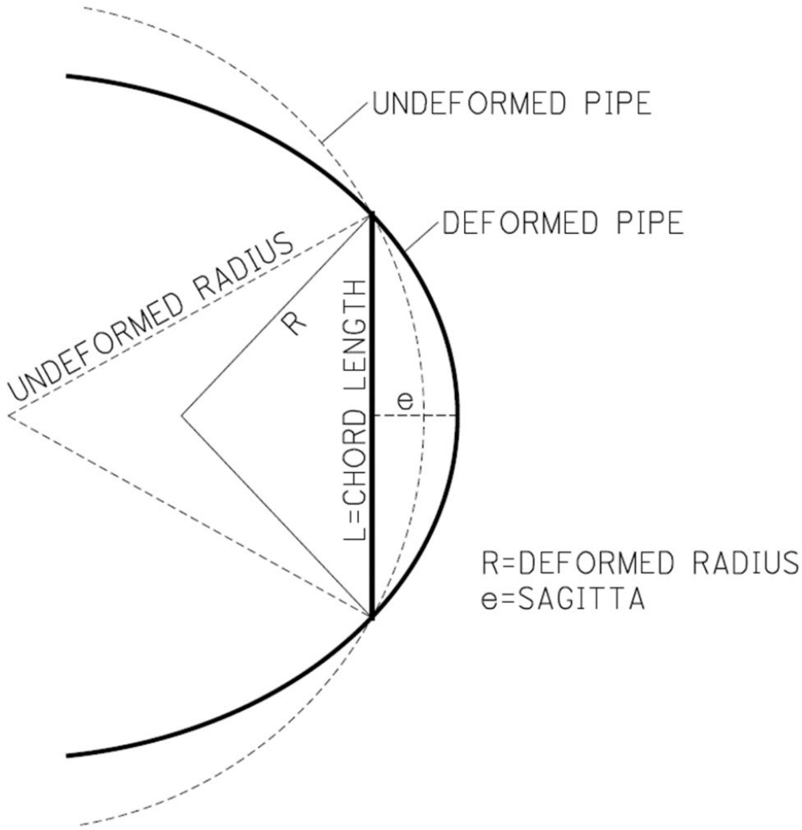

Figure 4 - Sagitta nomenclature

Once the changed radius is calculated, the equation for flexural strain can be calculated from three relationships (Waktins & Andersen, 2000). The first is the general equation for flexural stress, σ, given as:

$$\sigma = \frac{Mc}{I} \tag{9}$$

where:

M = Moment at the point of radius measurement

The next is the relationship between the flexural moment and the change is radius of the conduit.

$$\frac{M}{EI} = \frac{1}{R} + \frac{1}{R'} \tag{10}$$

where:

R = Centroidal radius of the conduit

R' = Changed centroidal radius of the conduit (R_c, R_s or R_d from the above equations)

The final relationship is the stress/strain relationship of modulus.

Using these relationships, the flexural strain in the deflected conduit can be calculated as:

$$\varepsilon = c\left(\frac{1}{R} - \frac{1}{R'}\right) \tag{11}$$

3.5 Compression Strain

Compression strain in the racked conduit wall is assumed to be essentially equivalent to the compression strain in a conduit without racking. This approach is validated via finite element analysis herein as well as by the work of Domonell, *et. al.* (2015).

3.6 Assessment of Racking AASHTO Design Methodology

Once the estimated secant constrained soil modulus and field measured flexural strain are calculated using the methods described herein, it is possible to assess the long-term suitability of the installation using standard AASHTO design procedures. It is not necessary to check for deflection or to check the flexibility factor.

A spreadsheet has been developed to aid in the calculations. An electronic version of the spreadsheet was delivered to the ODOT Office of Hydraulic Engineering. The spreadsheet is included as Appendix A.

3.7 Finite Element Analysis

3.7.1 Introduction

Finite element analysis (FEA) was performed to assess the response of a racked conduit under soil loading. The FEA was completed using the specific purpose finite element software CANDE (Culvert Analysis and Design). The response of a 36-inch conduit to racking and soils loading was determined from the CANDE output. The CANDE model utilized a 75-year apparent modulus and apparent flexural strength. The 75-year values of 21 ksi and 800 ksi, respectively, were taken from AASHTO Section 12 tabular values.

The principal of superposition was utilized for the analysis. Within the linear elastic domain, superposition is a method wherein loads applied to a system are invoked (superimposed) one at a time. The resulting total deformation is then calculated as the summation of the deformations from each individual load.

3.7.2 HDPE Pipe Model

The model used to analyze the effect of earth load on a 36-inch diameter HDPE pipe is shown in Figure 5. The model consists of four components, an in-situ soil trench with height and width of 8 and 10 feet, respectively, structural backfilling of 5 feet, overfill of 4 feet, and the 36-inch diameter conduit. Beam element results that follow all follow the same node numbering convention with node 1 located at the crown of the pipe and numbering then moving about the pipe in a clockwise until node 17, concurrent with node 1, is reached, as shown in Figure 6.

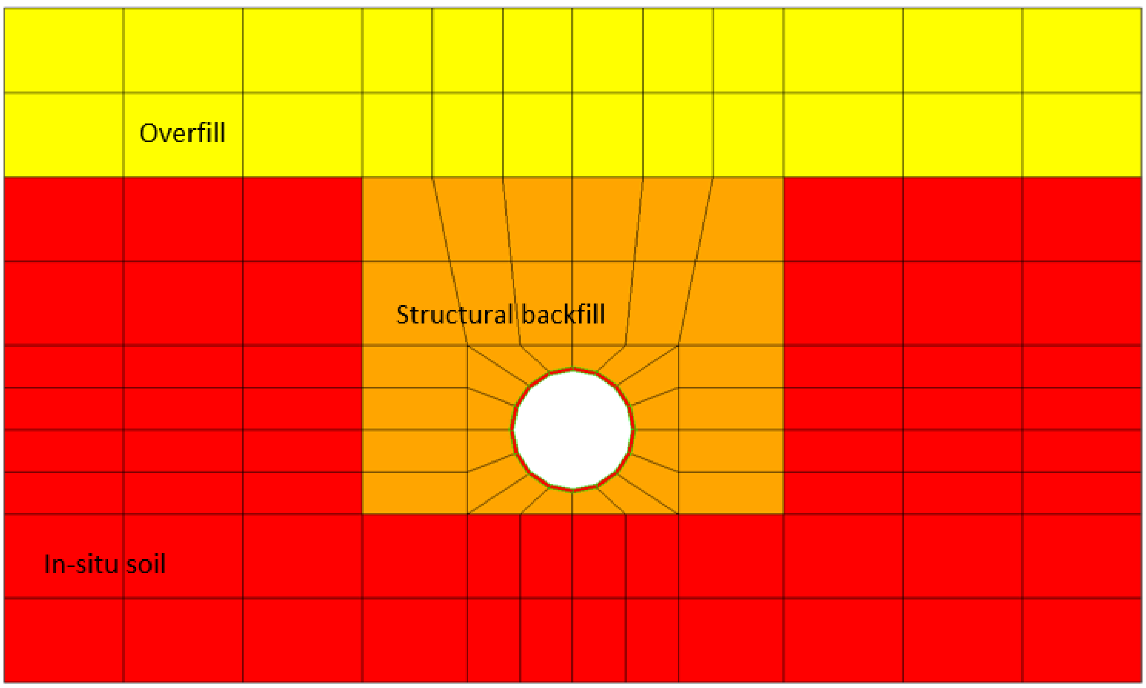

Figure 5 - CANDE model soil zones

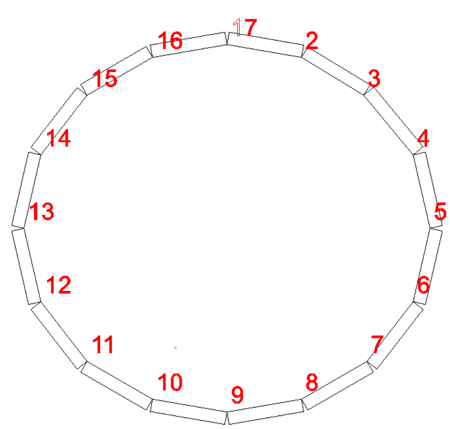

Figure 6 - CANDE Beam Element Results Numbering Convention

3.7.3 Load Step 1

The first load step shows the in-situ soil with the conduit ring sitting above the bedding layer as depicted in Figure 7. The deformed shape was created by applying a displacement boundary condition with a value of 1.8 inches on the node at the crown of the conduit. This deformation equates to a nominal 5 percent deflection.

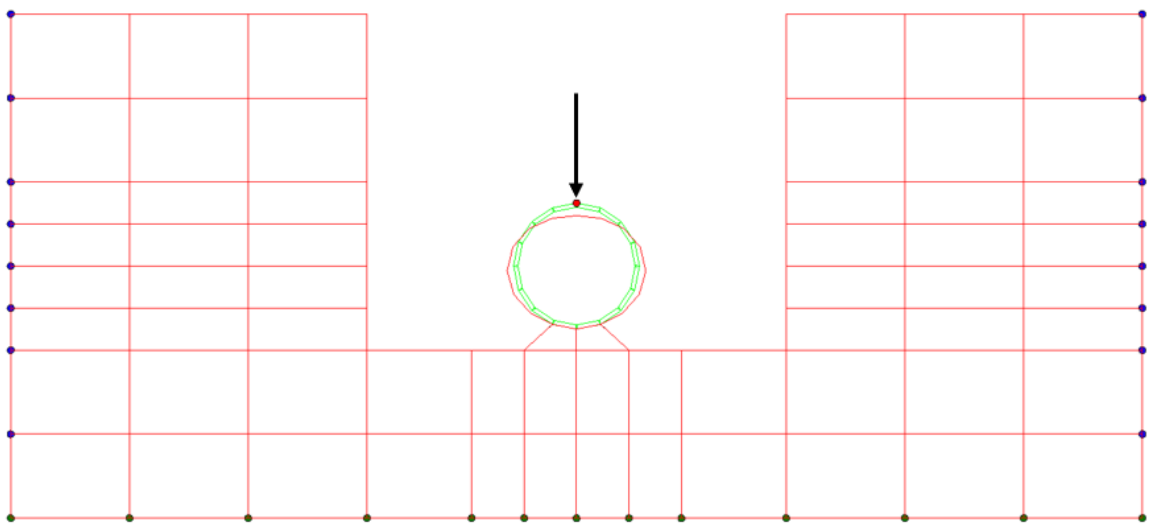

Figure 7 - CANDE Load step 1

3.7.4 Elliptical Pipe Model

The elliptical pipe model was created by using an elliptical conduit representative of a circular conduit deflected 5% of its nominal diameter. The CANDE model is shown in Figure 8.

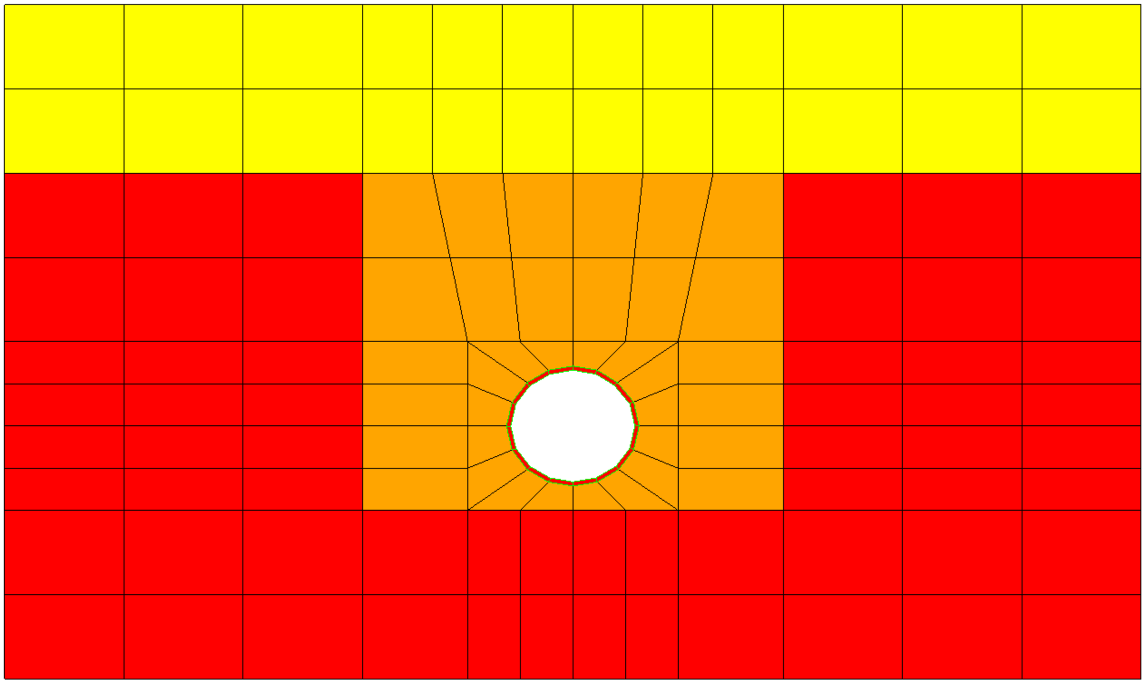

Figure 8 - Elliptically deformed conduit model

Results of the elliptical model are shown in Figure 9 through Figure 12.

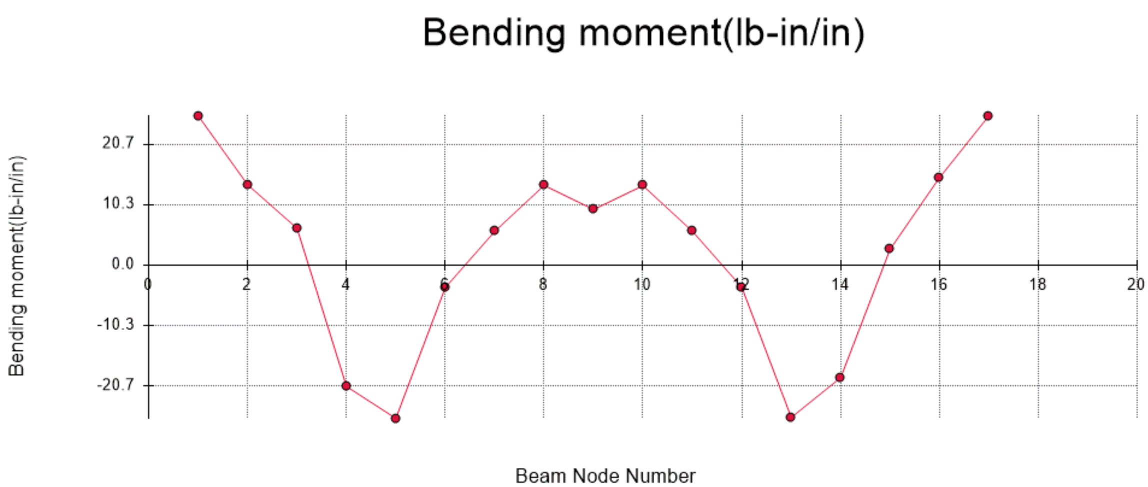

Figure 9 - Flexural moment for elliptical conduit model

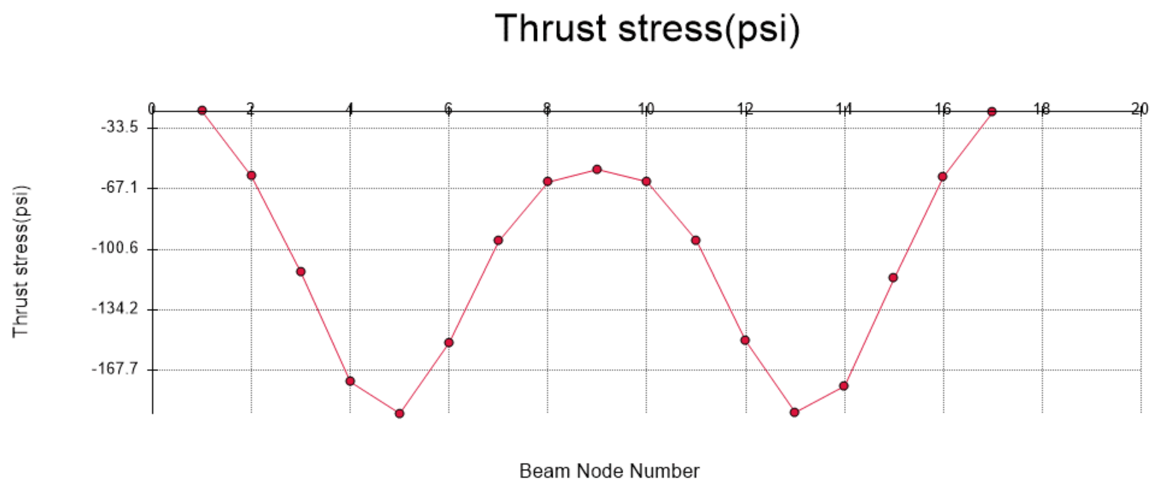

Figure 10 - Thrust stress for elliptical conduit model

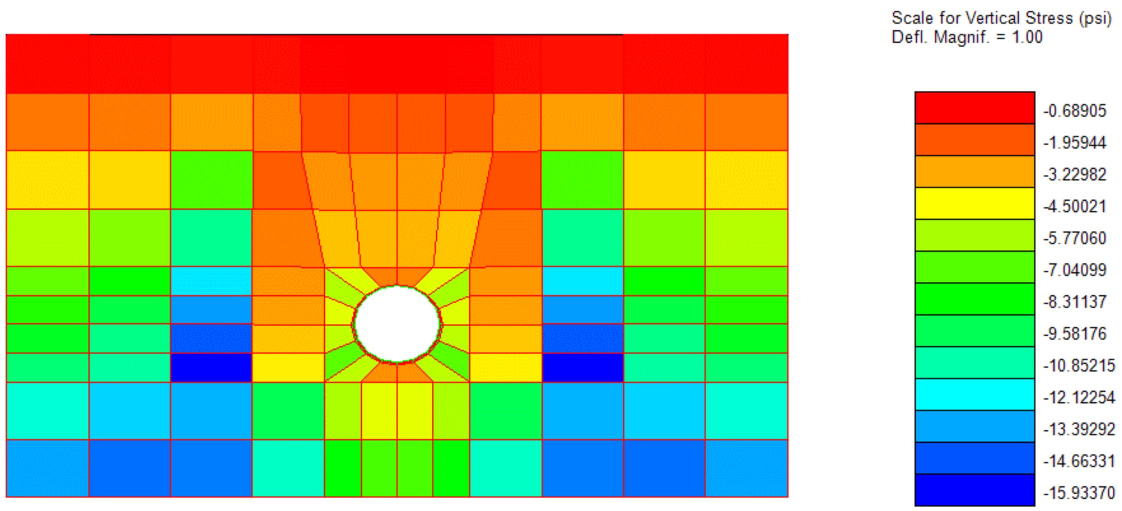

Figure 11 - Vertical soil stress for elliptical conduit model

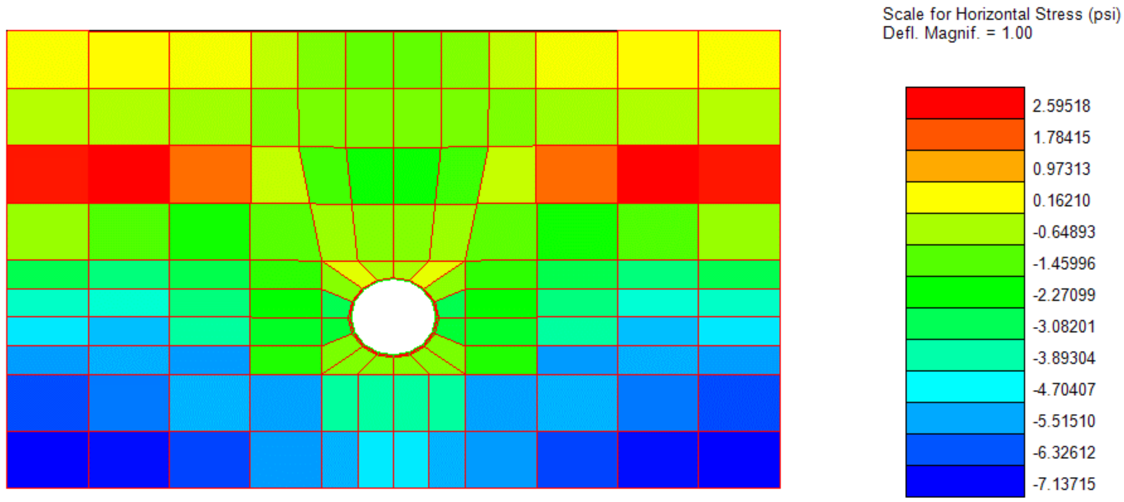

Figure 12 - Horizontal soil stress for elliptical conduit model

3.7.5 Elliptical Pipe Model Rotated Through 15°

The basic elliptical pipe model was rotated through 15° to create an idealized racked conduit. The CANDE model is shown in Figure 13.

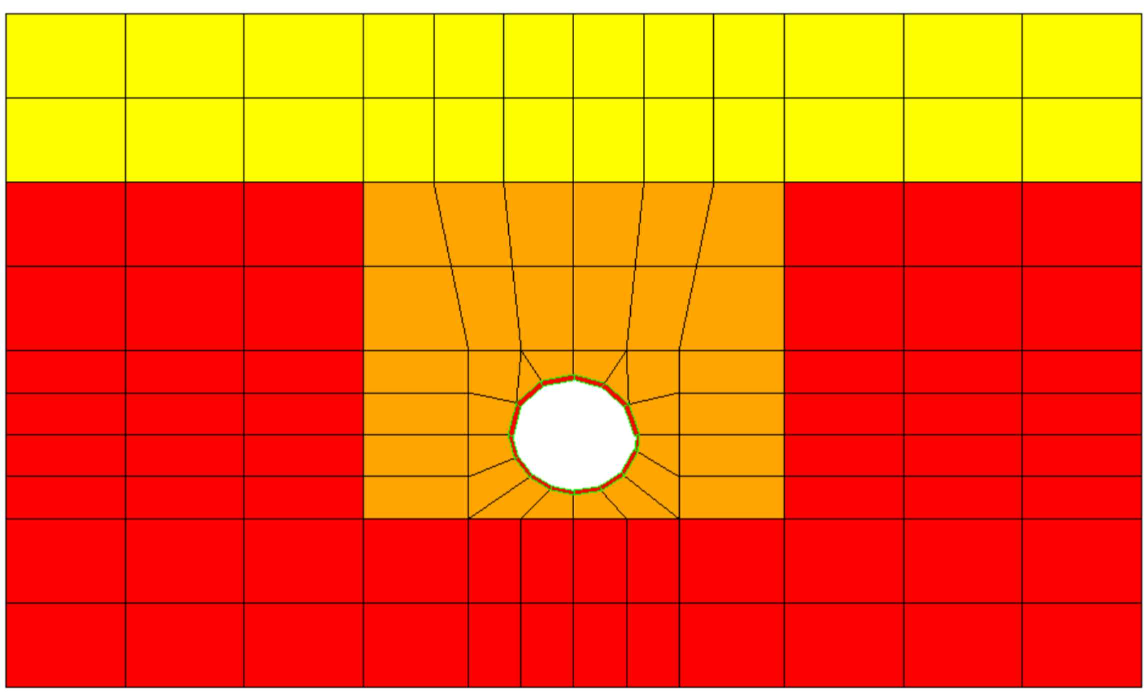

Figure 13 - Elliptical conduit model rotated through 15°

Results of the elliptical model rotated through 15° are shown in Figure 14 through Figure 17.

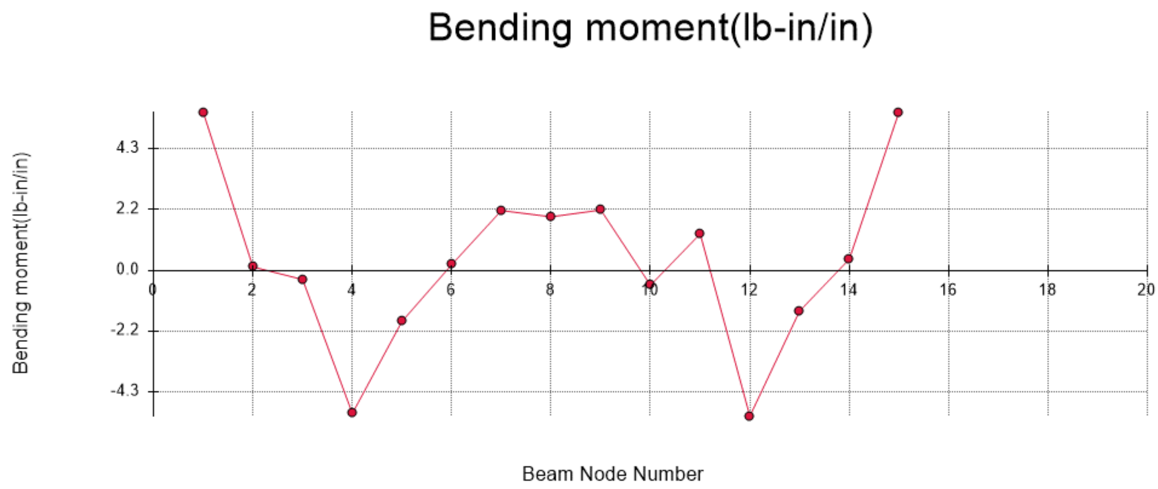

Figure 14 - Flexural moment for 15° rotated elliptical conduit model

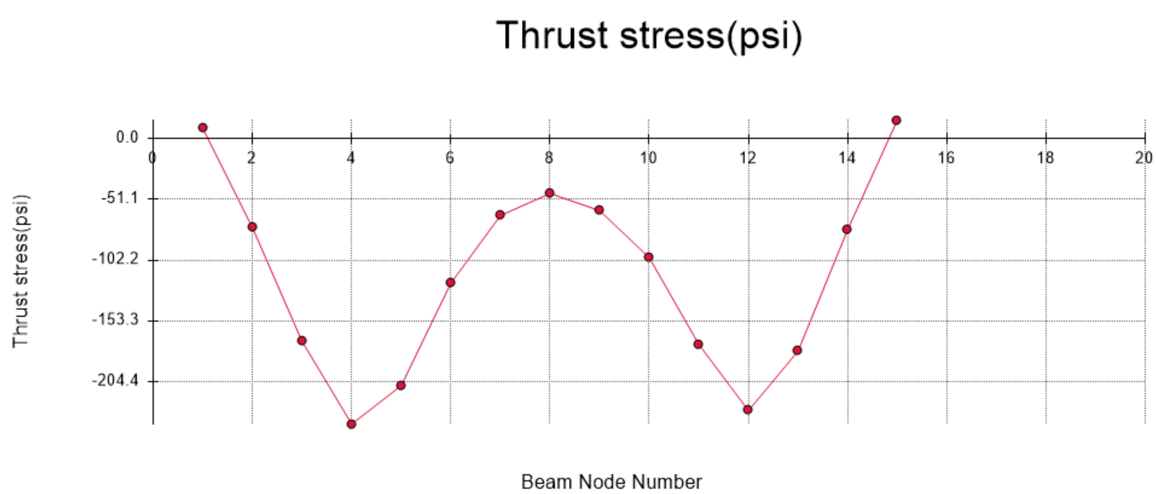

Figure 15 - Thrust stress for 15° rotated elliptical conduit model

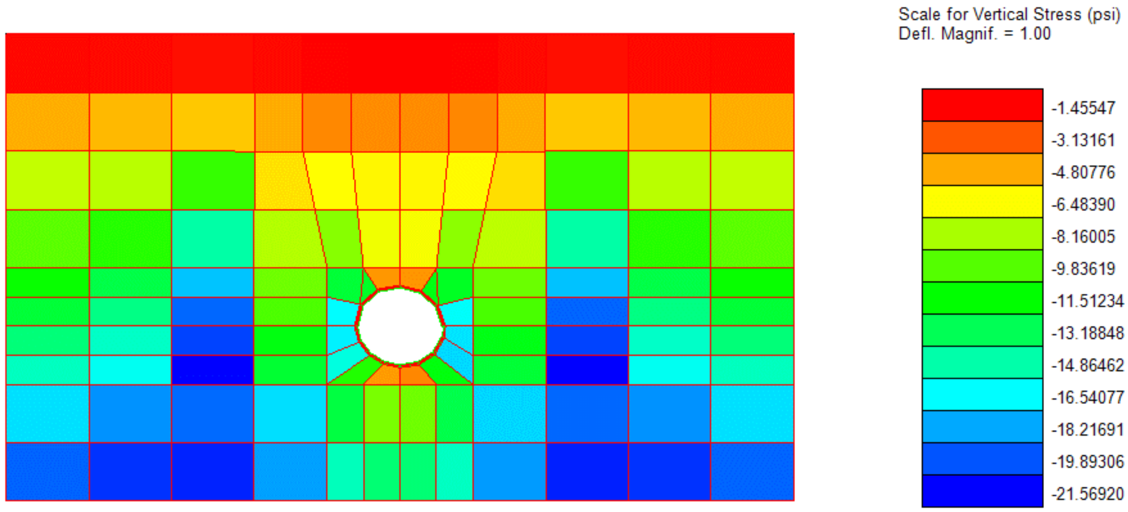

Figure 16 - Vertical soil stress for 15° rotated elliptical conduit model

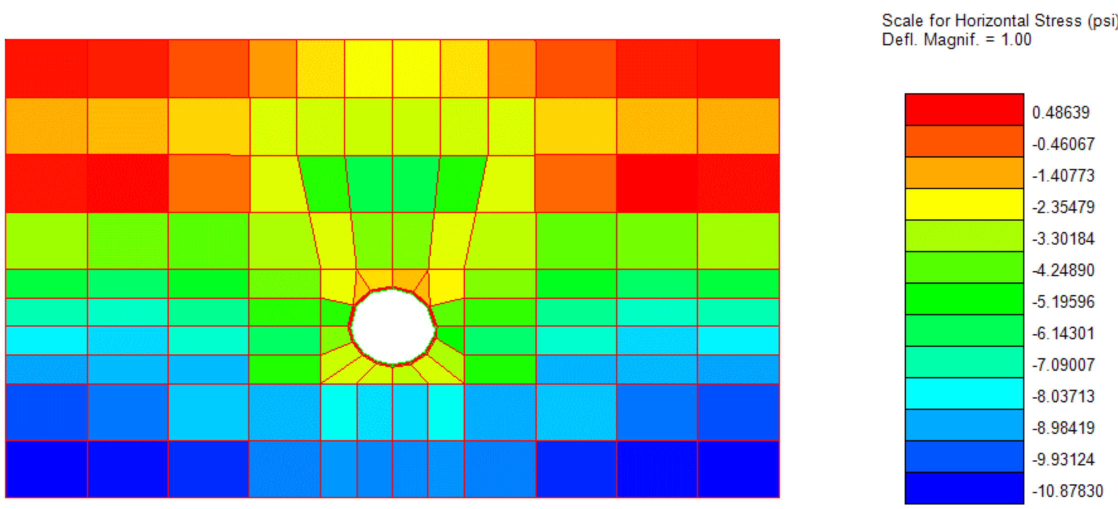

Figure 17 - Horizontal soil stress for 15° rotated elliptical conduit model

3.7.6 Elliptical Pipe Model Rotated Through 30°

The basic elliptical pipe model was rotated through 30° to create an idealized racked conduit. The CANDE model is shown in Figure 18.

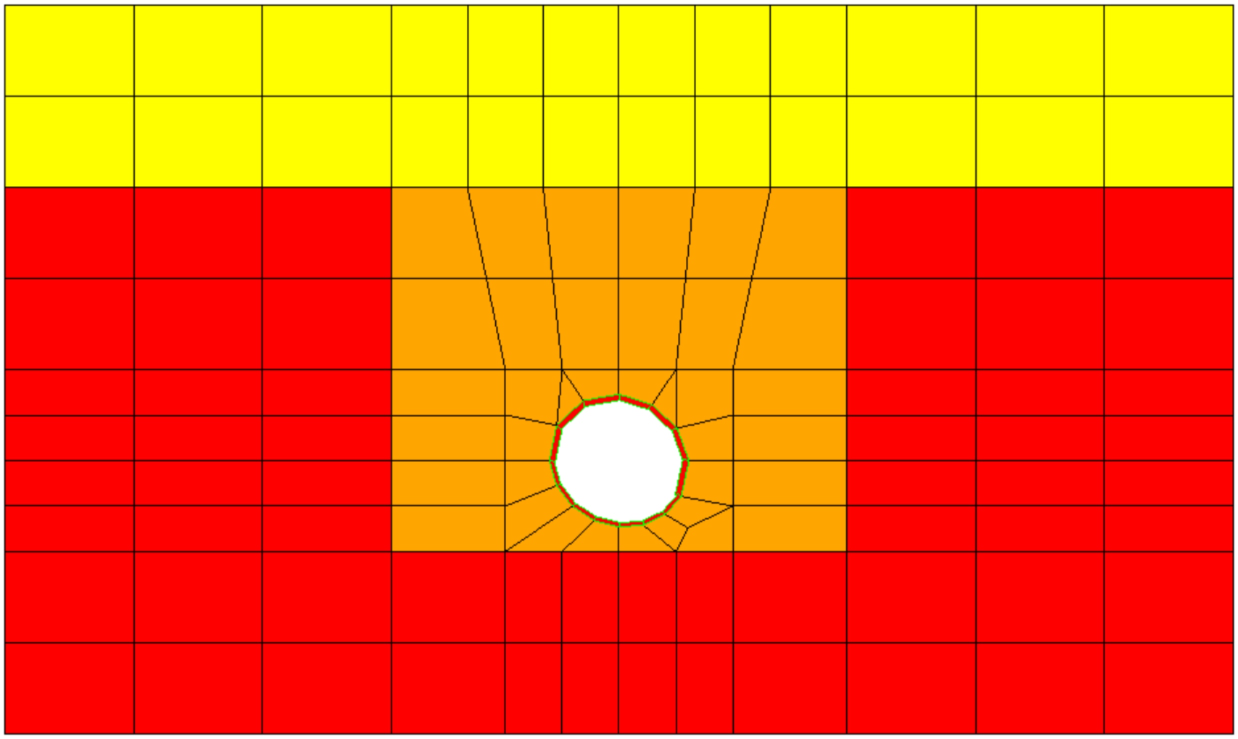

Figure 18 - Elliptical conduit model rotated through 30°

Results of the elliptical model rotated through 30° are shown in Figure 19 through Figure 22.

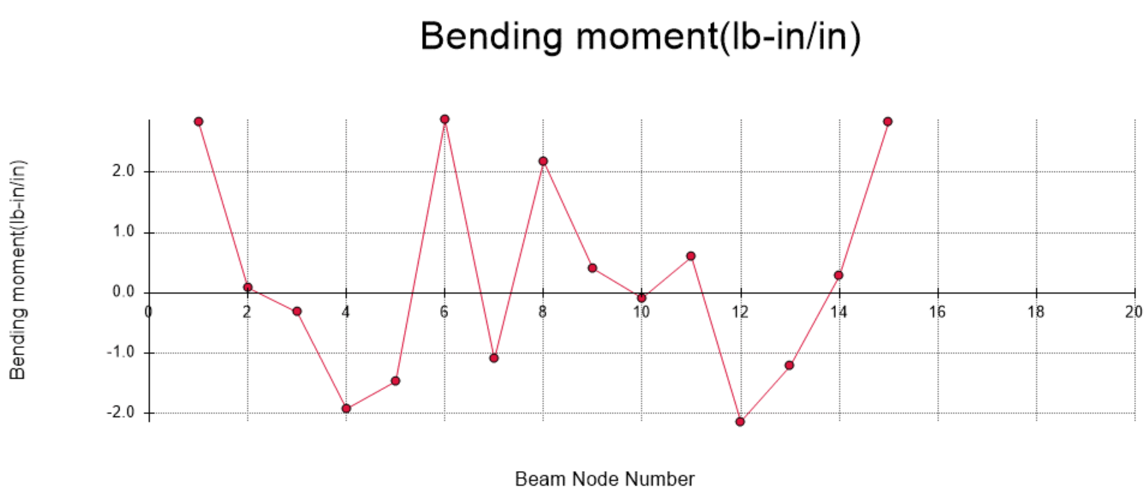

Figure 19 - Flexural moment for 30° rotated elliptical conduit model

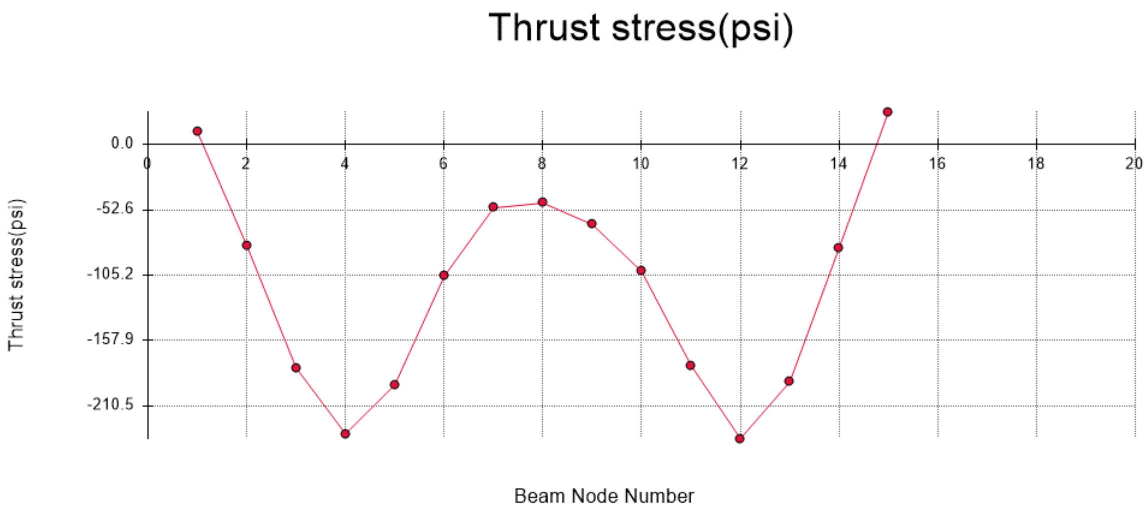

Figure 20 - Thrust stress for 30° rotated elliptical conduit model

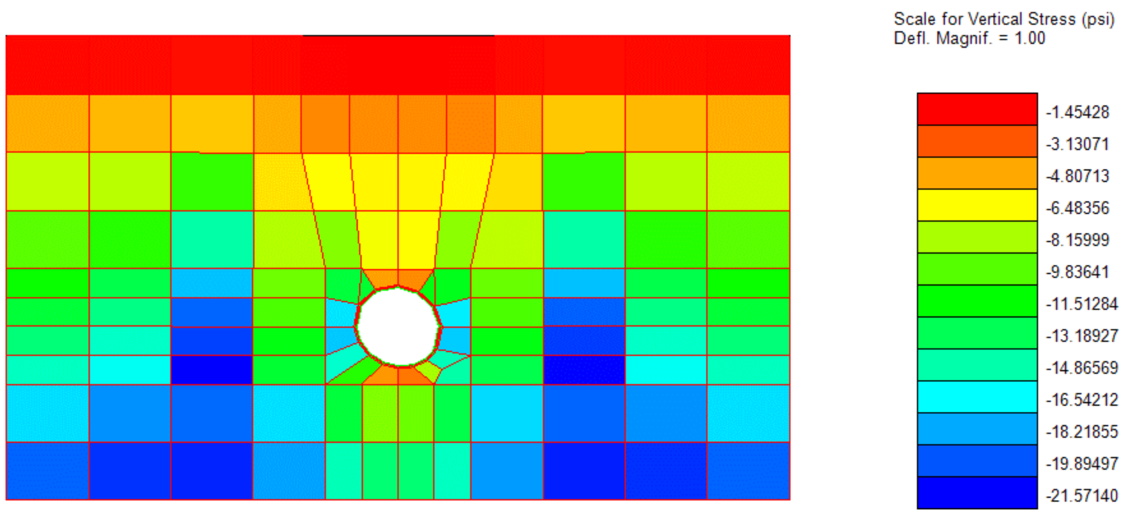

Figure 21 - Vertical soil stress for 30° rotated elliptical conduit model

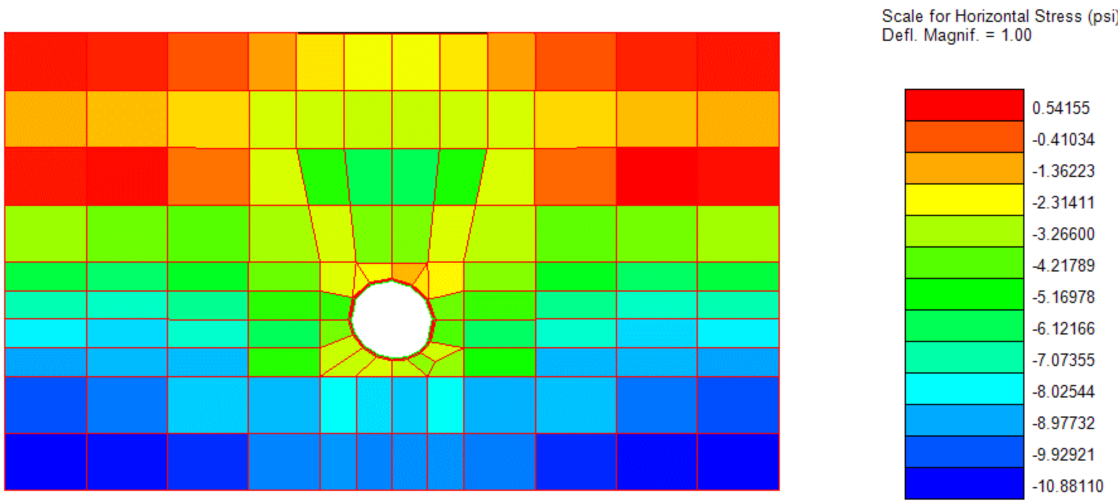

Figure 22 - Horizontal soil stress for 30° rotated elliptical conduit model

3.8 Validation of the Methodology

Results derived from the methodology presented in Sections 3.3 through 3.5 are compared to the results of the finite element analyses presented in Section 3.7 to assess the suitability of the methodology.

The FEA were conducted at service state without additional load or resistance factors. For consistency, all applicable load and resistance factors have been set to unity when calculating the response of the conduit using AASHTO Section 12 methodologies. AASHTO Section 12 computes the flexural and circumferential (thrust) strains independent of one another whereas CANDE provides the combined nodal strains. For the following narrative compressive reactions are presented as negative values whereas tensile reactions are presented as positive values.

The results of the analyses are presented in Table 1. Upon inspection the tensile zone results do not correlate well between the two methods. The FEA tends to underestimate tensile strains in the conduit wall when compared to the AASHTO method. Upon further inspection the reason for the difference becomes evident. Calculation differences between the two methodologies result in substantially different wall thrust forces. As an example, the AASHTO calculated thrust force at the springline and crown are 125 lb/in and 77 lb/in, respectively. Whereas the CANDE calculated thrust forces for the 15° Ellipse are 78 lb/in and 26 lb/in, respectively. This thrust force is a compression force and tends to offset the tensile strains in the pipe wall. Another limitation in comparing CANDE to AASHTO Section 12 is that AASHTO Section 12 provides results at two discrete locations: the crown and the springline, whereas CANDE provides results at all model nodes.

Table 1 - FEA and AASHTO Strain Results

	Crown		Springline	
	Inner Fiber Strain (in/in)	Outer Fiber Strain (in/in)	Inner Fiber Strain (in/in)	Outer Fiber Strain (in/in)
AASHTO	-0.0025	-0.0025	-0.0041	-0.0041
Step 1	0.0121	-0.0174	-0.0108	0.0155
Ellipse	0.0096	-0.0199	-0.0149	0.0114
15° Ellipse	0.0011	-0.0181	-0.0075	0.0095
30° Ellipse	0.0012	-0.0016	-0.0108	-0.0072
Step 1 + Ellipse	0.0015	-0.0016	-0.0110	-0.0079
Step 1 + 15° Ellipse	0.0016	-0.0015	-0.0104	-0.0083
Step 1 + 30° Ellipse	0.0023	-0.0197	-0.0182	0.0023

3.9 Example Calculations

3.9.1 Ellipse method

An example calculation using an actual conduit is provided to offer an overview of the proposed ellipse method contained within this report. A laser ring profiler obtained the deformed pipe cross-section shown in as part of an Item 611 Conduit Evaluation report. The pipe is a nominal 12-inch diameter pipe under 9 feet of cover. The installation date of the conduit was August 12, 2018 and the date of the video inspection was October 17, 2018. A portion of the laser ring report is provided in Figure 23.

For this example, a manufacturer profile was selected at random. The specific manufacturer is not identified herein since the use of such data should not be construed as an endorsement of the manufacturer. For a 12-inch pipe profile geometry values are given in Table 2.

Table 2 - HDPE pipe profile geometry parameters

Nominal Size (in)	Min. I.D. (in)	Max. O.D. (in)	Min. A (in^2/ft)	Min. C (in)	Min. I (in^4/in)	Min. PS (KSI)	Period (in)	Gross Area A_g (in^2/in)
12	12.2	14.4	2.340	0.429	0.029	0.050	2.0	0.195

Idealized profile geometry values are given in Table 3.

Table 3 - Idealize profile geometry

	WALL THICKNESS				UNSUPPORTED LENGTH			
Nominal Size (in)	Crest (in)	Web (in)	Valley (in)	Liner (in)	Crest (in)	Web (in)	Valley (in)	Liner (in)
12	0.0790	0.0960	0.1290	0.0560	0.7550	1.0420	0.3940	1.3750

Figure 23 - Laser ring profiler cross-section

Utilizing a CADD software, calibrated to the figure scale, a best fit ellipse is drawn over the laser ring and the semi-major and semi-minor axes are drawn. This is shown in Figure 24.

Figure 24 - Laser ring profiler with superimposed best-fit ellipse

From the CADD drawing the semi-major and semi-minor axes are measured as 12.3 in. and 10.0 in., respectively. The vertical deformation is taken as the difference between the pipe diameter and the measured semi-minor axis. This is calculated to be 2.2 in. These values were then input into the evaluation spreadsheet and the results determined at both the crown and springline.

The results indicate that the pipe is structurally adequate for the given height of cover with the deformed shape.

If the actual height of cover were 11 feet, the pipe would not meet the bucking capacity check at the pipe springline, and the pipe would be rejected as structurally inadequate.

3.9.2 Sagitta Method

An example calculation using the sagitta method is also provided. All material and physical pipe properties and installation details are as given in the previous example. A portion of the laser ring report is provided in Figure 23.

Utilizing a CADD software, calibrated to the figure scale, a representative chord estimated in a location with contract radius is drawn. The sagitta is also drawn. This is show in Figure 25.

From the CADD drawing the chord length and sagitta are measured as 3.133 in. and 0.3089 in., respectively. The vertical deformation is taken as the difference between the pipe diameter and the measured semi-minor axis. This is calculated to be 2.2 in. These values were then input into the evaluation spreadsheet and the results determined at the pipe springline.

Figure 25 - Laser ring profiler with chord and sagitta

The results for the second example are similar to that for the first example. The pipe is structurally adequate for the given height of cover with the deformed shape.

If the actual height of cover were 11 feet, the pipe would not meet the bucking capacity check at the pipe springline, and the pipe would be rejected as structurally inadequate.

3.10 Conclusions and Recommendations

This study evaluated a proposed simplified methodology for assessing asymmetrical deformations (racking) in thermoplastic conduit. The methodology was developed within the framework of the existing AASHTO design procedure for buried thermoplastic conduits. At its core, the proposed methodology uses the deformed shape of the conduit to estimate flexural strains in the conduit wall. The method also uses a procedure of calculating the apparent secant constrained soil modulus based on the measured conduit deflection.

The methodology was compared with CANDE finite element models with mixed success. The compressive zones between the AASHTO and CANDE models compared quite favorably. However, the tensile zones had large differences. This could lead to unconservative results where there is a large difference in the distances from the neutral axis to the extreme inner and outer surfaces of the pipe profile. In order to ensure conservatism in the assessment methodology, consideration may be given to limiting the factored tensile flexural strain to the AASHTO limit of 5%. This ignores the considerable benefit of ring compression in reducing flexural tensile strains. In practice, tensile strain would rarely be the limit state for a design. Using AASHTO equation 12.12.3.10.2b-3 for flexural strain and the AASHTO profile limits given in Table A12-11, the vertical deflections resulting in 5% tensile flexural strain are provided in Table 2.

Table 4 - Deflection for maximum tensile strain

Nominal Size (in)	Deflection for 5% Tensile Strain (%)
12	14.6
15	14.2
18	15.2
24	15.5
30	16.7
36	16.7
42	16.0
48	17.5

This effort is considered an initial step to better understand the performance of thermoplastic conduits with asymmetrical deformation. Currently there is no rational method for assessing this type of deformation. Without any such method, within the language of Item 611, ODOT is left to rely solely on the interpretation of the independent engineer.

Additional research including fully instrumented field installations is recommended. Assessing the stress distribution about the conduit circumference, assessing soil stresses and assessing the resistance to ring collapse are all important topics which warrant further research.

CHAPTER 4: DEVELOPMENT OF FEA TRAINING SESSION

At the request of the Ohio Department of Transportation Office of Hydraulic Engineering, a finite element analysis training course was developed. The FEM training session covered general topics on the finite element analysis as they relate to the design and analysis of buried conduits. The participants were introduced to the basics of FEA, what it is, and what it can and cannot do. Several example problems were highlighted, and the participant were given the the opportunity to develop and solve a buried pipe problem using FEA.

The goals of the course were to introduce FEA with enough detail to allow the participants to:

- Discuss the basic FEA theory
- Understand the FEA procedures necessary to develop and execute an FEA model
- Understand the limits of FEA

The training session was conducted on October 17, 2019 for ODOT staff members. The presentations utilized for the training session are included as Appendix B.

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American Association of State Highway and Transportation Officials. (2017). Section 12: Buried Structures and Tunnel Liners. In *AASHTO LRFD Bridge Design Specifications, 7th Edition, with 2017 Interim.* Washington, DC: American Association of State Highway and Transportation Officials.

Domonell, E., Mailhot, D., & Beaver, J. (2015). Evaluating Installation Racking in Buried Thermoplastic Conduits. *TRB 94th Annual Meeting Compendium of Papers*.

Pluimer, M., & et al. (2018). *NCHRP Report 870: Field performance of corrugated pipe manufactured with recycled polyethylene content.* Washington, DC: Transportation Research Board of the National Academies.

Waktins, R. K., & Andersen, L. R. (2000). *Structural Mechanics of Buried Pipes.* Boca Raton, FL: CRC Press, LLC.

Appendices:

Appendix A: Racking Assessment Spreadsheet
Appendix B: FEA Training Session Presentations

APPENDIX 1: RACKING ASSESSMENT SPREADSHEET

HDPE PIPE DESIGN - RACKING ASSESSMENT
AASHTO LRFD BRIDGE DESIGN SPECIFICATIONS, EIGHTH EDITION, 2017

Design Criteria	
Nominal Pipe Size (in)	12
Live Load	No Load
Investigation Location	Crown
Effective Area Computation Method	Idealized Profile

	Min. I.D. (in)	Max. O.D. (in)	Min. A (in^2/in)	Min. C (in)	Min. I (in^4/in)	Pipe Stiffness (ksi)	Period (in)	Gross Area A_g (in^2/in)
Pipe Profile	12.20	14.40	0.195	0.43	0.029	0.050	2.00	0.195
AASHTO	11.80	14.70	0.125	0.35	0.024	0.050	-	-

Depth of Soil Cover H (ft)	11.00
Height of Water above Springline HW (ft)	0.00
Wet Soil Unit Weight (pcf)	120.0
Water Unit Weight (pcf)	62.4
Buoyant Soil Unit Weight (pcf)	57.6
Poisson's Ratio of Soil ν	0.45
Live Load (Wheel Load) (kips) P	0.0
Design Lane Load (KSF)	0.000
Length of Wheel Contact Area (in) L_t	10
Width of Wheel Contact Area (in) W_t	20
Wheel Spacing s_w	6
Axle Spacing s_a	14
Initial Modulus of Elasticity (KSI) E_i	110
Initial Tensile Strength (KSI) F_u	3
Long Term Modulus of Elasticity (KSI) E_{50}	21
Long Term Tensile Strength (KSI) F_{50}	0.8
Radius to Centroid (in)	6.53
Diameter to Centroid (in)	13.06
Extreme Distance from Neutral Axis c_x (in)	0.67
Pipe Stiffness (Calc) - Long Term (ksi)	0.0146

Vertical Deflection (in) Δ_A	2.20
Dead Load Modifier η_{EV}	1.00
Dead Load Factor γ_{EV}	1.30
Hydrostatic Load Factor γ_{WA}	1.00
Live Load Factor γ_{LL}	1.75
Live Load Modifier η_{LL}	1.00
Multi-Presence Factor	1.20
Live Load Distribution Factor LLDF	1.15
Buckling Coefficient k	4.00
Hydrostatic Uncertainty Factor K_{wa}	1.30
Installation Factor $K_{\gamma E}$	1.50
Factored Compressive Strain Limit (%) ε_{yc}	4.10
Service Long-term Tension Strain Limit (%) ε_{yt}	5.00
Thrust Variation Coefficient K_2	0.60
Non-Linear Calibration Factor C_N	0.55
Bedding Coefficient K_B	0.10
Deflection Lag Factor D_L	1.5
Time Factor K_{t50}	0.3

Resistance Factor for Soil Stiffness Φ_s	0.90
Resistance Factor for Thrust Φ_T	1.00
Resistance Factor for Global Buck. Φ_{bck}	0.70
Resistance Factor for Flexure Φ_f	1.00

Racking Radius Estimation Method	Ellipse
Chord Length (in) L	n/a
Sagitta Length (in) e	n/a
Semi Major Axis Length (in) a	12.3
Semi Minor Axis Length (in) b	10
Radius of Curvature r_c	7.97
Total Outer Wall Unfactored Strain	0.0186
Total Inner Wall Unfactored Strain	0.0119

Date of Conduit Installation	8/12/2018
Date of Conduit Measurement	10/17/2018
Apparent Modulus of Elasticity (KSI) E_a	57.90
Apparent Deflection Lag Factor D_{LA}	0.79

IDEALIZED PROFILE												
Pipe Properties	WALL THICKNESS				UNSUPPORTED LENGTH				W/t Ratio			
DIAMETER (in)	Crest (in)	Web (in)	Valley (in)	Liner (in)	Crest (in)	Web (in)	Valley (in)	Liner (in)	Crest	Web	Valley	Liner
12	0.0790	0.0960	0.1290	0.0560	0.7550	1.0420	0.3940	1.3750	9.5570	10.8542	3.0543	24.5536

LOAD CALCULATION	
Soil Prism Load (psi) - Case 1	4.453
Soil Prism Load (psi) - Case 2	9.479
Soil Prism Load (psi) - Case 3	9.277
Governing Soil Prism Load Case	3
Soil Prism Load P_{SP} (psi)	9.277
Hydrostatic Pressure P_W (psi)	0.000
Calculated Constrained Soil Modulus (ksi)	0.024
Minimum Constrained Soil Modulus (ksi)	0.399
Constrained Soil Modulus (ksi)	0.399
Hoop Stiffness Factor S_H	0.572
Hoop Stiffness Factor S_H - Initial	0.109
Vertical Arching Factor VAF	0.882
Impact Factor IM	1.00
Wheel Interaction Depth- transverse H_{int-t}	3.72
Wheel Interaction Depth- parallel H_{int-p}	11.45
Live Load Application Width W_w (ft)	20.4
Live Load Application Length L_w (ft)	13.5
Rectangular Area at Depth H (sf)	274.76
Tire Pressure at Depth H (ksf)	0.00
Total Live Load Pressure (ksf)	0.00
Total Live Load Pressure P_L (psi)	0.00
Live Load Distribution Coefficient C_L	1.00
F_{min}	1.23
F_1	1.00
F_2	0.89

EFFECTIVE WALL AREA CALCULATION	
Slenderness Factor λ 12.12.3.10.1b Crest	0.968
Slenderness Factor λ 12.12.3.10.1b Web	1.099
Slenderness Factor λ 12.12.3.10.1b Valley	0.673
Slenderness Factor λ 12.12.3.10.1b Liner	2.486
Effective Width Factor ρ 12.12.3.10.1b Crest	0.799
Effective Width Factor ρ 12.12.3.10.1b Web	0.728
Effective Width Factor ρ 12.12.3.10.1b Valley	1.000
Effective Width Factor ρ 12.12.3.10.1b Liner	0.367
Element Effective Width b 12.12.3.10.1b Crest	0.603
Element Effective Width b 12.12.3.10.1b Web	0.758
Element Effective Width b 12.12.3.10.1b Valley	0.394
Element Effective Width b 12.12.3.10.1b Liner	0.504
(w-be)t Crest	0.012
(w-be)t Web	0.027
(w-be)t Valley	0.000
(w-be)t Liner	0.049
Stub Compression Capacity T341 (kpi) P_{st}	n/a
Effective Area of Pipe Wall A_{eff} (in^2/in)	0.137

AXIAL THRUST CALCULATIONS	
Service Thrust Dead Loads	35.3
Service Thrust Live Loads	0.0
Service Thrust T_s (lb/in)	35.3
Factored Thrust Dead Loads	68.9
Factored Thrust Live Loads	0.0
Factored Thrust T_u (lb/in)	68.9

STRAIN CALCULATIONS AND DESIGN CHECKS	
Service Compressive Strain ε_{sc} (in/in)	0.0122
Factored Compressive Strain ε_{uc} (in/in)	0.0239
Compressive Thrust Strain Check	OK
Nominal Buckling Strain Capacity ε_{bck} (in/in)	0.0480
Buckling Strain Check	OK
Factored Tensile Flexural Strain ε_f (in/in)	0.0155
Factored Compressive Flexural Strain ε_f (in/in)	0.0242
Combined Tensile Zone Strain Check	OK
Combined Compressive Zone Strain Check	OK
Allowable Installation Check Yes or No	YES

APPENDIX 2: FEA TRAINING SESSION PRESENTATIONS

FINITE ELEMENT METHOD

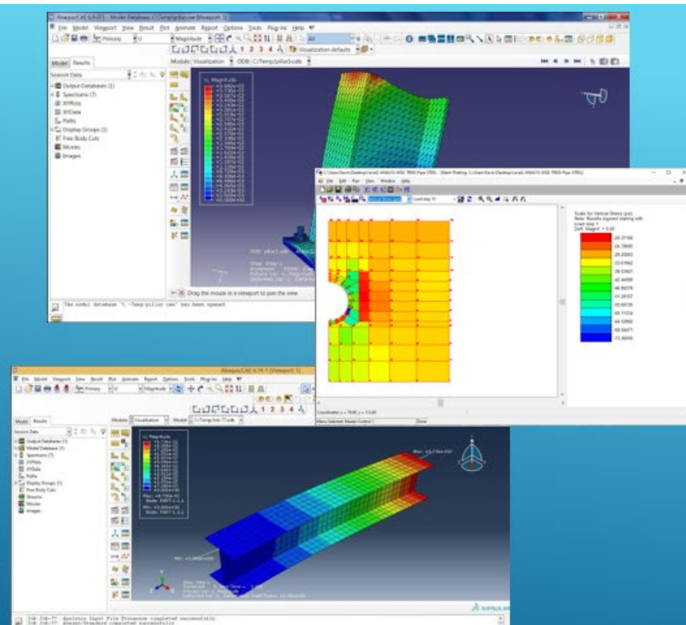
Introduction to Finite Element Analysis

Ohio Department of Transportation

Kevin White, PE

E.L. Robinson Engineering

- Introduction
- Mathematic Overview
- FEM Software
- CANDE Tutorial



INTRODUCTION

FINITE ELEMENT METHOD

- The Finite Element Method (FEM) is a numerical method for simulating and analyzing engineering products and systems
- Useful for problems with complicated geometries, loadings, and material properties where analytical solutions can not be obtained
- Finite element method follows on from matrix analysis and became viable with the advent of computers. It is a computer-based analysis tool

ANALYTICAL SOLUTIONS

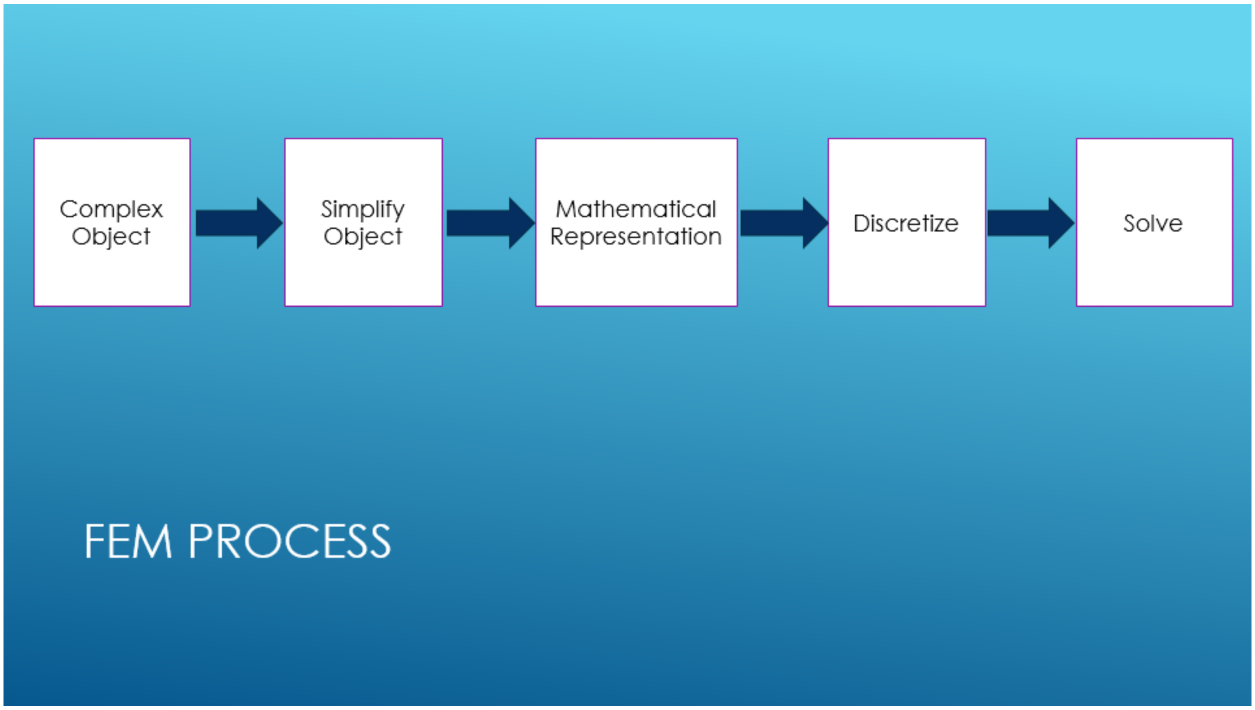
- Typical undergraduate analysis methods
- Stress analysis for trusses, beams, and other simple structures are carried out based on dramatic simplification and idealization:
  - mass concentrated at the center of gravity
  - beam simplified as a line segment (same cross-section)
- Design is based on the calculation results of the idealized structure along with load and resistance factors based on empirical or statistical evidence

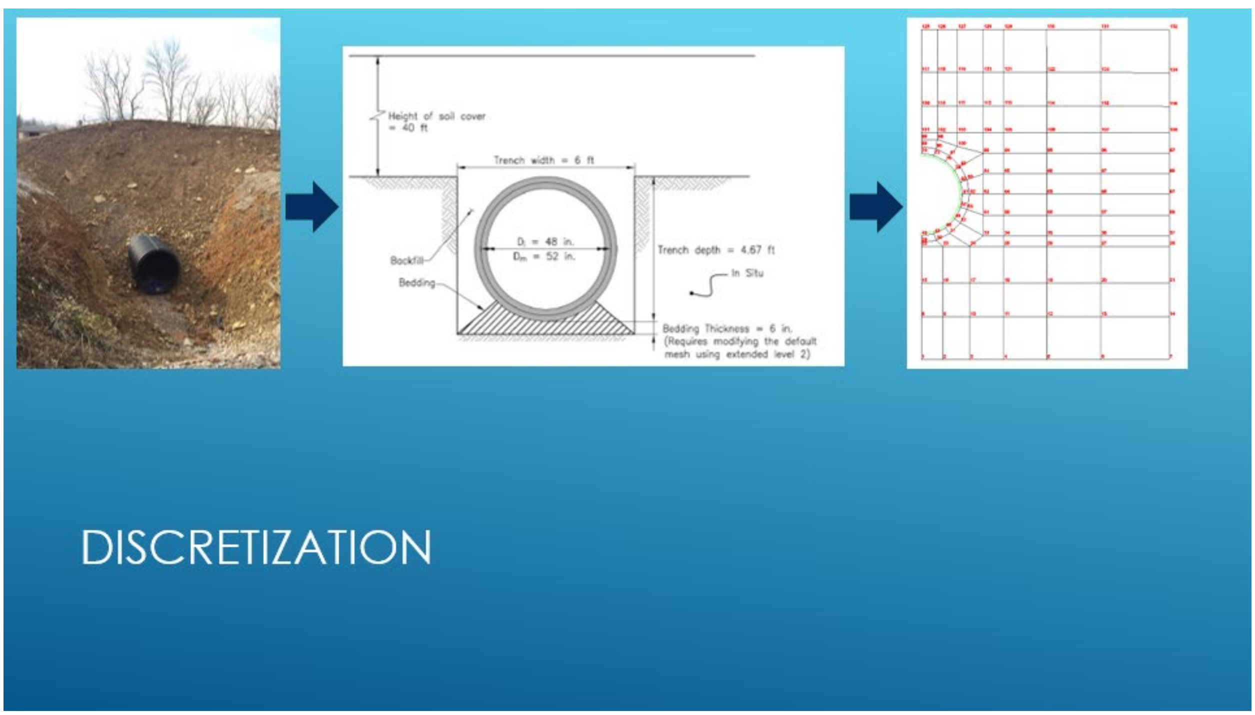
WHEN FEM?

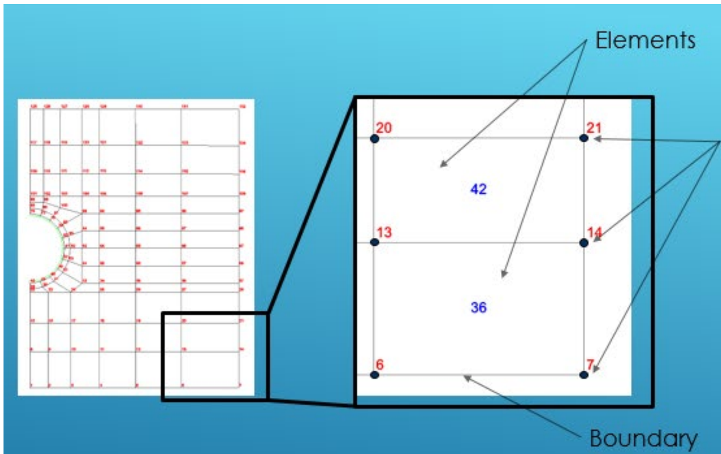
- Complex geometry
- Local accuracy is necessary.
- Understand the physical behaviors of a complex object (structural integrity, heat transfer, fluid flow, etc.)
- To predict the performance and behavior of the design
- To calculate reliability and to identify the weakness of a design accurately
    - Survivability of your iphone when dropped from a distance

WHEN FEM?

- Mechanical/Aerospace/Civil/Automotive Engineering
- Structural/Stress Analysis
    - Static/Dynamic
    - Linear/Nonlinear
    - Plastic
    - Visco-plastic/elastic
- Fluid Flow
- Heat Transfer
- Soil Mechanics
- Acoustics
- Biomechanics


Complex Object
Simplify Object
Mathematical Representation
Discretize
Solve
FEM PROCESS


Height of soil cover = 40 ft
Trench width = 6 ft
D_i = 48 in.
D_m = 52 in.
Backfill
Bedding
Trench depth = 4.67 ft
In Situ
Bedding Thickness = 6 in.
(Requires modifying the default mesh using extended level 2)
DISCRETIZATION



- Model simplified object by dividing it into an equivalent system of smaller finite numbered elements interconnected at common points to two or more elements (nodes) and/or boundaries

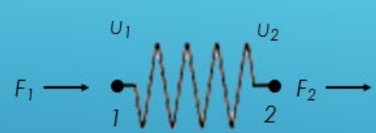
DISCRETIZATION

- Use matrix algebra to solve system of equations to determine unknown nodal displacements
- Use calculated nodal displacements to solve for:
  - Stress
  - Strain
  - Moment
  - Deformation
  - Rotation
  - Etc.
- ALL CALCULATED VALUES ARE ONLY AT NODES!!!

FEM PROCESS

- Use matrix algebra to solve system of equations to determine unknown nodal displacements
- Use calculated nodal displacements to solve for:
  - Stress
  - Strain
  - Moment
  - Deformation
  - Rotation
  - Etc.
- ALL CALCULATED VALUES ARE ONLY AT NODES!!!

FEM PROCESS



$F = k\,\delta$

$\delta = u_2 - u_1$

$F = k(u_2 - u_1)$

$F_1 = -k(u_2 - u_1)$

$F_2 = k(u_2 - u_1)$

$$\begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix}$$

$\{F\} = [K]\{u\}$

FEM PROCESS


Finite Element Methods
Ohio Department of Transportation
October 17-18, 2019
Shad Sargand
Russ Professor and Vice Director for Business Development
Ohio Research Institute for Transportation and the Environment
Russ College of Engineering and Technology
Ohio University, Athens, Ohio

Finite Element Method Overview

- Set up the problem
- Decide dimensionality, discretize problem, and create mesh
- Determine solution for each element
- Select and apply constitutive laws
- Write element equation
- Assemble equation for entire system
- Determine and apply boundary conditions
- Solve simultaneous equations
- Find solution for primary unknown, then secondary unknowns
- Interpret results

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Determine dimensionality

Is this problem best solved in one, two, or three dimensions?

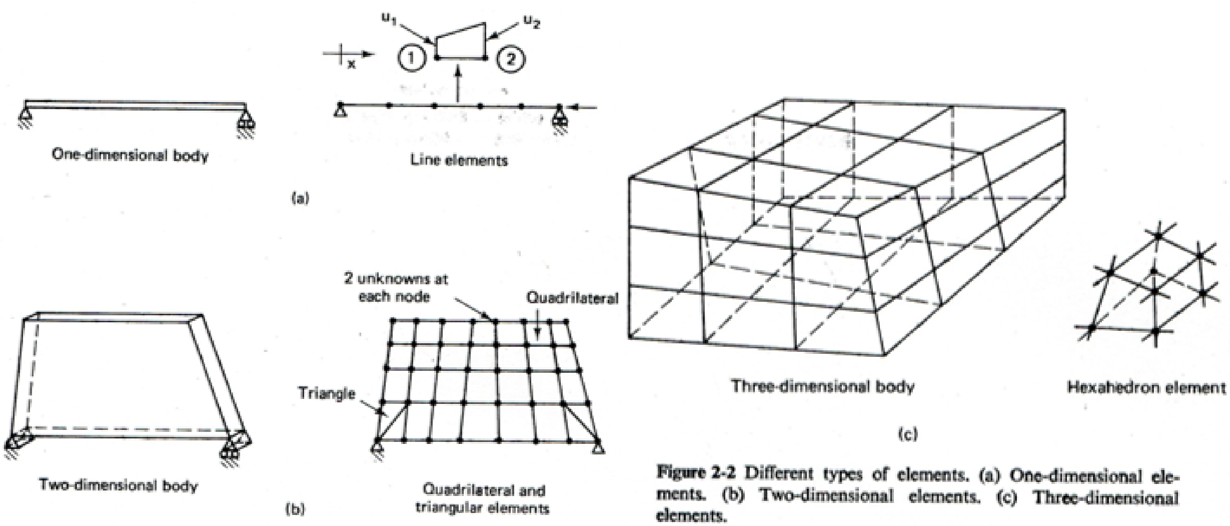

Figure 2-2 Different types of elements. (a) One-dimensional elements. (b) Two-dimensional elements. (c) Three-dimensional elements.

from C.S. Desai, 1979, *Elementary Finite Element Method*, (Prentice-Hall, Englewood Cliffs NJ).

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Discretize Problem

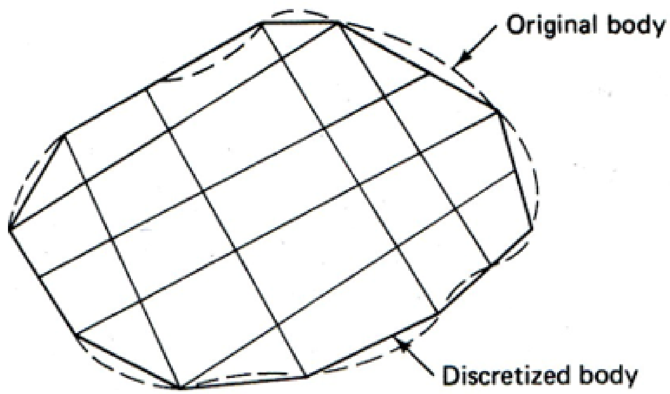

Figure 2-3 Discretization for irregular boundary.

from C.S. Desai, 1979, *Elementary Finite Element Method*, (Prentice-Hall, Englewood Cliffs NJ).

Write solution for each element

- Need a continuous function
  - Polynomial
  - Trigonometric
  - Other
- Need derivative of function

Select and apply constitutive laws

Material properties

- For strain:
  - Hooke's law (elastic behavior)
  - Plasticity
  - Viscoelasticity
- For thermal problems
  - Thermal conductivity
  - Coefficient of expansion
- Other problems
  - Viscosity
- Constitutive laws depend on type of material being modeled (steel is different than thermoplastic is different than concrete)

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Write element equation

Various approaches

- Potential energy method
- Weighted residual method (Galerkin method)

Potential Energy

$$\Pi_p = U + W_p$$

$$\delta\Pi_p = \delta U - \delta W_p = 0$$

$$\delta W = -\delta W_p$$

$$\frac{\partial \Pi_p}{\partial u_1} = 0$$
$$\frac{\partial \Pi_p}{\partial u_2} = 0$$
$$\vdots$$
$$\frac{\partial \Pi_p}{\partial u_n} = 0$$

Weighted Residual Method

$$\frac{\partial^2 u^*}{\partial x^2} - \frac{\partial u^*}{\partial t} = f(x)$$

$$Lu^* = f \text{ where } L \equiv \frac{\partial^2}{\partial x^2} - \frac{\partial}{\partial t}$$

$$u = \sum_{i=1}^{n} \alpha_i \varphi_i$$

$$R(x) = Lu - f$$

$$\int_D R(x) W_i(x) dx = 0 \qquad i = 1, 2, \ldots, n$$

$$[\mathbf{k}]\{\mathbf{q}\} = \{\mathbf{Q}\}$$

One-Dimensional Stress Deformation

- Solve for primary result, then secondary results
- Primary result: displacement
- Secondary results: stress and strain

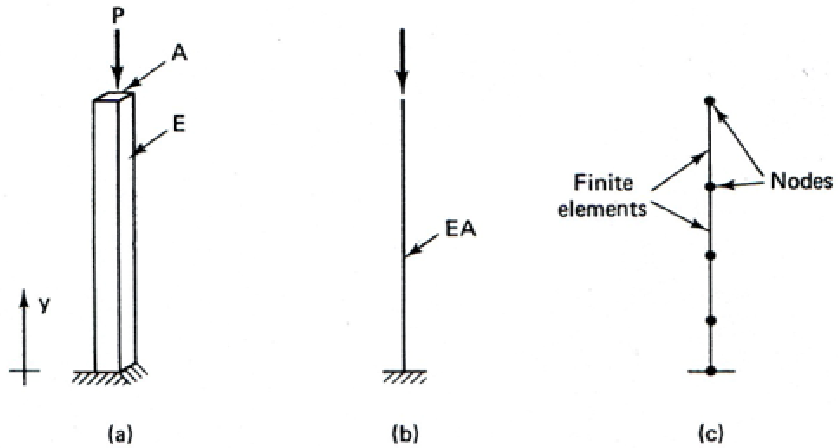


Figure 3-1 Axially loaded column. (a) Actual column. (b) One-dimensional idealization. (c) Discretization.

One-Dimensional Stress Deformation

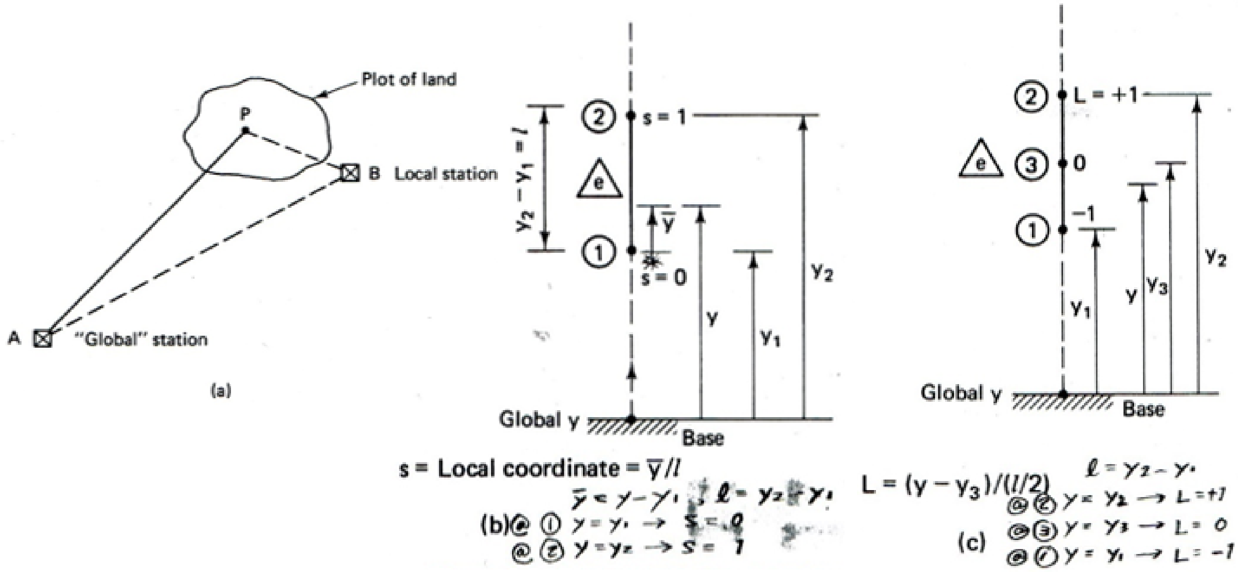


Figure 3-2 Global and local coordinates. (a) Concept of global and local coordinate systems. (b) Local coordinate measured from node point 1. (c) Local coordinate measured from midnode 3.

from C.S. Desai, 1979, *Elementary Finite Element Method*, (Prentice-Hall, Englewood Cliffs NJ).

One-Dimensional Stress Deformation

$$v = \alpha_1 + \alpha_2 y$$

$$\{\mathbf{v}\} = [1 \quad y] \begin{Bmatrix} \alpha_1 \\ \alpha_2 \end{Bmatrix}$$

$$\{\mathbf{v}\} = [\boldsymbol{\phi}]\{\boldsymbol{\alpha}\}$$

$$v_1 = \alpha_1 + \alpha_2 y_1$$
$$v_2 = \alpha_1 + \alpha_2 y_2$$

$$\begin{Bmatrix} v_1 \\ v_2 \end{Bmatrix} = \begin{bmatrix} 1 & y_1 \\ 1 & y_2 \end{bmatrix} \begin{Bmatrix} \alpha_1 \\ \alpha_2 \end{Bmatrix}$$

$$\{\mathbf{q}\} = [\mathbf{A}]\{\boldsymbol{\alpha}\}$$

One-Dimensional Stress Deformation

$$\begin{Bmatrix} \alpha_1 \\ \alpha_2 \end{Bmatrix} = \frac{1}{l} \begin{bmatrix} y_2 & -y_1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} v_1 \\ v_2 \end{Bmatrix}$$

$(2 \times 1) \qquad (2 \times 2) \qquad (2 \times 1)$

$$\alpha_1 = \frac{y_2 v_1 - y_1 v_2}{l}$$

$$\alpha_2 = \frac{-v_1 + v_2}{l}$$

One-Dimensional Stress Deformation

$$v = \frac{1}{2}(1 - L)v_1 + \frac{1}{2}(1 + L)v_2$$

$$= N_1 v_1 + N_2 v_2$$

$$= [N_1 \quad N_2] \begin{Bmatrix} v_1 \\ v_2 \end{Bmatrix}$$

$$= [N]\{q\}$$

One-Dimensional Stress Deformation

$$\Pi_p = \iiint_V \frac{1}{2}\sigma_y \epsilon_y dV - \iiint_V \bar{Y} v dV - \iint_{S_1} \bar{T}_y \, v dS - \sum_{i=1}^{M} P_{ii} v_i$$

$$\frac{AE}{l}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}\begin{Bmatrix} v_1 \\ v_2 \end{Bmatrix} = \frac{Al\bar{Y}}{2}\begin{Bmatrix} 1 \\ 1 \end{Bmatrix} + \frac{\bar{T}_y l}{2}\begin{Bmatrix} 1 \\ 1 \end{Bmatrix} + \begin{Bmatrix} P_{1l} \\ P_{2l} \end{Bmatrix}$$

$$[\mathbf{k}]\{\mathbf{q}\} = \{\mathbf{Q}\}$$

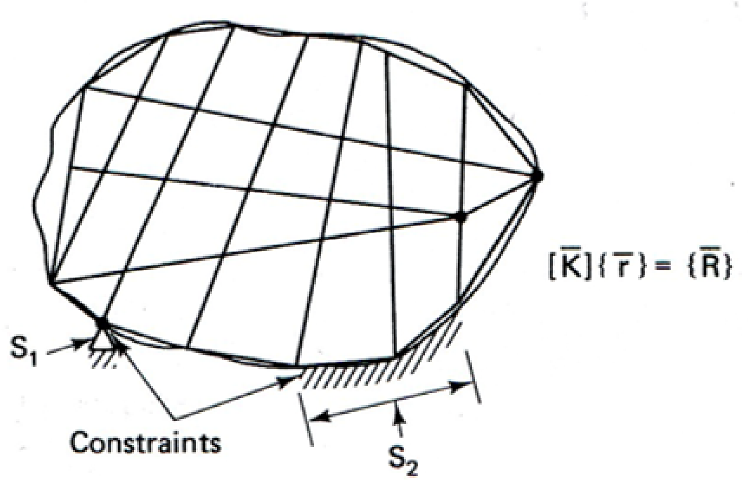
$$[\mathbf{k}] = \frac{Al}{2}\int_{-1}^{1} [\mathbf{B}]^T E [\mathbf{B}] \, dL$$

$$\{\mathbf{Q}\} = \frac{Al}{2}\int_{-1}^{1} [\mathbf{N}]^T \bar{Y} dL + \frac{l}{2}\int_{-1}^{1} [\mathbf{N}]^T \, \bar{T}_y dL + \{P_{il}\}$$

Integrate elements into larger system

- Assemble equation for entire problem

Apply boundary conditions



Body with constraints.

from C.S. Desai, 1979, *Elementary Finite Element Method*, (Prentice-Hall, Englewood Cliffs NJ).

Solve simultaneous equations

- Solve for primary unknown
- Find secondary unknown(s)

Interpret Results

One-Dimensional Flow

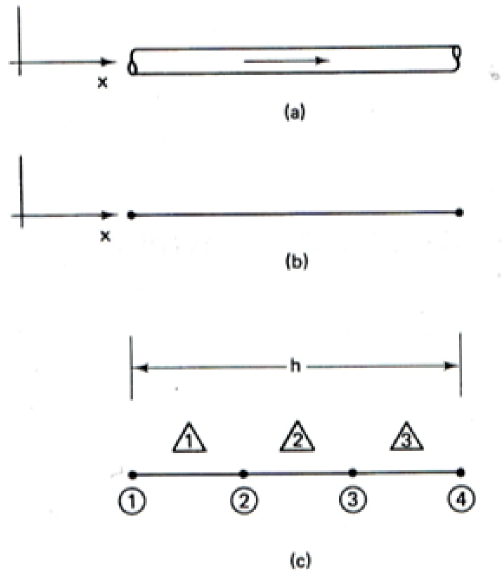


Figure 4-1 Idealization for flow in pipe. (a) Flow through pipe. (b) One-dimensional idealization. (c) Discretization in three elements.

from C.S. Desai, 1979, *Elementary Finite Element Method*, (Prentice-Hall, Englewood Cliffs NJ).

One-Dimensional Flow

$$k_x \frac{\partial^2 \varphi^*}{\partial x^2} = f(x) = \bar{q}(x)$$

$$\varphi = \alpha_1 + \alpha_2 x$$

$$\varphi = N_1 \varphi_1 + N_2 \varphi_2 = [\mathbf{N}]\{\boldsymbol{\varphi}_n\}$$

$$g_x = \frac{\partial \varphi}{\partial x}$$

$$v_x = -k_x \frac{\partial \varphi}{\partial x} = -k_x g_x$$

One-Dimensional Temperature

Uncoupled problem

$$\epsilon_{y_0} = \alpha' T$$

$$\epsilon_{y_n} = \epsilon_y - \epsilon_{y_0}$$

$$\sigma_y = E\epsilon_{y_n} = E(\epsilon_y - \epsilon_{y_0})$$

One-Dimensional Temperature

Uncoupled problem

$$\Pi_p = \frac{A}{2}\int_{y_1}^{y_2} \sigma_y \epsilon_{y_n} dy - A\int_{y_1}^{y_2} \bar{Y}_y v dy - \int_{y_1}^{y_2} \bar{T}_y v dy - \sum P_{il} v_i$$

$$U' = \frac{A}{2}\int_{y_1}^{y_2} E(\epsilon_y - \epsilon_{y_0})(\epsilon_y - \epsilon_{y_0}) dy$$

$$= \frac{A}{2}\int_{y_1}^{y_2} E\epsilon_y^2\, dy - A\int_{y_1}^{y_2} E\epsilon_y \epsilon_{y_0} dy + \frac{A}{2}\int_{y_1}^{y_2} E\epsilon_{y_0}^2 dy$$

$$= U_1 + U_2$$

One-Dimensional Temperature

$$U_2 = A \int_{y_1}^{y_2} [v_1 \quad v_2] \frac{1}{l} \begin{Bmatrix} -1 \\ 1 \end{Bmatrix} E\epsilon_{y_0} dy$$

$$= A\{\mathbf{q}\}^T \int_{y_1}^{y_2} [\mathbf{B}]^T [\mathbf{C}] \{\epsilon_{y_0}\} dy$$

$$= \frac{AE\epsilon_{y_0}}{l} \int_{y_1}^{y_2} (-v_1 + v_2) dy$$

$$= \frac{AE\epsilon_{y_0}}{l} \frac{l}{2} \int_{-1}^{1} (-v_1 + v_2) dL$$

$$= \frac{AE\epsilon_{y_0}}{2} \left[(-v_1 L)|_{-1}^{1} + (v_2 L|_{-1}^{1}\right]$$

$$= AE\epsilon_{y_0}(-v_1 + v_2)$$

One-Dimensional Temperature

$$\{\mathbf{Q}_0\} = AE\epsilon_{y_0}\begin{Bmatrix}-1\\1\end{Bmatrix} = A\sigma_{y_0}\begin{Bmatrix}-1\\1\end{Bmatrix}$$

$$\{\mathbf{Q}_0\} = A\int_{y_1}^{y_2}[\mathbf{B}]^T[\mathbf{C}]\{\epsilon_{y_0}\}dy$$

$$[\mathbf{k}]\{\mathbf{q}\} = \{\mathbf{Q}\} + \{\mathbf{Q}_0\}$$

Beam Bending and Beam-Column

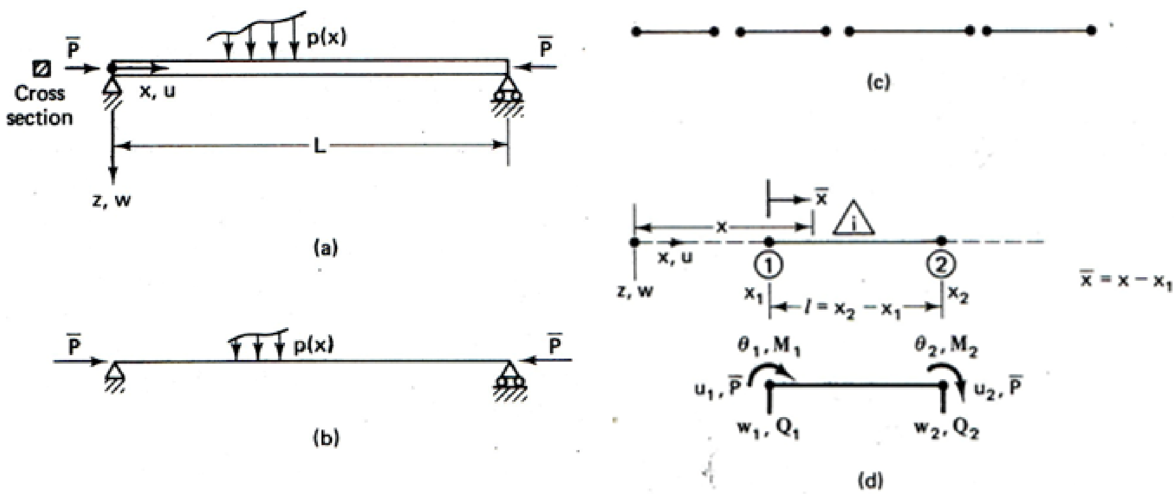


Figure 7-1 Beam bending and beam-column. (a) Beam with transverse and axial loads. (b) One-dimensional idealization. (c) Discretized beam. (d) Generic element.

from C.S. Desai, 1979, *Elementary Finite Element Method*, (Prentice-Hall, Englewood Cliffs NJ).

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Beam Bending and Beam-Column

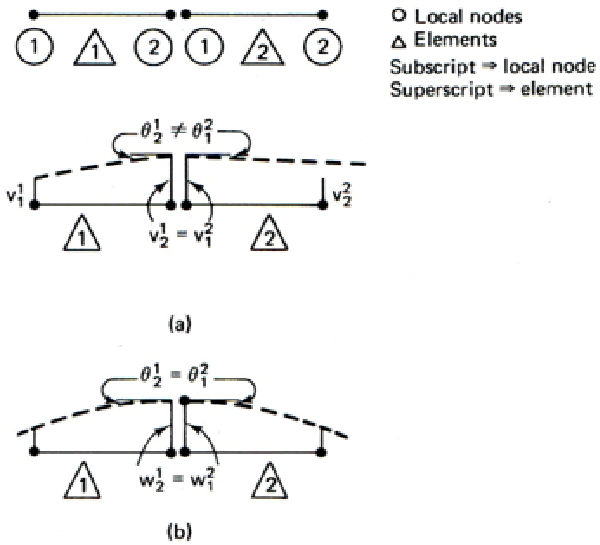

Figure 7-2 Requirements of interelement compatibility. (a) Interelement compatibility for axial deformation (Chapter 3). (b) Interelement compatibility for beam bending.

from C.S. Desai, 1979, *Elementary Finite Element Method*, (Prentice-Hall, Englewood Cliffs NJ).

Beam Bending and Beam-Column

$$F\frac{d^4w^*}{dx^4} = p(x)$$

$$w(x) = N_1 w_1 + N_2\theta_1 + N_3 w_2 + N_4\theta_2$$

$$w(x) = [\mathbf{N}]\{\mathbf{q}\}$$

Beam Bending and Beam-Column

$$N_1 = 1 - 3s^2 + 2s^3$$

$$N_2 = ls(1 - 2s + s^2)$$

$$N_3 = s^2(3 - 2s)$$

$$N_4 = ls^2(s - 1)$$

$$w(x) = \alpha_1 + \alpha_2 x + \alpha_3 x^2 + \alpha_4 x^3$$

$$\Pi_p = \int_{x_1}^{x_2} \frac{1}{2} F(w'')^2 dx - \int_{x_1}^{x_2} pw dx$$

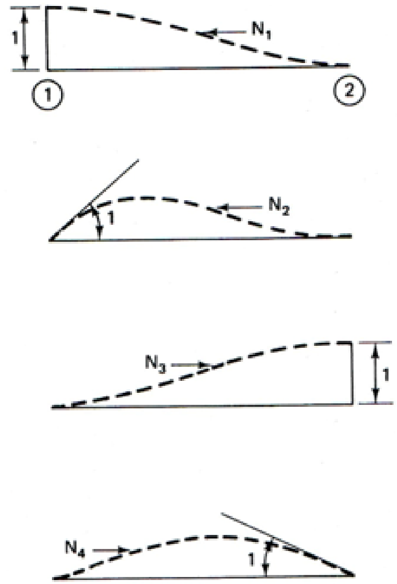

Figure 7-3 Plots of N_i, $i = 1, 2, 3, 4$,

from C.S. Desai, 1979, *Elementary Finite Element Method*, (Prentice-Hall, Englewood Cliffs NJ).

Beam Bending and Beam-Column

$$[\mathbf{k}] = \frac{F}{l^3}\begin{bmatrix} 12 & 6l & -12 & 6l \\ & 4l^2 & -6l & 2l^2 \\ & & 12 & -6l \\ symmetric & & & 4l^2 \end{bmatrix}$$

$$\{\mathbf{Q}\} = \frac{l}{20}\begin{Bmatrix} 7p_1 + 3p_2 \\ \frac{l}{3}(3p_1 + 2p_2) \\ 3p_1 + 7p_2 \\ -\frac{l}{3}(2p_1 + 3p_2) \end{Bmatrix}$$

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Two-Dimensional Stress-Deformation Analysis

$$\{\boldsymbol{\sigma}\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}$$

$$\{\boldsymbol{\epsilon}\} = \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

$$\{\boldsymbol{\sigma}\} = [\mathbf{C}]\{\boldsymbol{\epsilon}\} = \frac{E}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix}\{\boldsymbol{\epsilon}\}$$

Two-Dimensional Stress-Deformation Analysis

Plane strain approximation

$$\{\boldsymbol{\sigma}\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \qquad \{\boldsymbol{\epsilon}\} = \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

$$\sigma_z = \nu(\sigma_x + \sigma_y)$$

$$\{\boldsymbol{\sigma}\} = [\mathbf{C}]\{\boldsymbol{\epsilon}\} = \frac{E}{(1-\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & \dfrac{1-2\nu}{2} \end{bmatrix} \{\boldsymbol{\epsilon}\}$$

$$\{\boldsymbol{\epsilon}\} = \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial u}{\partial x} \\ \dfrac{\partial v}{\partial y} \\ \dfrac{\partial u}{\partial y} + \dfrac{\partial v}{\partial x} \end{Bmatrix}$$

Two-Dimensional Stress-Deformation Analysis

Axisymmetric approximation

$$\{\boldsymbol{\sigma}\} = \begin{Bmatrix} \sigma_r \\ \sigma_\theta \\ \sigma_z \\ \tau_{rz} \end{Bmatrix} \qquad \{\boldsymbol{\epsilon}\} = \begin{Bmatrix} \epsilon_r \\ \epsilon_\theta \\ \epsilon_z \\ \gamma_{rz} \end{Bmatrix}$$

$$\{\boldsymbol{\sigma}\} = [\mathbf{C}]\{\boldsymbol{\epsilon}\} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 \\ \nu & 1-\nu & \nu & 0 \\ \nu & \nu & 1-\nu & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} \{\boldsymbol{\epsilon}\}$$

$$\{\boldsymbol{\epsilon}\} = \begin{Bmatrix} \epsilon_r \\ \epsilon_\theta \\ \epsilon_z \\ \gamma_{rz} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial r} \\ \frac{u}{r} \\ \frac{\partial w}{\partial z} \\ \frac{\partial u}{\partial z} + \frac{\partial w}{\partial r} \end{Bmatrix}$$

Two-Dimensional Stress-Deformation Analysis

Finite element formulation

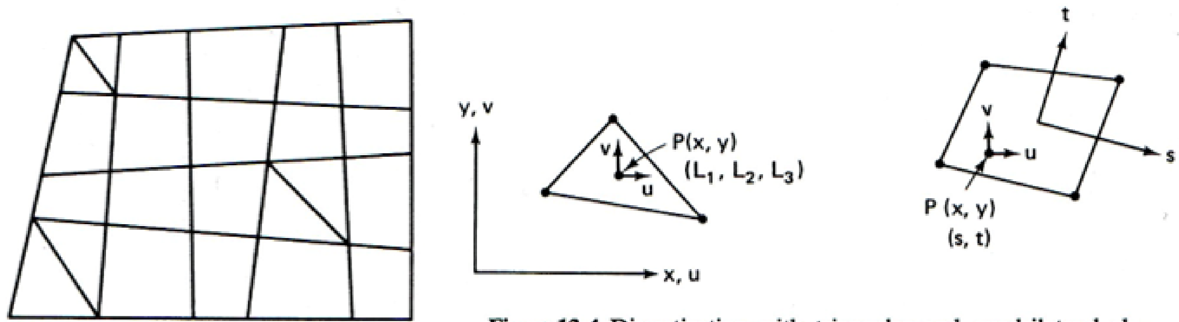

Figure 13-4 Discretization with triangular and quadrilateral elements.

$$u(x,y) = \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 xy$$
$$v(x,y) = \beta_1 + \beta_2 x + \beta_3 y + \beta_4 xy$$

from C.S. Desai, 1979, *Elementary Finite Element Method*, (Prentice-Hall, Englewood Cliffs NJ).

Two-Dimensional Stress-Deformation Analysis

$$N_1 = \frac{1}{4}(1-s)(1-t)$$

$$N_2 = \frac{1}{4}(1+s)(1-t)$$

$$N_3 = \frac{1}{4}(1+s)(1+t)$$

$$N_4 = \frac{1}{4}(1-s)(1+t)$$

Two-Dimensional Stress-Deformation Analysis

$$x = \sum_{i=1}^{4} N_i x_i \qquad i = 1, 2, 3, 4$$

$$y = \sum_{i=1}^{4} N_i y_i \qquad i = 1, 2, 3, 4$$

$$\begin{Bmatrix} x \\ y \end{Bmatrix} = \begin{bmatrix} [\mathbf{N}] & [\mathbf{0}] \\ [\mathbf{0}] & [\mathbf{N}] \end{bmatrix} \begin{Bmatrix} \{x_n\} \\ \{y_n\} \end{Bmatrix}$$

$(2 \times 1) \qquad (2 \times 8) \qquad (8 \times 1)$

Two-Dimensional Stress-Deformation Analysis

$$[\mathbf{k}] \simeq h \sum_{i=1}^{N} [\mathbf{B}(s_i, t_i)]^T [\mathbf{C}] [\mathbf{B}(s_i, t_i)] \, |J(s_i, t_i)| W_i$$

$$\{\mathbf{Q}_1\} = h \sum_{i=1}^{N} [N(s_i, t_i)]^T \{\overline{\mathbf{X}}\} W_i$$

Construction sequence FEM

Initial set up – embankment

- When simulating the stresses on an embankment, it is important to model the construction process.
- Create a mesh for the existing system.
- Compute the initial stresses due to the weight
  - In many cases, if you assume a reasonable modulus, you will have a realistic level of stress
- After calculating the initial stresses, set the initial strains and displacements to 0.
  - These developed over an essentially infinite time and have no impact on the final result.

Construction sequence FEM

Adding layers to embankment

- Model adding a layer of soil by adding a layer(s) of elements to the mesh
  - Simulate with nonlinear nodal forces
  - Use the nonlinear constituent laws to compute stresses, strains, and displacements.
  - Adjust mesh.
  - Update constituent laws/material properties in response to new conditions
    - strains and displacements are no longer 0, so stress-strain relationship will be different
- Add additional layers of soil as above until full embankment is constructed
  - Material properties are adjusted with each layer

Construction sequence FEM

Simulating excavation

- Excavation is the reverse of embankment
  - Create initial mesh
  - Remove a layer of soil from the mesh
  - Adjust material properties following nonlinear constitutive relations
  - Iterate by removing layers and adjusting properties until excavation is complete

Interface elements

- Interface elements are crucial in soil-structure interaction problems
- Interface elements are located where one material is adjacent to another
  - For example pipe (e.g. thermoplastic) and soil
- Interface elements are nonlinear
  - Allow separation of materials
  - Allow slippage


Create
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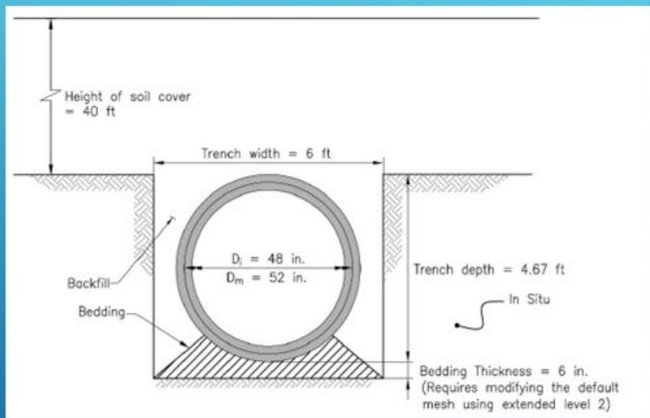
CANDE 2007 TUTORIAL

Introduction to Finite Element Analysis

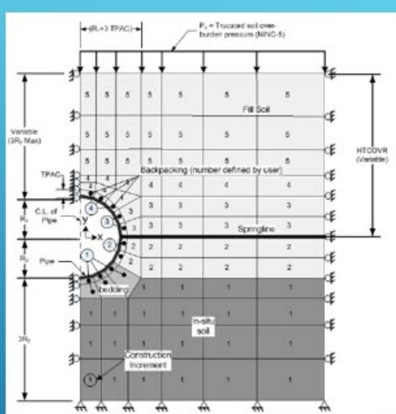
Ohio Department of Transportation

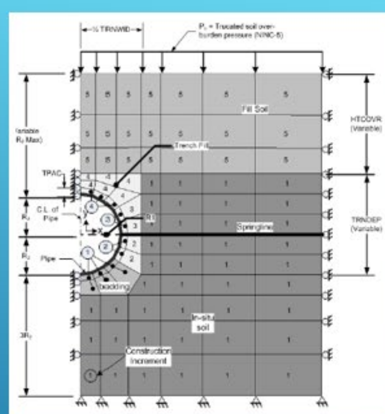
- Analyze a 48-inch corrugated steel pipe
  - Service load
  - Level 2 analysis
    - Modified automatic meshing
      - 6-inch bedding
      - Haunch zone material
  - Trench installation

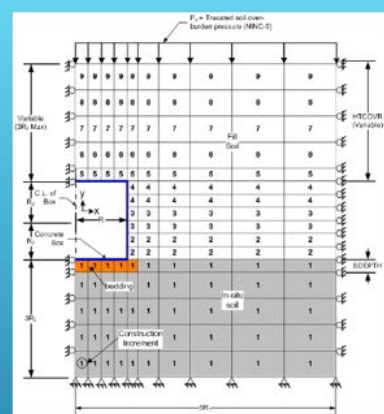
STATEMENT OF THE PROBLEM



PROBLEM DETAILS



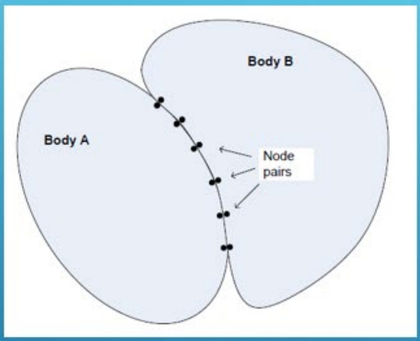


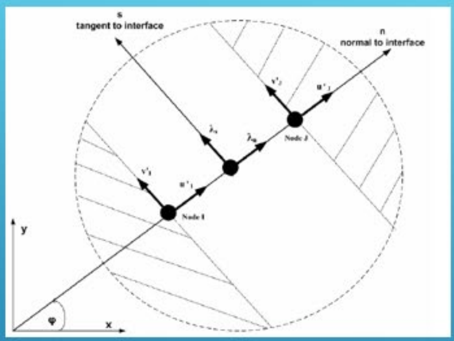


CANDE AUTOMATED MESH

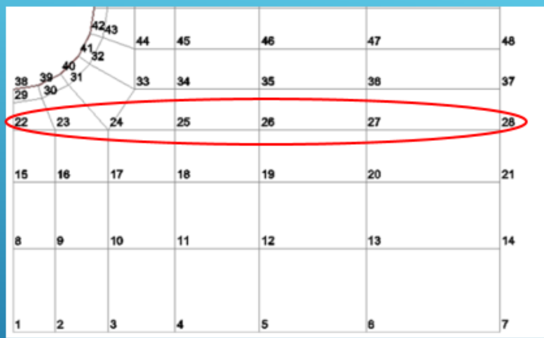
- Analysis method
- Analyze at service load
- Level 2 solution
- Canned pipe mesh
- Trench mesh
- Pipe-soil interface elements
- Modified level 2 mesh
  - 7 nodes will have changed coordinates
  - 2 elements with new material properties

STATEMENT OF THE PROBLEM



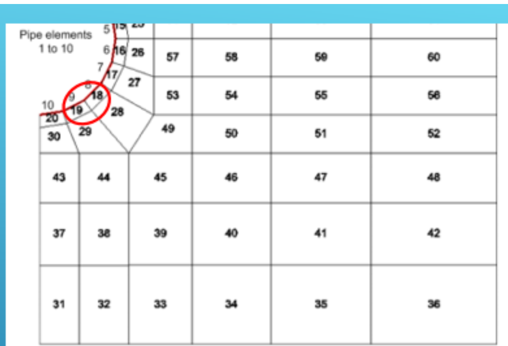


INTERFACE ELEMENTS



Node Numbers	X-coordinate	Y-coordinate
22	0	-30
23	12.47	-30
24	28.19	-30
25	47.99	-30
26	72.95	-30
27	104.38	-30
28	144	-30

NODE CHANGES



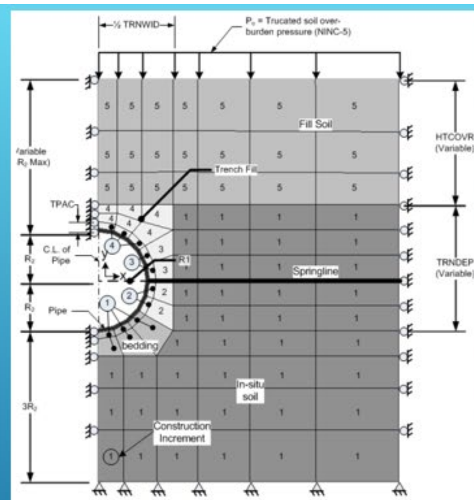
Element Number	Node I	Node J	Node K	Node L	Material	Const. Step
18	49	46	31	32	5	1
19	46	43	30	31	5	1

ELEMENT CHANGES

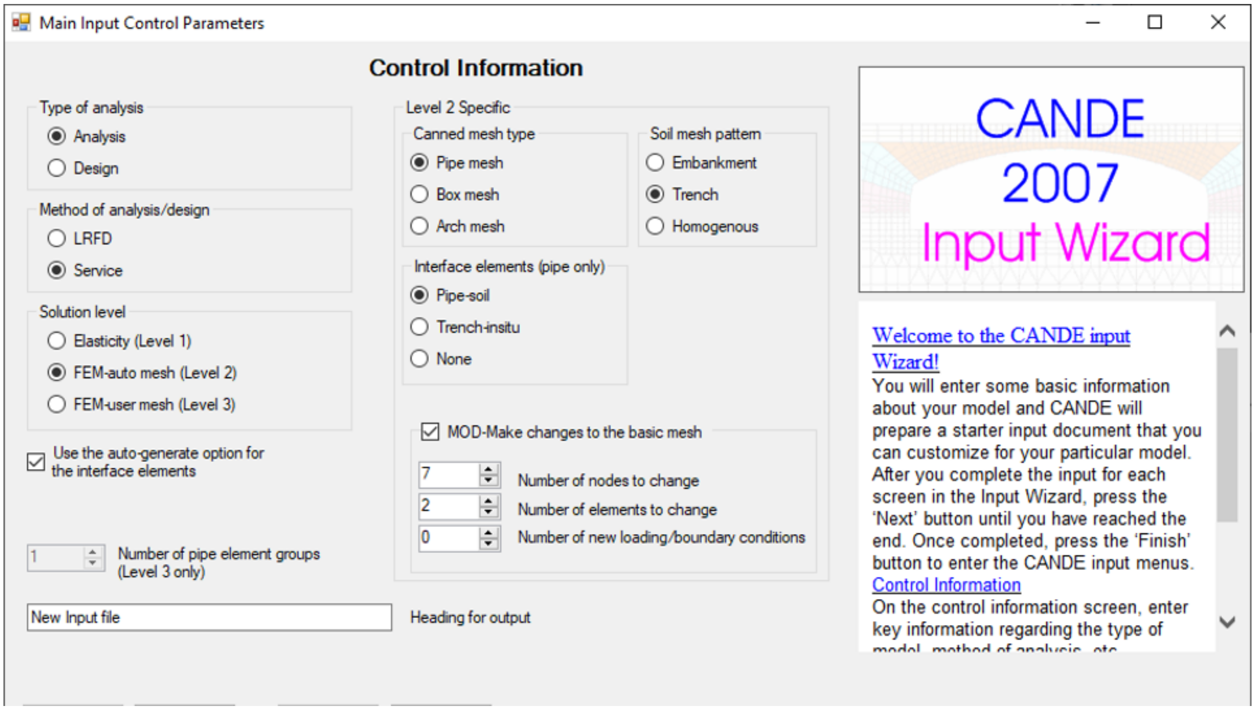
- 2 2/3" X 1/2" corrugation profile
  - Young's modulus =29,000,000 psi
  - Yield stress = 33,000 psi
  - Poisson's ratio = 0.3
  - Area of pipe wall = 0.0806 in^2/in
  - Moment of inertia of pipe wall = 0.0019 in^4/in
  - Section modulus of pipe wall = 0.00667 in^3/in
- Soil properties
  - Good cohesive soil for in situ material
  - Good granular soil for bedding and backfill
  - Good cohesive soil for overfill
- Small deformation analysis

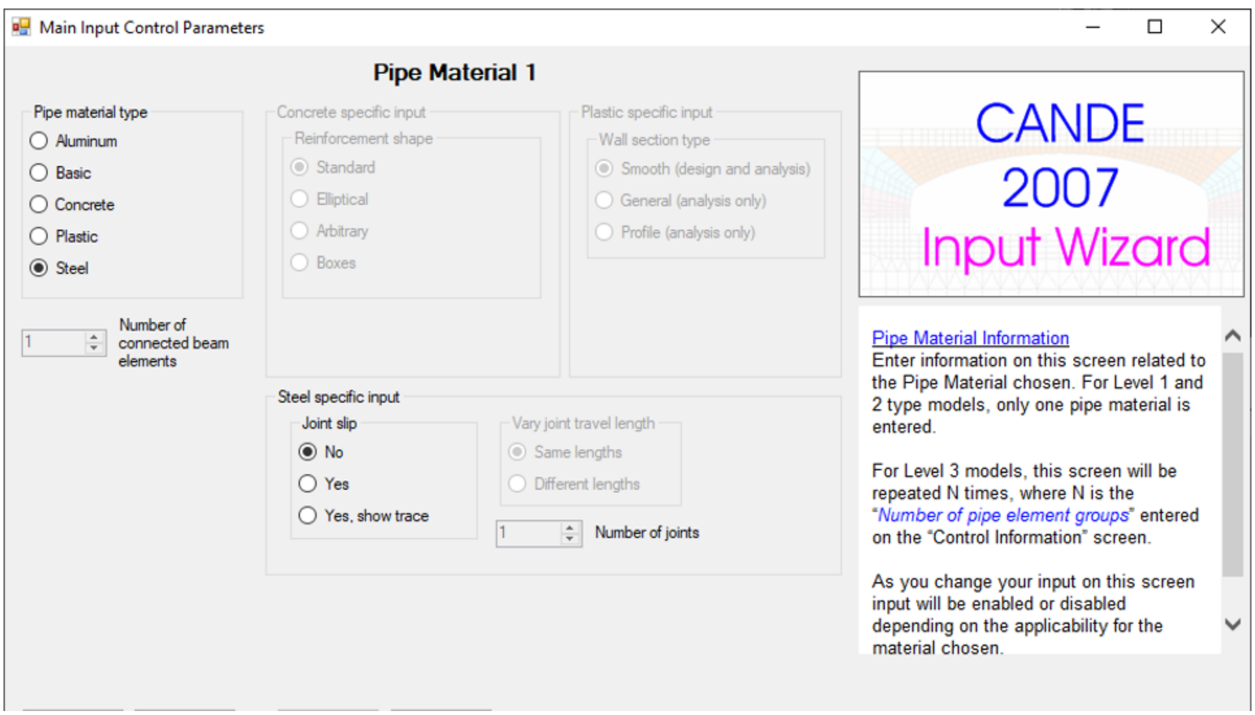
STATEMENT OF THE PROBLEM

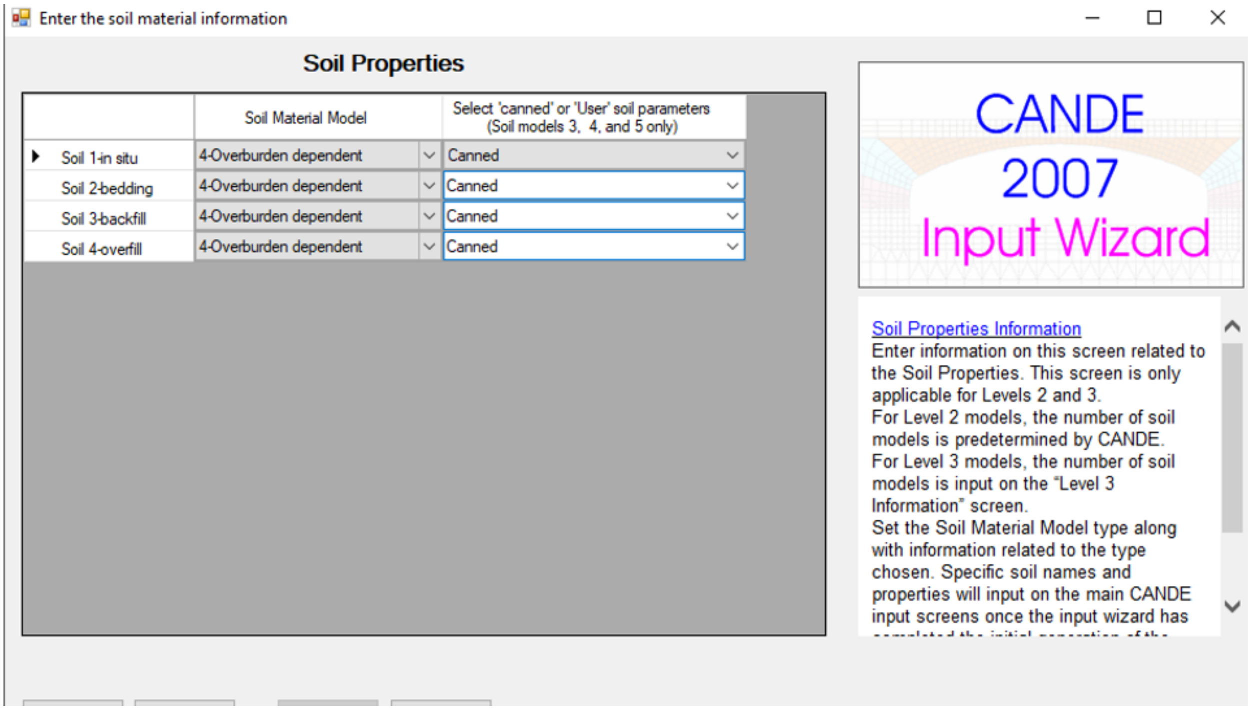
- 48-inch pipe diameter
- Trench width of 1.5*D = 6 ft
- Trench depth = 4.67 ft
- Height of soil = 40 ft (above trench)
- Density of soil above mesh =120 pcf
- 10 load steps
  - 5 inherent in canned mesh
  - 5 for boundary loads

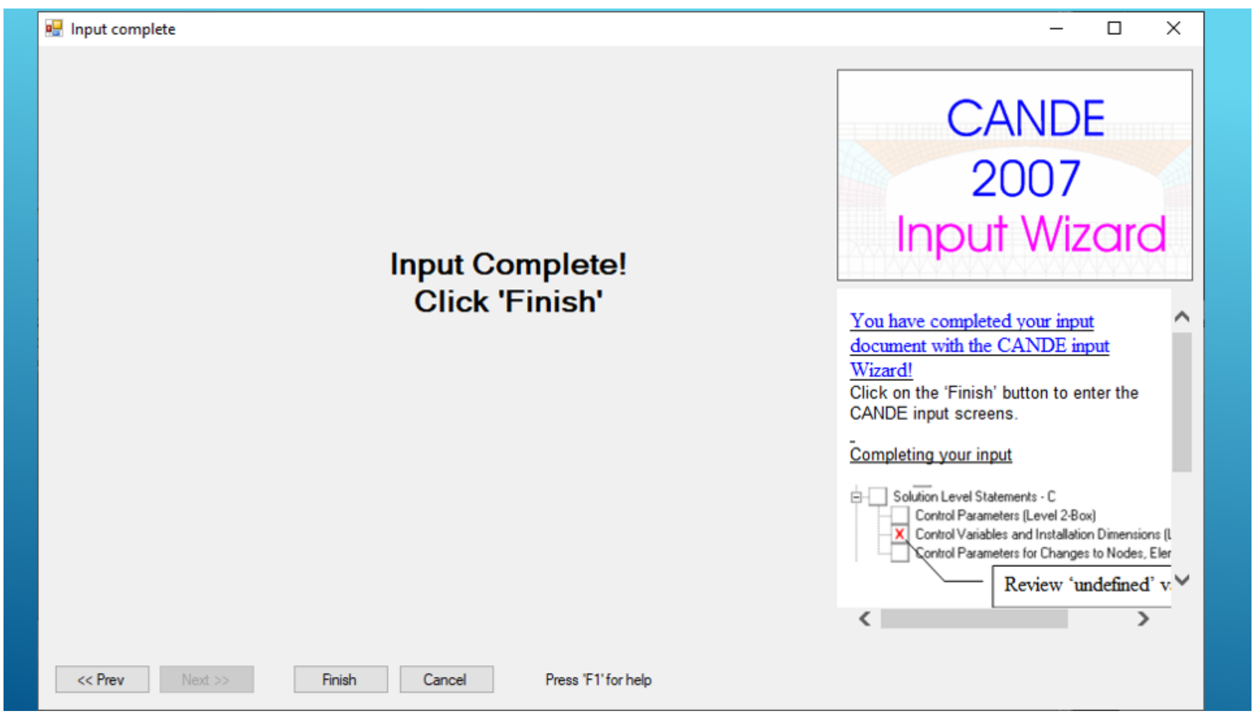


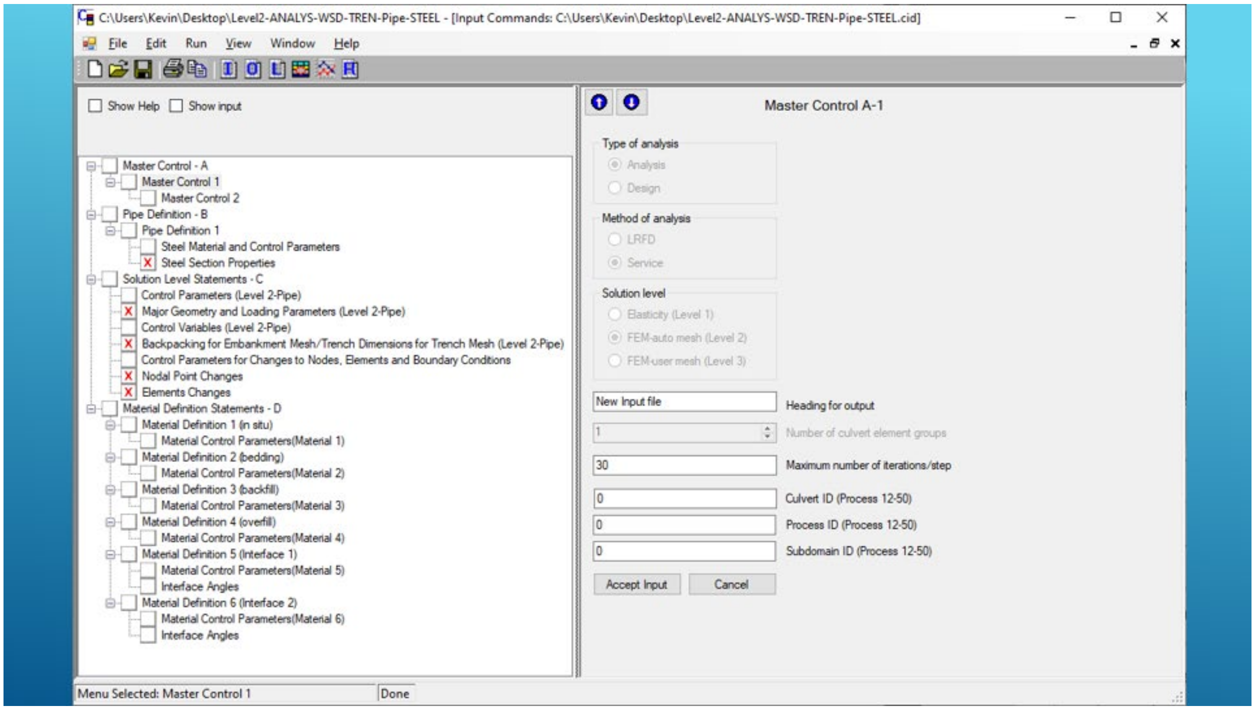
STATEMENT OF THE PROBLEM


Main Input Control Parameters
Control Information
Type of analysis
Analysis
Design
Method of analysis/design
LRFD
Service
Solution level
Elasticity (Level 1)
FEM-auto mesh (Level 2)
FEM-user mesh (Level 3)
Use the auto-generate option for the interface elements
Number of pipe element groups (Level 3 only)
New Input file
Heading for output
Level 2 Specific
Canned mesh type
Pipe mesh
Box mesh
Arch mesh
Soil mesh pattern
Embankment
Trench
Homogenous
Interface elements (pipe only)
Pipe-soil
Trench-insitu
None
MOD-Make changes to the basic mesh
Number of nodes to change
Number of elements to change
Number of new loading/boundary conditions
CANDE 2007 Input Wizard
Welcome to the CANDE input Wizard!
You will enter some basic information about your model and CANDE will prepare a starter input document that you can customize for your particular model. After you complete the input for each screen in the Input Wizard, press the 'Next' button until you have reached the end. Once completed, press the 'Finish' button to enter the CANDE input menus.
Control Information
On the control information screen, enter key information regarding the type of

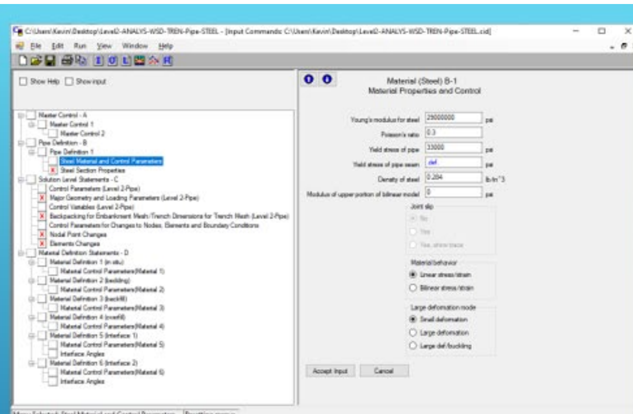

Main Input Control Parameters
Pipe Material 1
Pipe material type
Aluminum
Basic
Concrete
Plastic
Steel
Number of connected beam elements
Concrete specific input
Reinforcement shape
Standard
Elliptical
Arbitrary
Boxes
Plastic specific input
Wall section type
Smooth (design and analysis)
General (analysis only)
Profile (analysis only)
Steel specific input
Joint slip
No
Yes
Yes, show trace
Vary joint travel length
Same lengths
Different lengths
Number of joints
CANDE 2007 Input Wizard
Pipe Material Information
Enter information on this screen related to the Pipe Material chosen. For Level 1 and 2 type models, only one pipe material is entered.
For Level 3 models, this screen will be repeated N times, where N is the "Number of pipe element groups" entered on the "Control Information" screen.
As you change your input on this screen input will be enabled or disabled depending on the applicability for the material chosen.


Enter the soil material information
Soil Properties
Soil Material Model
Select 'canned' or 'User' soil parameters (Soil models 3, 4, and 5 only)
Soil 1-in situ
Soil 2-bedding
Soil 3-backfill
Soil 4-overfill
4-Overburden dependent
Canned
CANDE
2007
Input Wizard
Soil Properties Information
Enter information on this screen related to the Soil Properties. This screen is only applicable for Levels 2 and 3.
For Level 2 models, the number of soil models is predetermined by CANDE.
For Level 3 models, the number of soil models is input on the "Level 3 Information" screen.
Set the Soil Material Model type along with information related to the type chosen. Specific soil names and properties will input on the main CANDE input screens once the input wizard has

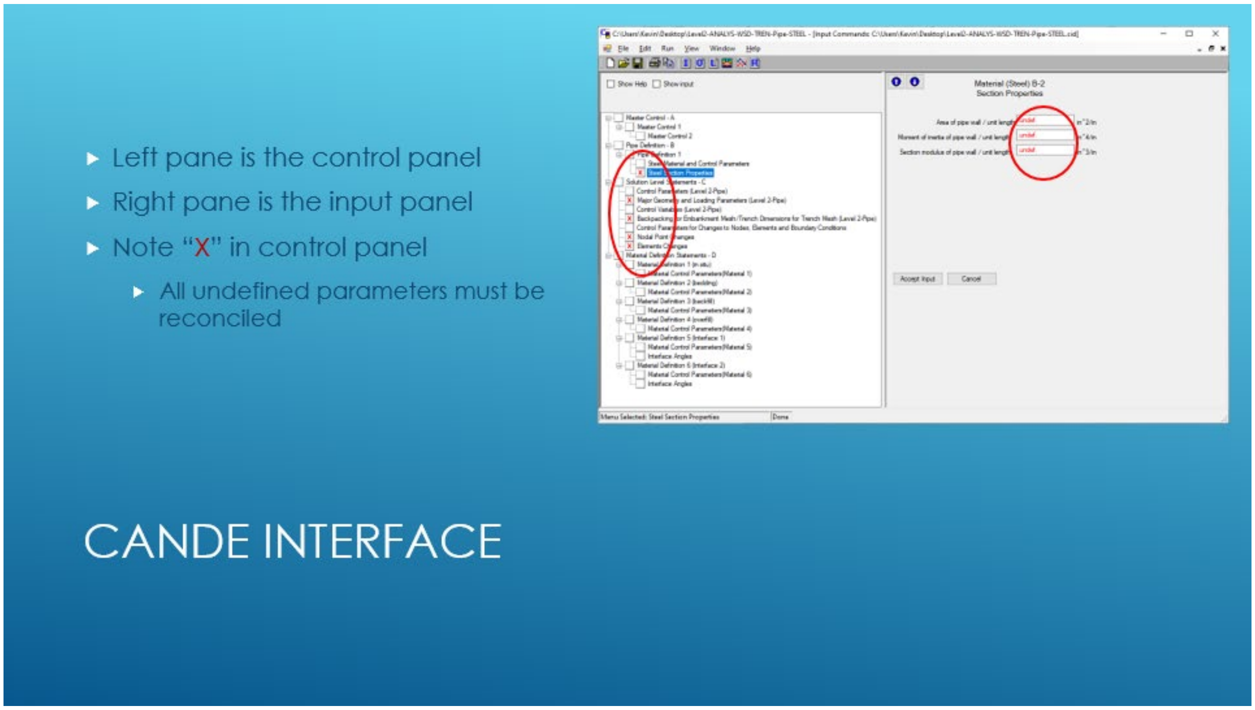

Input complete
Input Complete!
Click 'Finish'
CANDE
2007
Input Wizard
You have completed your input document with the CANDE input Wizard!
Click on the 'Finish' button to enter the CANDE input screens.
Completing your input
Solution Level Statements - C
Control Parameters (Level 2-Box)
Control Variables and Installation Dimensions
Control Parameters for Changes to Nodes, Eler
Review 'undefined' v
<< Prev
Next >>
Finish
Cancel
Press 'F1' for help

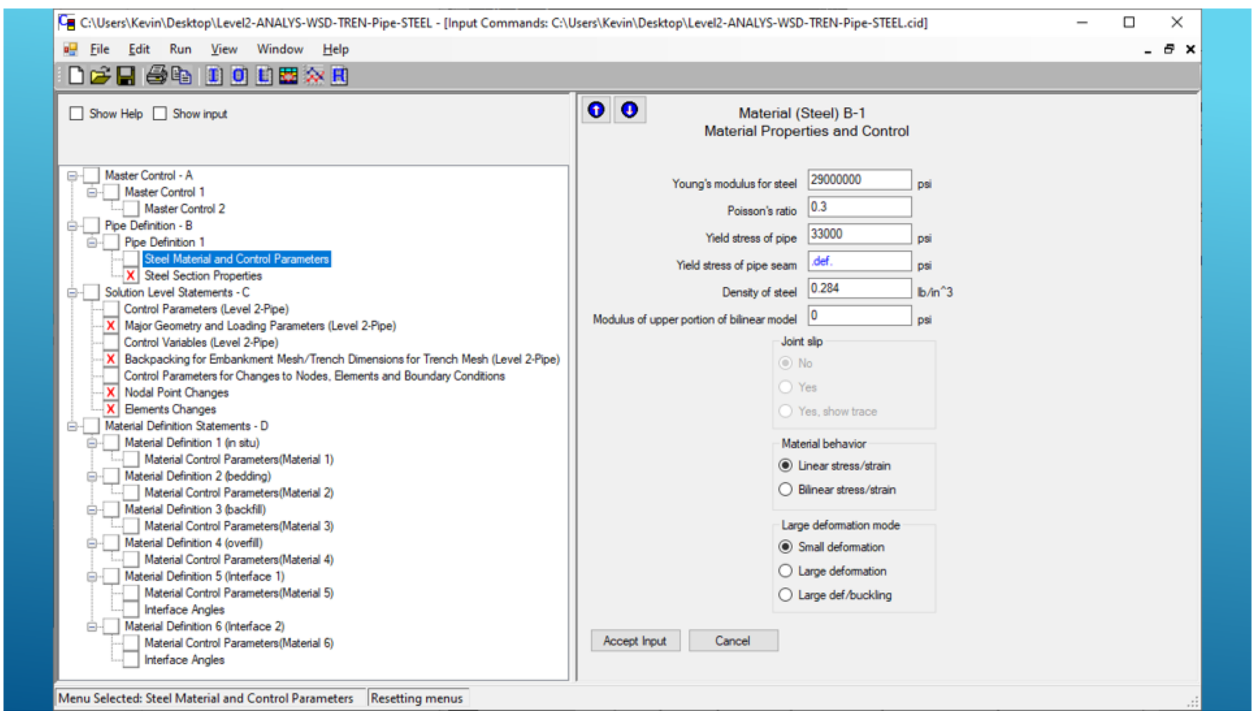


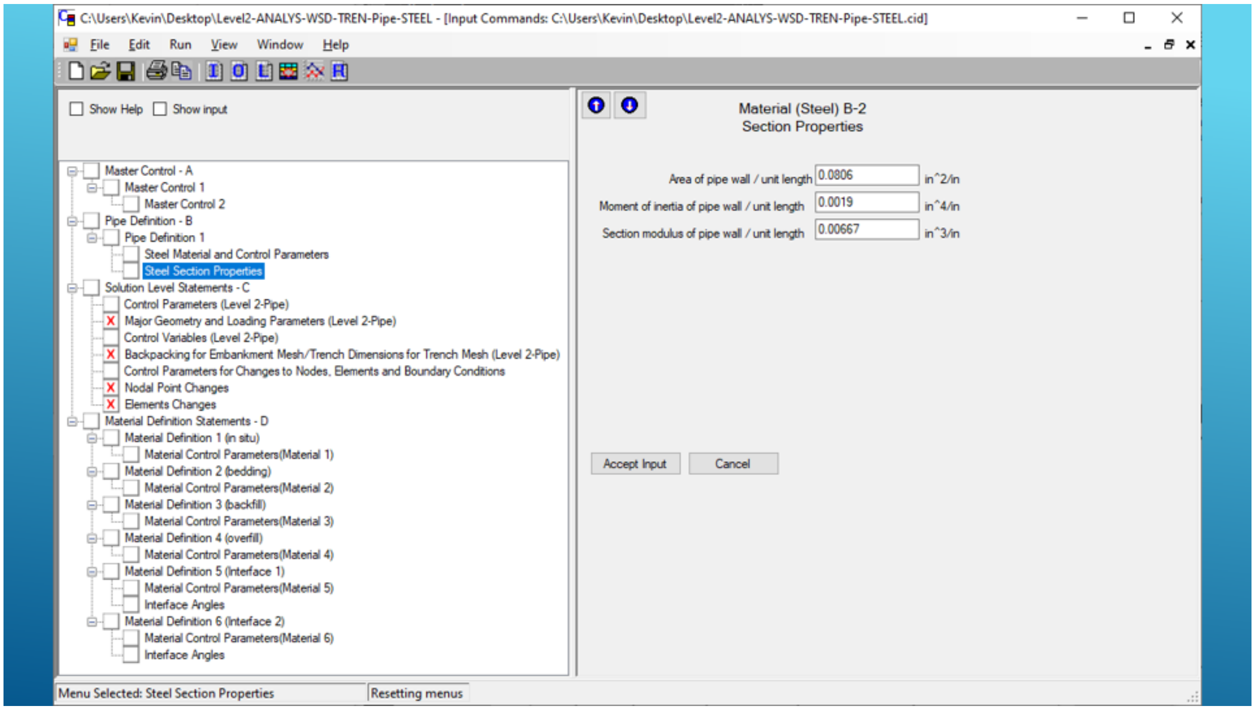
- Left pane is the control panel
- Right pane is the input panel
- Note ".def" in input panel
  - Default value – must verify appropriateness

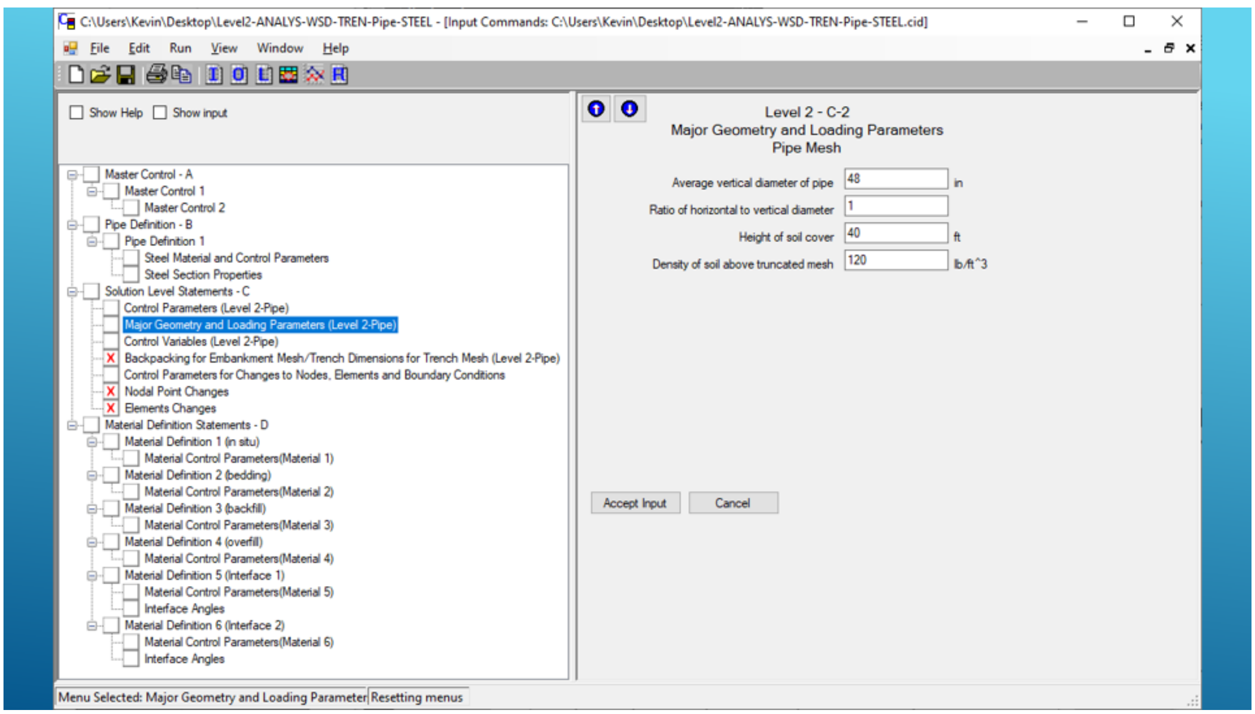


CANDE INTERFACE


Left pane is the control panel
Right pane is the input panel
Note "X" in control panel
All undefined parameters must be reconciled
CANDE INTERFACE
Material (Steel) B-2
Section Properties


C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
File Edit Run View Window Help
Show Help Show input
Master Control - A
Master Control 1
Master Control 2
Pipe Definition - B
Pipe Definition 1
Steel Material and Control Parameters
X Steel Section Properties
Solution Level Statements - C
Control Parameters (Level 2-Pipe)
X Major Geometry and Loading Parameters (Level 2-Pipe)
Control Variables (Level 2-Pipe)
X Backpacking for Embankment Mesh/Trench Dimensions for Trench Mesh (Level 2-Pipe)
Control Parameters for Changes to Nodes, Elements and Boundary Conditions
X Nodal Point Changes
X Elements Changes
Material Definition Statements - D
Material Definition 1 (in situ)
Material Control Parameters(Material 1)
Material Definition 2 (bedding)
Material Control Parameters(Material 2)
Material Definition 3 (backfill)
Material Control Parameters(Material 3)
Material Definition 4 (overfill)
Material Control Parameters(Material 4)
Material Definition 5 (Interface 1)
Material Control Parameters(Material 5)
Interface Angles
Material Definition 6 (Interface 2)
Material Control Parameters(Material 6)
Interface Angles
Material (Steel) B-1
Material Properties and Control
Young's modulus for steel 29000000 psi
Poisson's ratio 0.3
Yield stress of pipe 33000 psi
Yield stress of pipe seam def. psi
Density of steel 0.284 lb/in^3
Modulus of upper portion of bilinear model 0 psi
Joint slip
No
Yes
Yes, show trace
Material behavior
Linear stress/strain
Bilinear stress/strain
Large deformation mode
Small deformation
Large deformation
Large def/buckling
Accept Input
Cancel
Menu Selected: Steel Material and Control Parameters
Resetting menus


C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
File Edit Run View Window Help
Show Help Show input
Master Control - A
Master Control 1
Master Control 2
Pipe Definition - B
Pipe Definition 1
Steel Material and Control Parameters
Steel Section Properties
Solution Level Statements - C
Control Parameters (Level 2-Pipe)
Major Geometry and Loading Parameters (Level 2-Pipe)
Control Variables (Level 2-Pipe)
Backpacking for Embankment Mesh/Trench Dimensions for Trench Mesh (Level 2-Pipe)
Control Parameters for Changes to Nodes, Elements and Boundary Conditions
Nodal Point Changes
Elements Changes
Material Definition Statements - D
Material Definition 1 (in situ)
Material Control Parameters(Material 1)
Material Definition 2 (bedding)
Material Control Parameters(Material 2)
Material Definition 3 (backfill)
Material Control Parameters(Material 3)
Material Definition 4 (overfill)
Material Control Parameters(Material 4)
Material Definition 5 (Interface 1)
Material Control Parameters(Material 5)
Interface Angles
Material Definition 6 (Interface 2)
Material Control Parameters(Material 6)
Interface Angles
Material (Steel) B-2
Section Properties
Area of pipe wall / unit length 0.0806 in^2/in
Moment of inertia of pipe wall / unit length 0.0019 in^4/in
Section modulus of pipe wall / unit length 0.00667 in^3/in
Accept Input
Cancel
Menu Selected: Steel Section Properties
Resetting menus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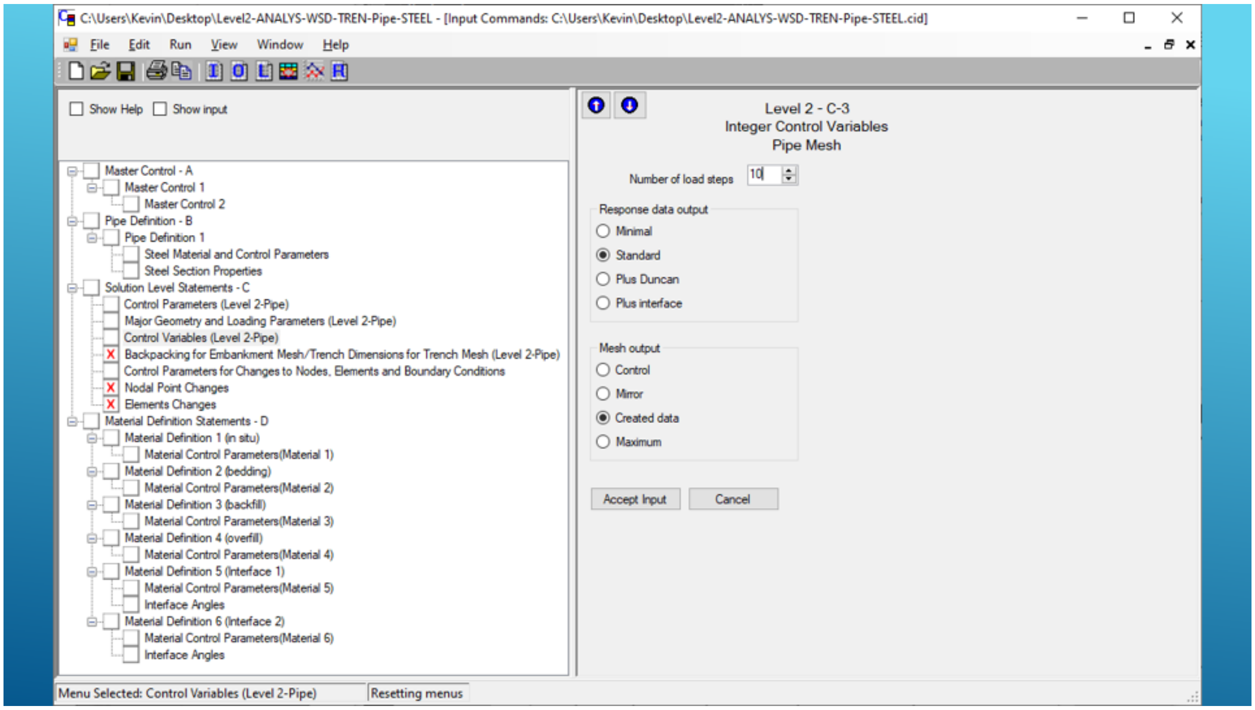
File Edit Run View Window Help
Show Help Show input
Master Control - A
Master Control 1
Master Control 2
Pipe Definition - B
Pipe Definition 1
Steel Material and Control Parameters
Steel Section Properties
Solution Level Statements - C
Control Parameters (Level 2-Pipe)
Major Geometry and Loading Parameters (Level 2-Pipe)
Control Variables (Level 2-Pipe)
Backpacking for Embankment Mesh/Trench Dimensions for Trench Mesh (Level 2-Pipe)
Control Parameters for Changes to Nodes, Elements and Boundary Conditions
Nodal Point Changes
Elements Changes
Material Definition Statements - D
Material Definition 1 (in situ)
Material Control Parameters(Material 1)
Material Definition 2 (bedding)
Material Control Parameters(Material 2)
Material Definition 3 (backfill)
Material Control Parameters(Material 3)
Material Definition 4 (overfill)
Material Control Parameters(Material 4)
Material Definition 5 (Interface 1)
Material Control Parameters(Material 5)
Interface Angles
Material Definition 6 (Interface 2)
Material Control Parameters(Material 6)
Interface Angles
Level 2 - C-2
Major Geometry and Loading Parameters
Pipe Mesh
Average vertical diameter of pipe 48 in
Ratio of horizontal to vertical diameter 1
Height of soil cover 40 ft
Density of soil above truncated mesh 120 lb/ft^3
Accept Input
Cancel
Menu Selected: Major Geometry and Loading Parameter
Resetting menus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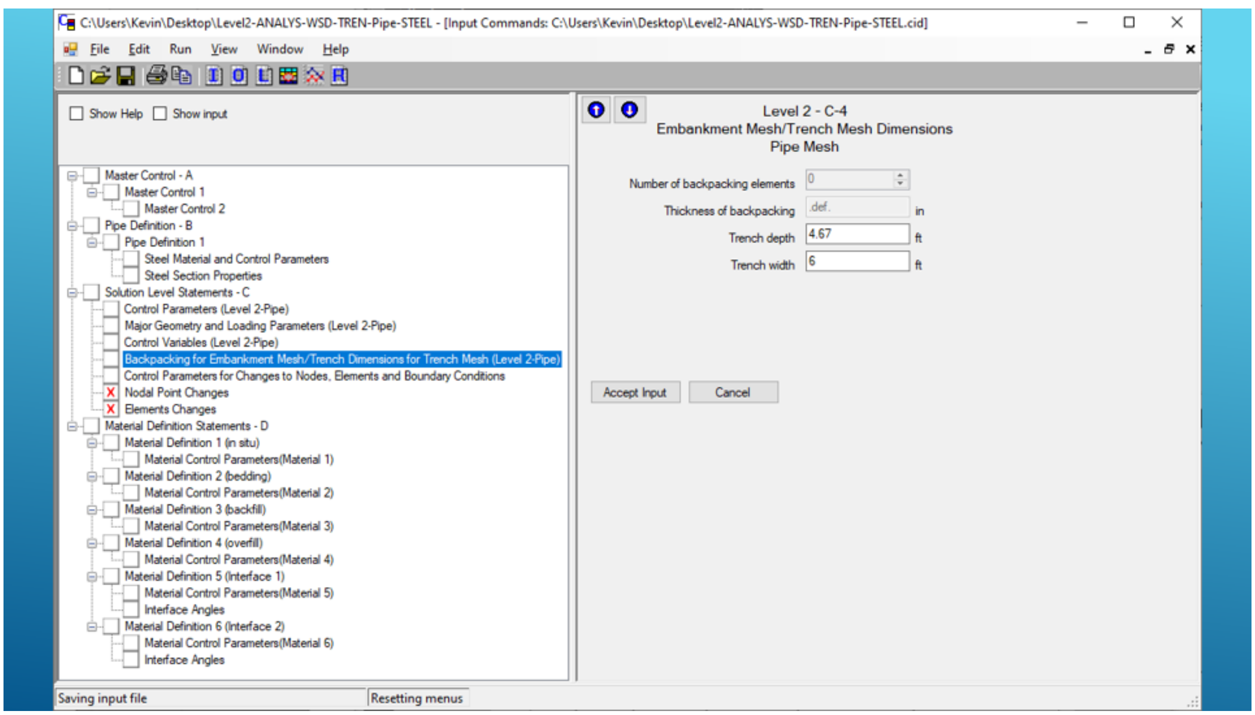
File Edit Run View Window Help
Show Help Show input
Master Control - A
Master Control 1
Master Control 2
Pipe Definition - B
Pipe Definition 1
Steel Material and Control Parameters
Steel Section Properties
Solution Level Statements - C
Control Parameters (Level 2-Pipe)
Major Geometry and Loading Parameters (Level 2-Pipe)
Control Variables (Level 2-Pipe)
Backpacking for Embankment Mesh/Trench Dimensions for Trench Mesh (Level 2-Pipe)
Control Parameters for Changes to Nodes, Elements and Boundary Conditions
Nodal Point Changes
Elements Changes
Material Definition Statements - D
Material Definition 1 (in situ)
Material Control Parameters(Material 1)
Material Definition 2 (bedding)
Material Control Parameters(Material 2)
Material Definition 3 (backfill)
Material Control Parameters(Material 3)
Material Definition 4 (overfill)
Material Control Parameters(Material 4)
Material Definition 5 (Interface 1)
Material Control Parameters(Material 5)
Interface Angles
Material Definition 6 (Interface 2)
Material Control Parameters(Material 6)
Interface Angles
Level 2 - C-3
Integer Control Variables
Pipe Mesh
Number of load steps 10
Response data output
Minimal
Standard
Plus Duncan
Plus interface
Mesh output
Control
Mirror
Created data
Maximum
Accept Input
Cancel
Menu Selected: Control Variables (Level 2-Pipe)
Resetting menus


C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
File Edit Run View Window Help
Show Help Show input
Master Control - A
Master Control 1
Master Control 2
Pipe Definition - B
Pipe Definition 1
Steel Material and Control Parameters
Steel Section Properties
Solution Level Statements - C
Control Parameters (Level 2-Pipe)
Major Geometry and Loading Parameters (Level 2-Pipe)
Control Variables (Level 2-Pipe)
Backpacking for Embankment Mesh/Trench Dimensions for Trench Mesh (Level 2-Pipe)
Control Parameters for Changes to Nodes, Elements and Boundary Conditions
Nodal Point Changes
Elements Changes
Material Definition Statements - D
Material Definition 1 (in situ)
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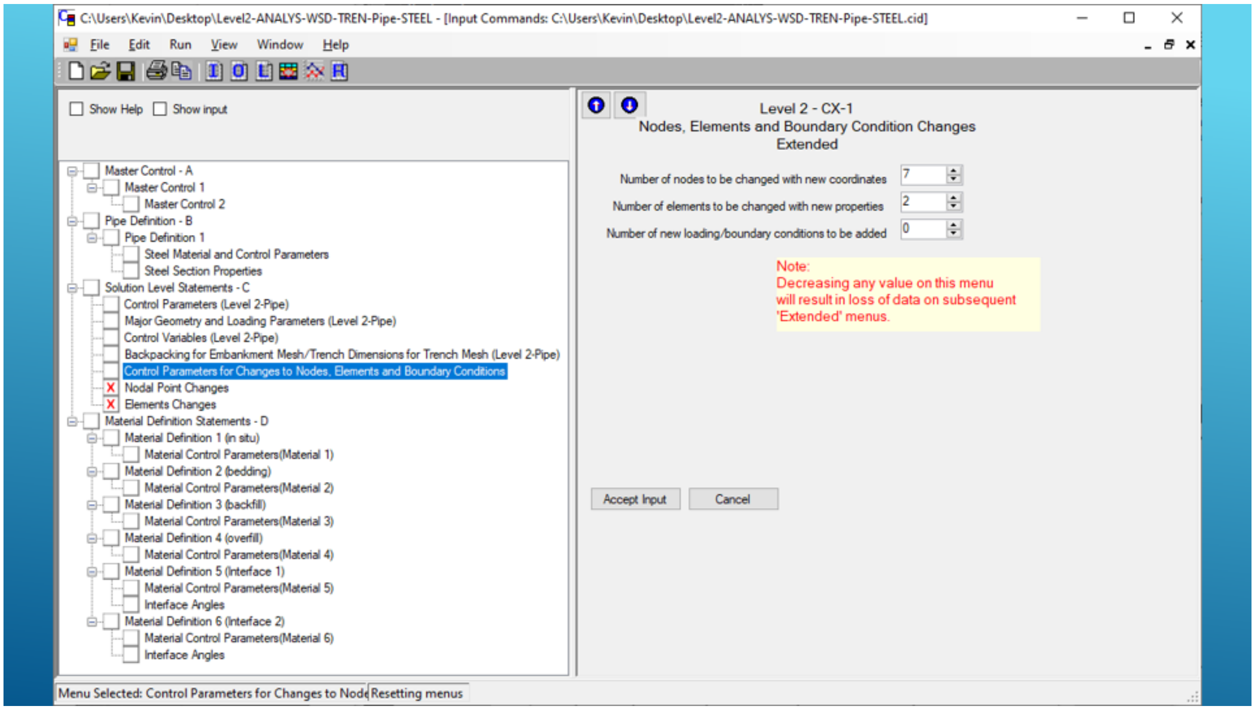
Material Definition 2 (bedding)
Material Control Parameters(Material 2)
Material Definition 3 (backfill)
Material Control Parameters(Material 3)
Material Definition 4 (overfill)
Material Control Parameters(Material 4)
Material Definition 5 (Interface 1)
Material Control Parameters(Material 5)
Interface Angles
Material Definition 6 (Interface 2)
Material Control Parameters(Material 6)
Interface Angles
Level 2 - C-4
Embankment Mesh/Trench Mesh Dimensions
Pipe Mesh
Number of backpacking elements 0
Thickness of backpacking def. in
Trench depth 4.67 ft
Trench width 6 ft
Accept Input
Cancel
Saving input file
Resetting menus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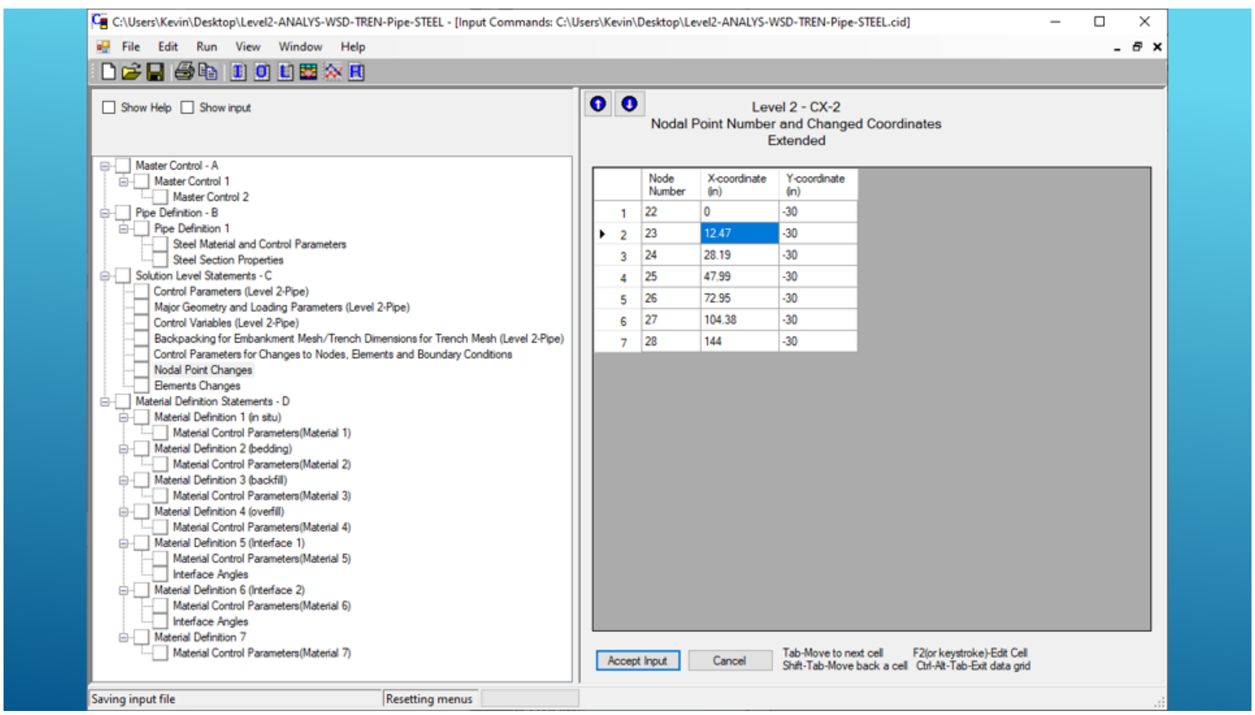
File Edit Run View Window Help
Show Help
Show input
Master Control - A
Master Control 1
Master Control 2
Pipe Definition - B
Pipe Definition 1
Steel Material and Control Parameters
Steel Section Properties
Solution Level Statements - C
Control Parameters (Level 2-Pipe)
Major Geometry and Loading Parameters (Level 2-Pipe)
Control Variables (Level 2-Pipe)
Backpacking for Embankment Mesh/Trench Dimensions for Trench Mesh (Level 2-Pipe)
Control Parameters for Changes to Nodes, Elements and Boundary Conditions
Nodal Point Changes
Elements Changes
Material Definition Statements - D
Material Definition 1 (in situ)
Material Control Parameters(Material 1)
Material Definition 2 (bedding)
Material Control Parameters(Material 2)
Material Definition 3 (backfill)
Material Control Parameters(Material 3)
Material Definition 4 (overfill)
Material Control Parameters(Material 4)
Material Definition 5 (Interface 1)
Material Control Parameters(Material 5)
Interface Angles
Material Definition 6 (Interface 2)
Material Control Parameters(Material 6)
Interface Angles
Level 2 - CX-1
Nodes, Elements and Boundary Condition Changes
Extended
Number of nodes to be changed with new coordinates 7
Number of elements to be changed with new properties 2
Number of new loading/boundary conditions to be added 0
Note:
Decreasing any value on this menu
will result in loss of data on subsequent
'Extended' menus.
Accept Input
Cancel
Menu Selected: Control Parameters for Changes to Node
Resetting menus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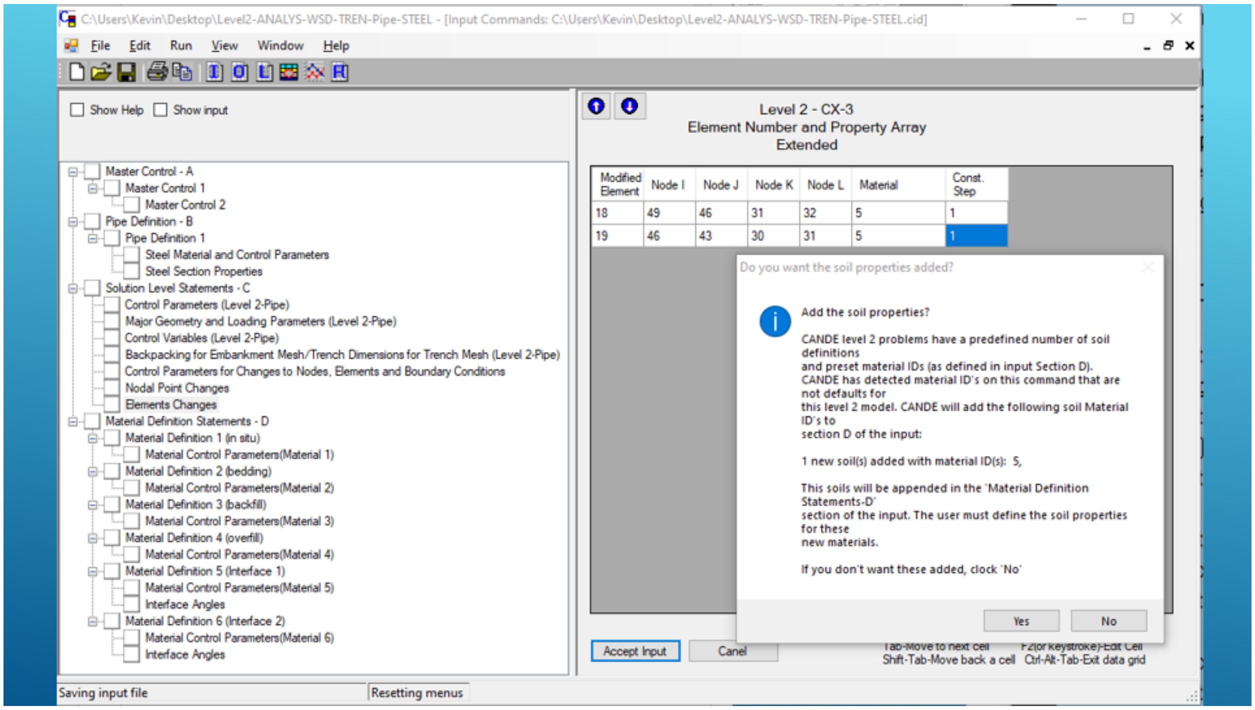
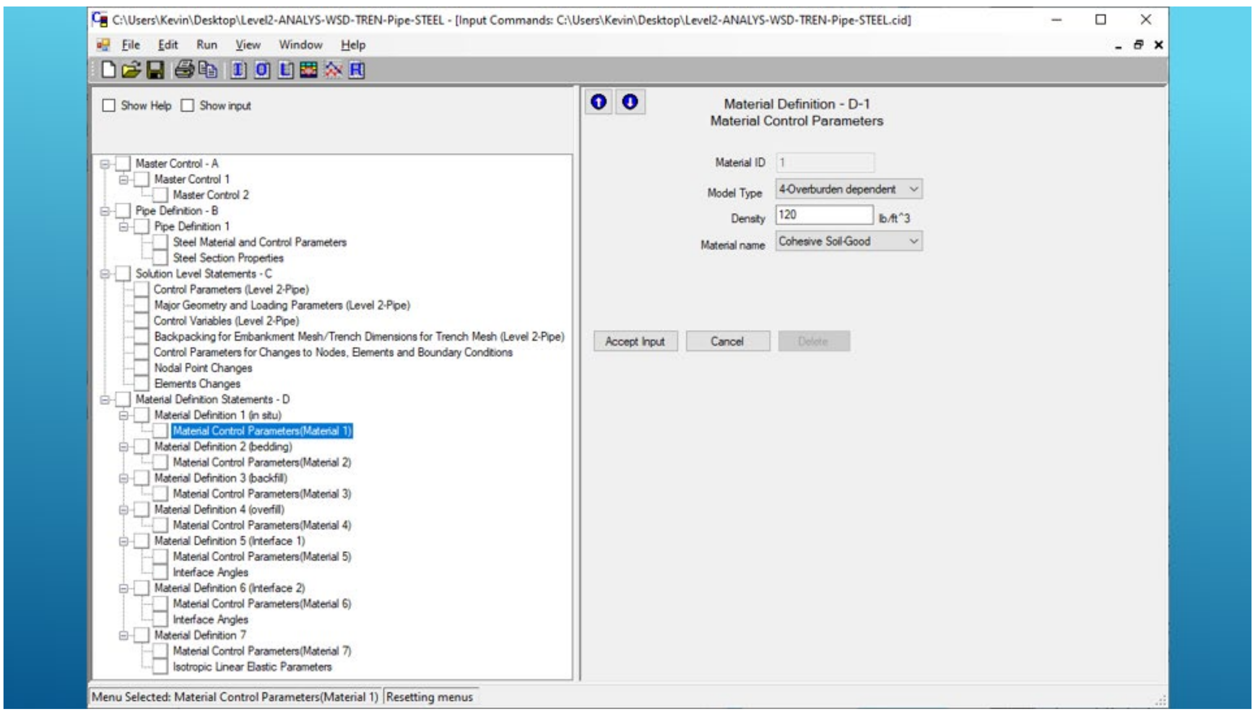
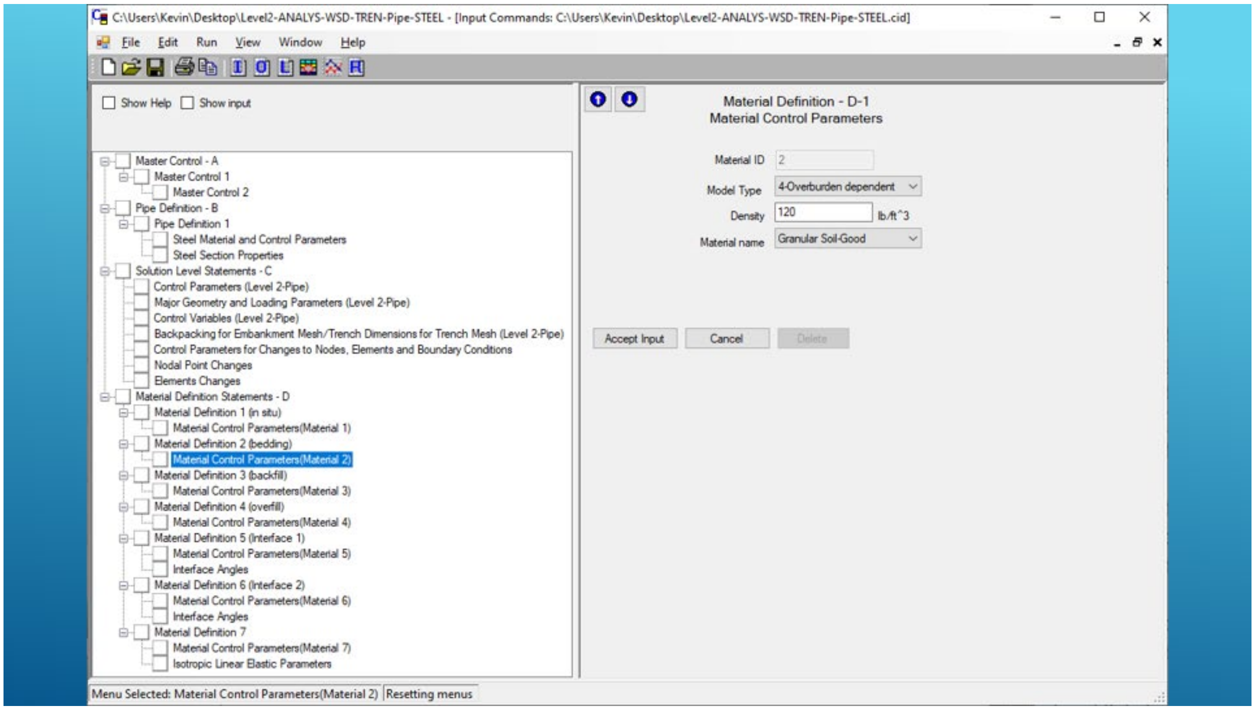
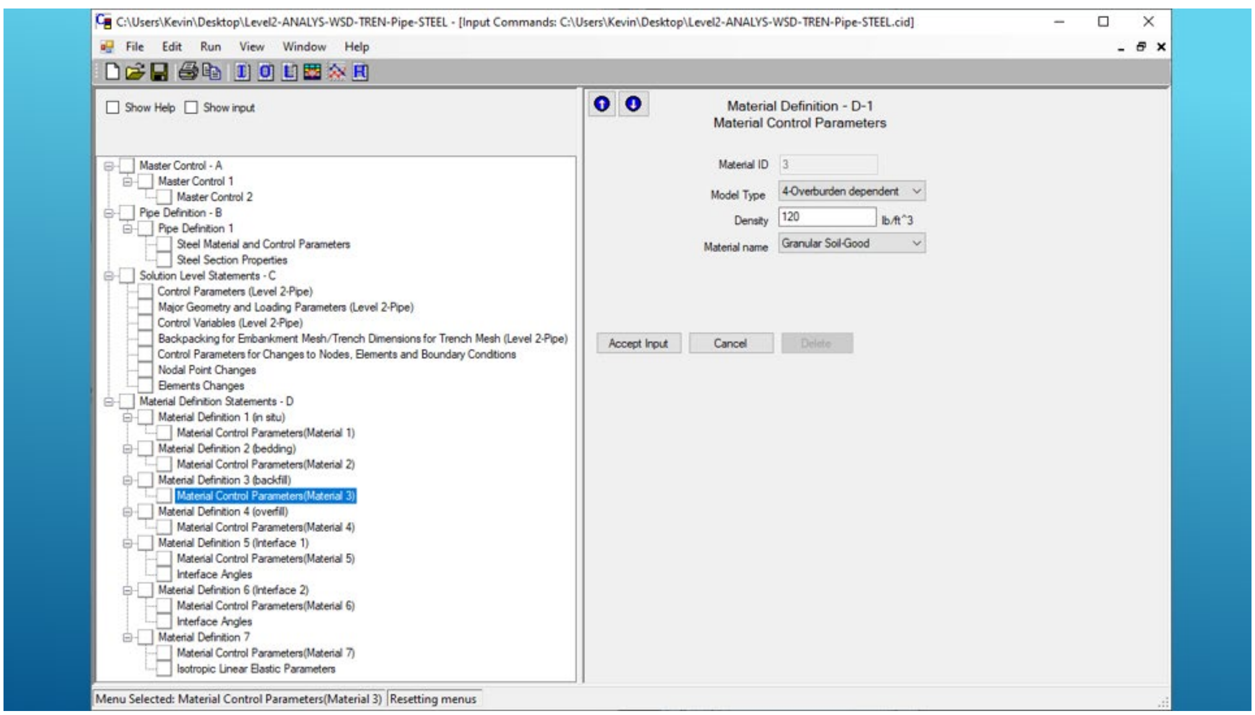
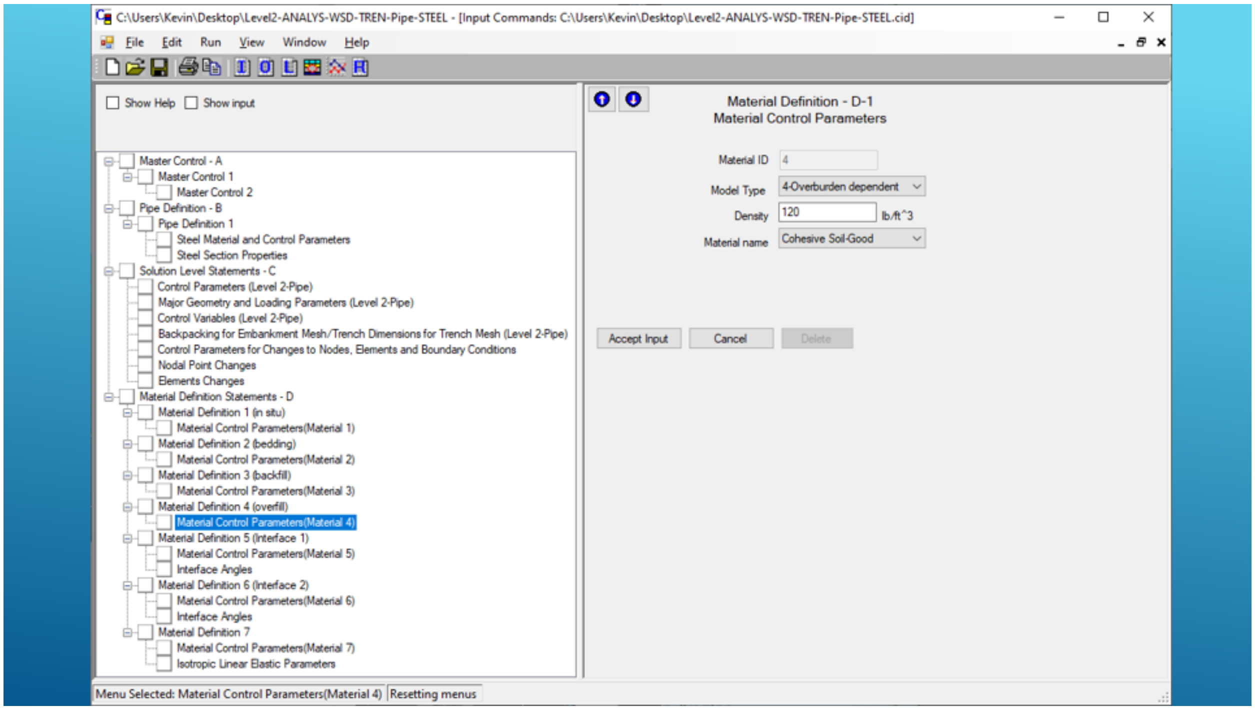
File Edit Run View Window Help
Show Help
Show input
Level 2 - CX-2
Nodal Point Number and Changed Coordinates
Extended
Node Number
X-coordinate (in)
Y-coordinate (in)
1 22 0 -30
2 23 12.47 -30
3 24 28.19 -30
4 25 47.99 -30
5 26 72.95 -30
6 27 104.38 -30
7 28 144 -30
Material Definition 7
Material Control Parameters(Material 7)
Accept Input
Cancel
Tab-Move to next cell
Shift-Tab-Move back a cell
F2(or keystroke)-Edit Cell
Ctrl-Alt-Tab-Exit data grid
Saving input file
Resetting menus

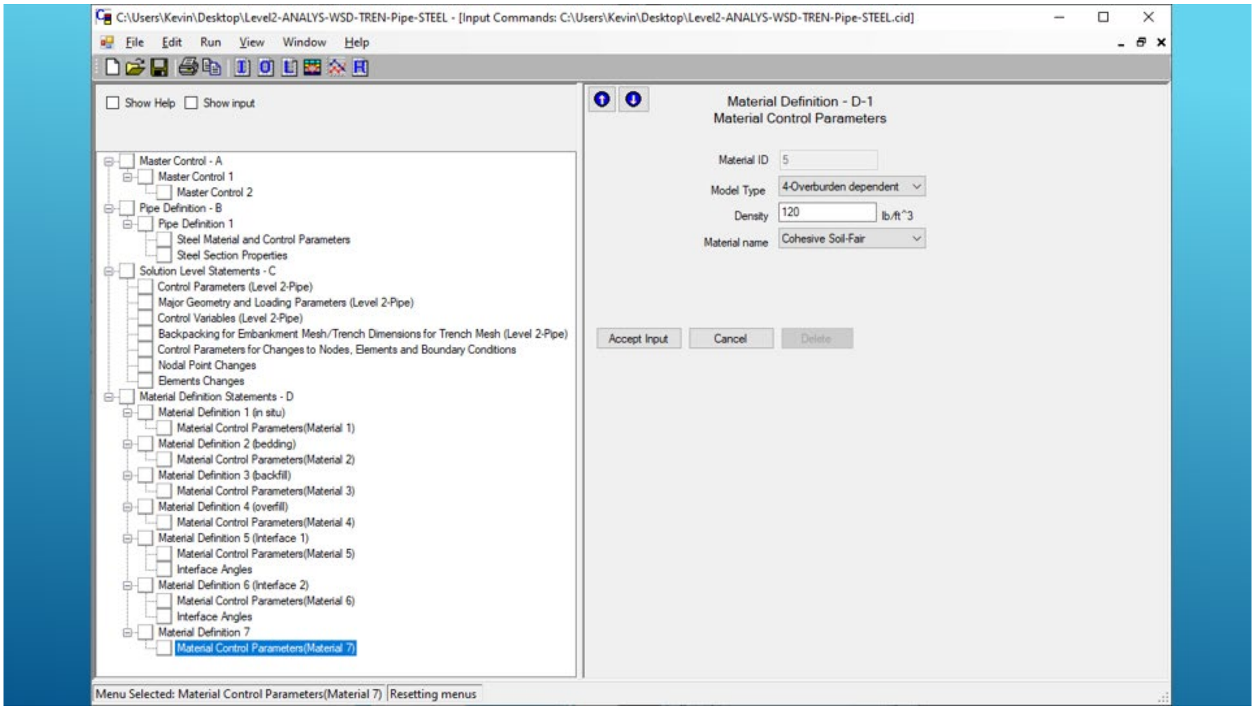

C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
Level 2 - CX-3
Element Number and Property Array
Extended
Do you want the soil properties added?
Add the soil properties?
CANDE level 2 problems have a predefined number of soil definitions
and preset material IDs (as defined in input Section D).
CANDE has detected material ID's on this command that are not defaults for
this level 2 model. CANDE will add the following soil Material ID's to
section D of the input:
1 new soil(s) added with material ID(s): 5,
This soils will be appended in the 'Material Definition Statements-D'
section of the input. The user must define the soil properties for these
new materials.
If you don't want these added, clock 'No'
Yes
No
Accept Input
Canel
Saving input file
Resetting menus

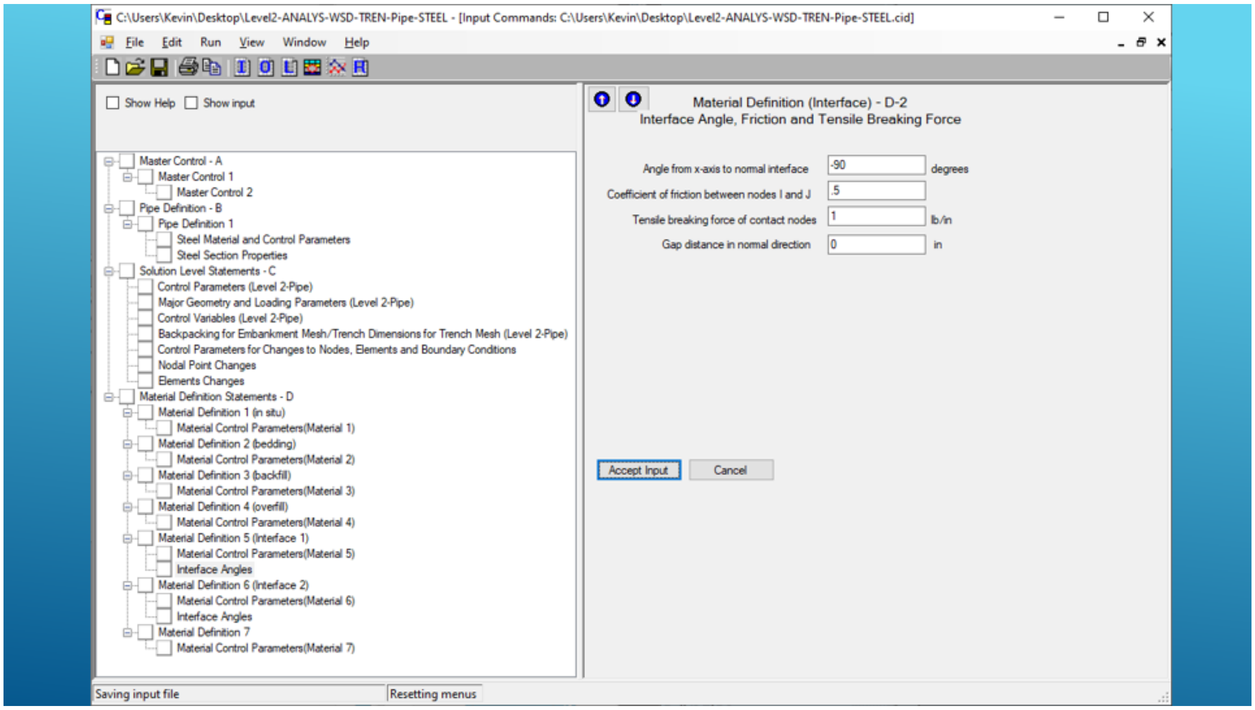

C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
Material Definition - D-1
Material Control Parameters
Material ID 1
Model Type 4-Overburden dependent
Density 120 lb/ft^3
Material name Cohesive Soil-Good
Accept Input
Cancel
Delete
Menu Selected: Material Control Parameters(Material 1)
Resetting menus

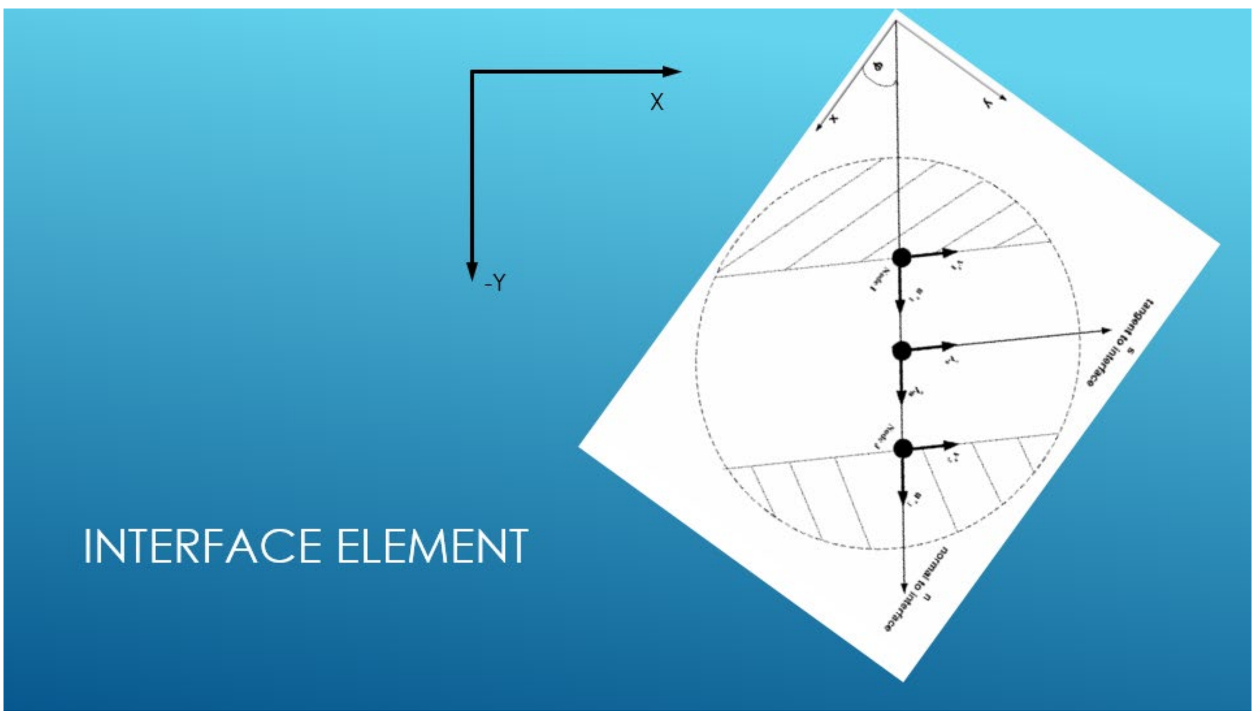

C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
File Edit Run View Window Help
Show Help Show input
Master Control - A
Master Control 1
Master Control 2
Pipe Definition - B
Pipe Definition 1
Steel Material and Control Parameters
Steel Section Properties
Solution Level Statements - C
Control Parameters (Level 2-Pipe)
Major Geometry and Loading Parameters (Level 2-Pipe)
Control Variables (Level 2-Pipe)
Backpacking for Embankment Mesh/Trench Dimensions for Trench Mesh (Level 2-Pipe)
Control Parameters for Changes to Nodes, Elements and Boundary Conditions
Nodal Point Changes
Elements Changes
Material Definition Statements - D
Material Definition 1 (in situ)
Material Control Parameters(Material 1)
Material Definition 2 (bedding)
Material Control Parameters(Material 2)
Material Definition 3 (backfill)
Material Control Parameters(Material 3)
Material Definition 4 (overfill)
Material Control Parameters(Material 4)
Material Definition 5 (Interface 1)
Material Control Parameters(Material 5)
Interface Angles
Material Definition 6 (Interface 2)
Material Control Parameters(Material 6)
Interface Angles
Material Definition 7
Material Control Parameters(Material 7)
Isotropic Linear Elastic Parameters
Material Definition - D-1
Material Control Parameters
Material ID 2
Model Type 4-Overburden dependent
Density 120 lb/ft^3
Material name Granular Soil-Good
Accept Input
Cancel
Delete
Menu Selected: Material Control Parameters(Material 2) Resetting menus

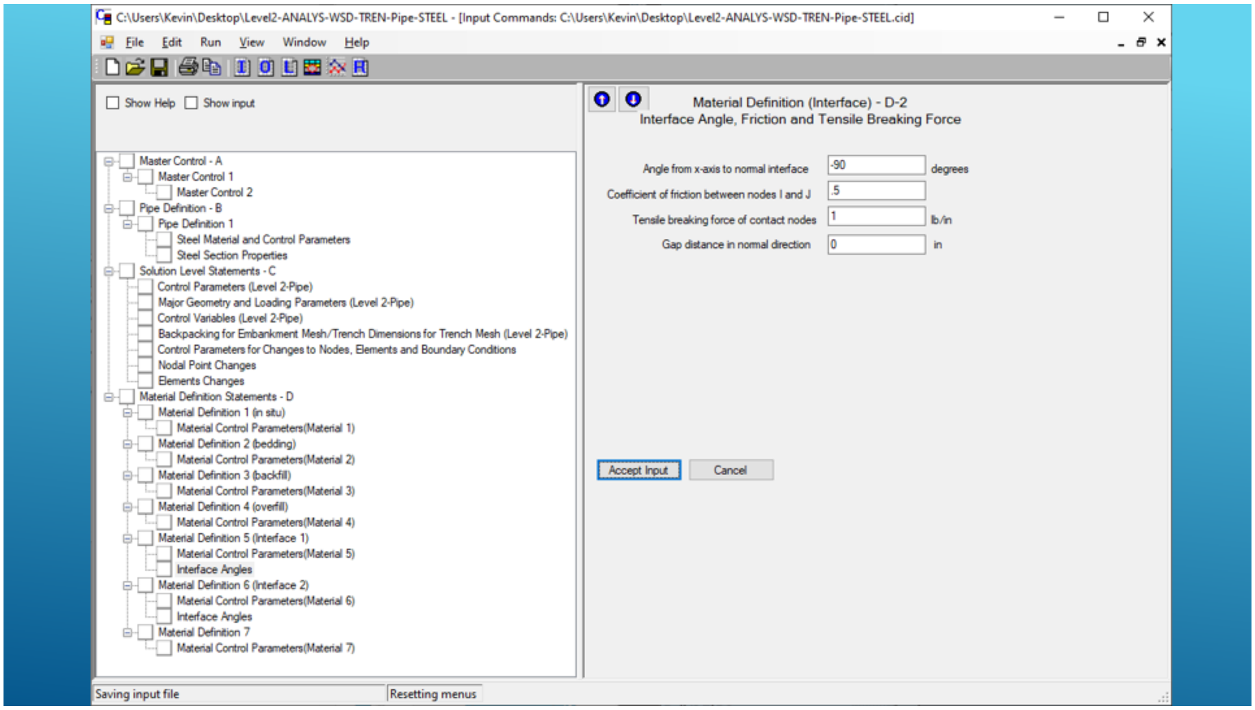

C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
File Edit Run View Window Help
Show Help Show input
Master Control - A
Master Control 1
Master Control 2
Pipe Definition - B
Pipe Definition 1
Steel Material and Control Parameters
Steel Section Properties
Solution Level Statements - C
Control Parameters (Level 2-Pipe)
Major Geometry and Loading Parameters (Level 2-Pipe)
Control Variables (Level 2-Pipe)
Backpacking for Embankment Mesh/Trench Dimensions for Trench Mesh (Level 2-Pipe)
Control Parameters for Changes to Nodes, Elements and Boundary Conditions
Nodal Point Changes
Elements Changes
Material Definition Statements - D
Material Definition 1 (in situ)
Material Control Parameters(Material 1)
Material Definition 2 (bedding)
Material Control Parameters(Material 2)
Material Definition 3 (backfill)
Material Control Parameters(Material 3)
Material Definition 4 (overfill)
Material Control Parameters(Material 4)
Material Definition 5 (Interface 1)
Material Control Parameters(Material 5)
Interface Angles
Material Definition 6 (Interface 2)
Material Control Parameters(Material 6)
Interface Angles
Material Definition 7
Material Control Parameters(Material 7)
Isotropic Linear Elastic Parameters
Material Definition - D-1
Material Control Parameters
Material ID 3
Model Type 4-Overburden dependent
Density 120 lb/ft^3
Material name Granular Soil-Good
Accept Input
Cancel
Delete
Menu Selected: Material Control Parameters(Material 3) Resetting menus

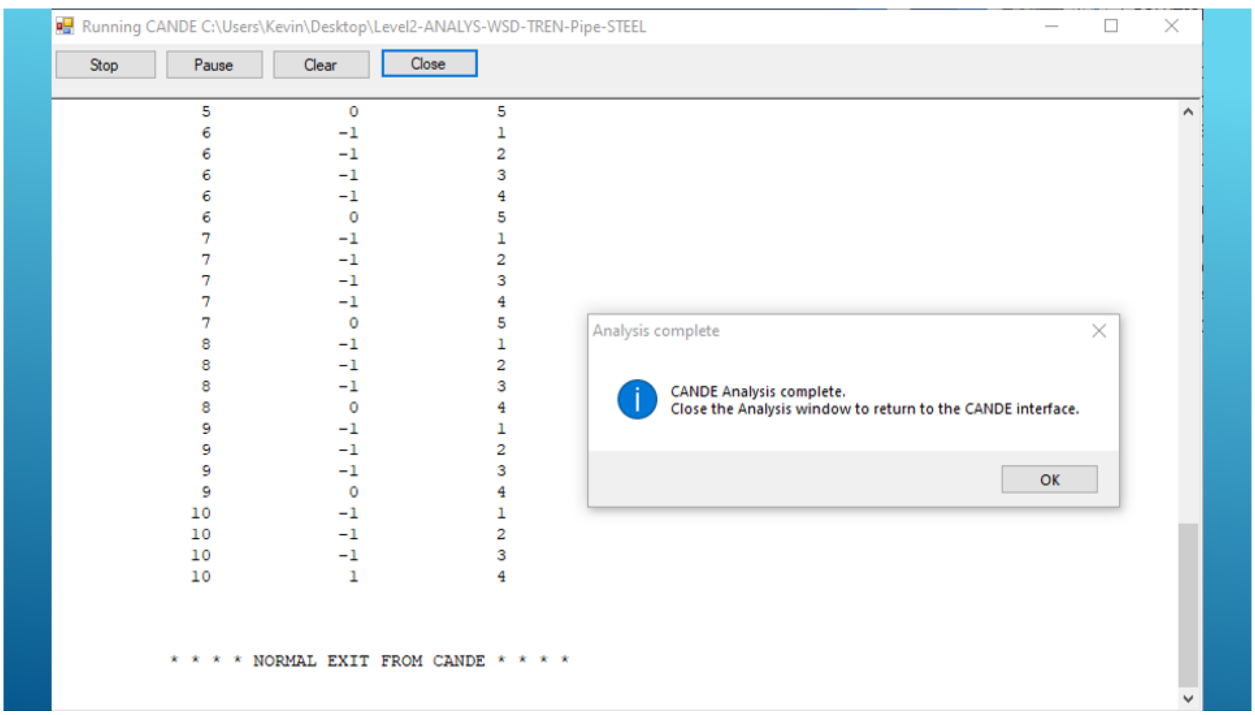

C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
Material Definition - D-1
Material Control Parameters
Material ID 4
Model Type 4-Overburden dependent
Density 120 lb/ft^3
Material name Cohesive Soil-Good
Accept Input
Cancel
Delete
Menu Selected: Material Control Parameters(Material 4)
Resetting menus


C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
Material Definition - D-1
Material Control Parameters
Material ID 5
Model Type 4-Overburden dependent
Density 120 lb/ft^3
Material name Cohesive Soil-Fair
Accept Input
Cancel
Delete
Menu Selected: Material Control Parameters(Material 7)
Resetting menus

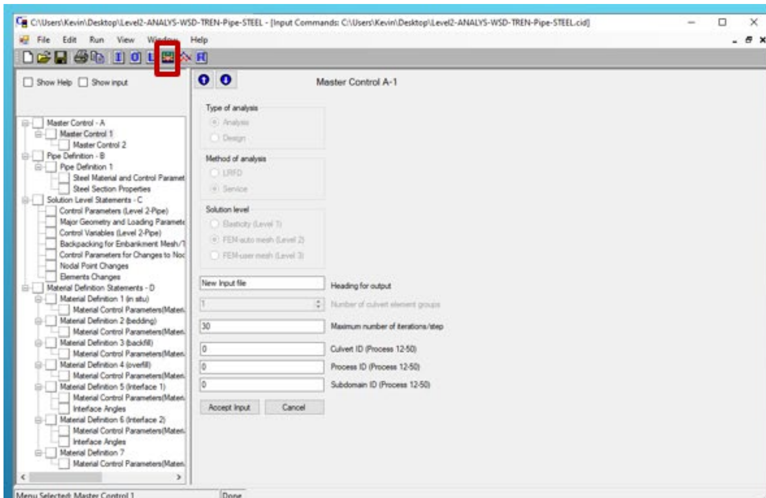

C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
File Edit Run View Window Help
Show Help
Show input
Master Control - A
Master Control 1
Master Control 2
Pipe Definition - B
Pipe Definition 1
Steel Material and Control Parameters
Steel Section Properties
Solution Level Statements - C
Control Parameters (Level 2-Pipe)
Major Geometry and Loading Parameters (Level 2-Pipe)
Control Variables (Level 2-Pipe)
Backpacking for Embankment Mesh/Trench Dimensions for Trench Mesh (Level 2-Pipe)
Control Parameters for Changes to Nodes, Elements and Boundary Conditions
Nodal Point Changes
Elements Changes
Material Definition Statements - D
Material Definition 1 (in situ)
Material Control Parameters(Material 1)
Material Definition 2 (bedding)
Material Control Parameters(Material 2)
Material Definition 3 (backfill)
Material Control Parameters(Material 3)
Material Definition 4 (overfill)
Material Control Parameters(Material 4)
Material Definition 5 (Interface 1)
Material Control Parameters(Material 5)
Interface Angles
Material Definition 6 (Interface 2)
Material Control Parameters(Material 6)
Interface Angles
Material Definition 7
Material Control Parameters(Material 7)
Material Definition (Interface) - D-2
Interface Angle, Friction and Tensile Breaking Force
Angle from x-axis to normal interface -90 degrees
Coefficient of friction between nodes I and J .5
Tensile breaking force of contact nodes 1 lb/in
Gap distance in normal direction 0 in
Accept Input
Cancel
Saving input file
Resetting menus


X
-Y
INTERFACE ELEMENT
tangent to interface
normal to interface

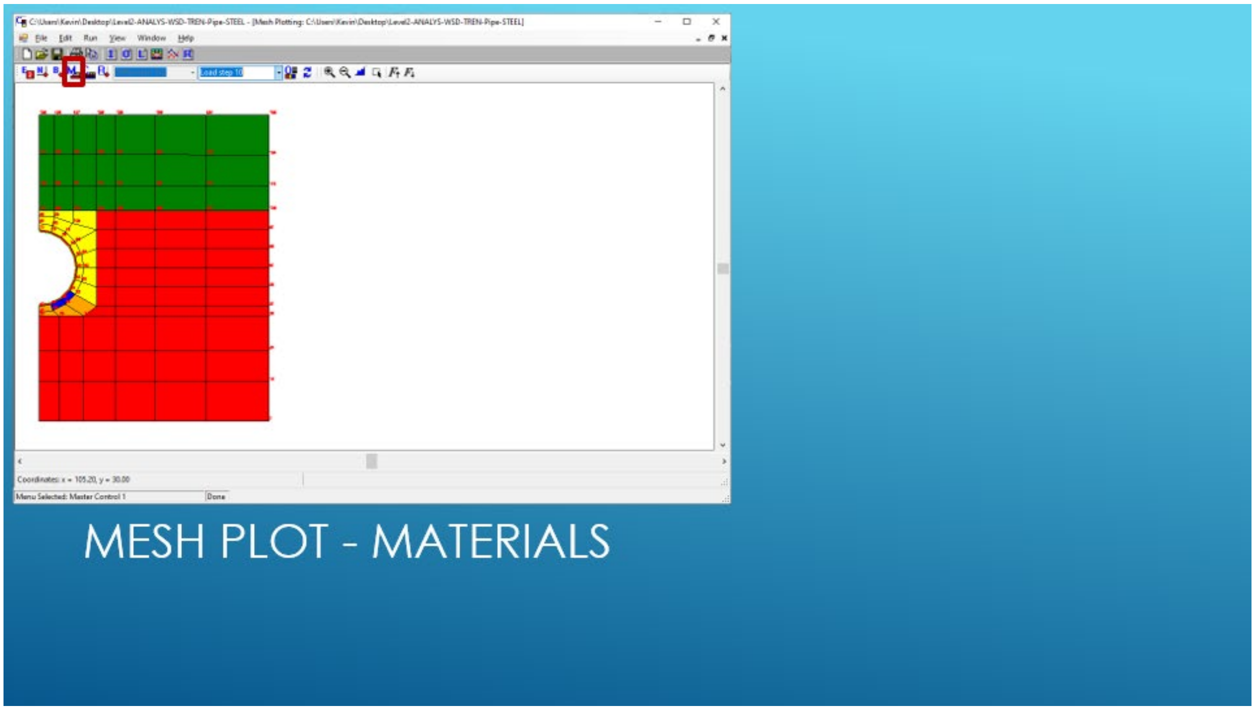

C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL - [Input Commands: C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL.cid]
File Edit Run View Window Help
Show Help
Show input
Master Control - A
Master Control 1
Master Control 2
Pipe Definition - B
Pipe Definition 1
Steel Material and Control Parameters
Steel Section Properties
Solution Level Statements - C
Control Parameters (Level 2-Pipe)
Major Geometry and Loading Parameters (Level 2-Pipe)
Control Variables (Level 2-Pipe)
Backpacking for Embankment Mesh/Trench Dimensions for Trench Mesh (Level 2-Pipe)
Control Parameters for Changes to Nodes, Elements and Boundary Conditions
Nodal Point Changes
Elements Changes
Material Definition Statements - D
Material Definition 1 (in situ)
Material Control Parameters(Material 1)
Material Definition 2 (bedding)
Material Control Parameters(Material 2)
Material Definition 3 (backfill)
Material Control Parameters(Material 3)
Material Definition 4 (overfill)
Material Control Parameters(Material 4)
Material Definition 5 (interface 1)
Material Control Parameters(Material 5)
Interface Angles
Material Definition 6 (interface 2)
Material Control Parameters(Material 6)
Interface Angles
Material Definition 7
Material Control Parameters(Material 7)
Material Definition (Interface) - D-2
Interface Angle, Friction and Tensile Breaking Force
Angle from x-axis to normal interface -90 degrees
Coefficient of friction between nodes I and J .5
Tensile breaking force of contact nodes 1 lb/in
Gap distance in normal direction 0 in
Accept Input
Cancel
Saving input file
Resetting menus

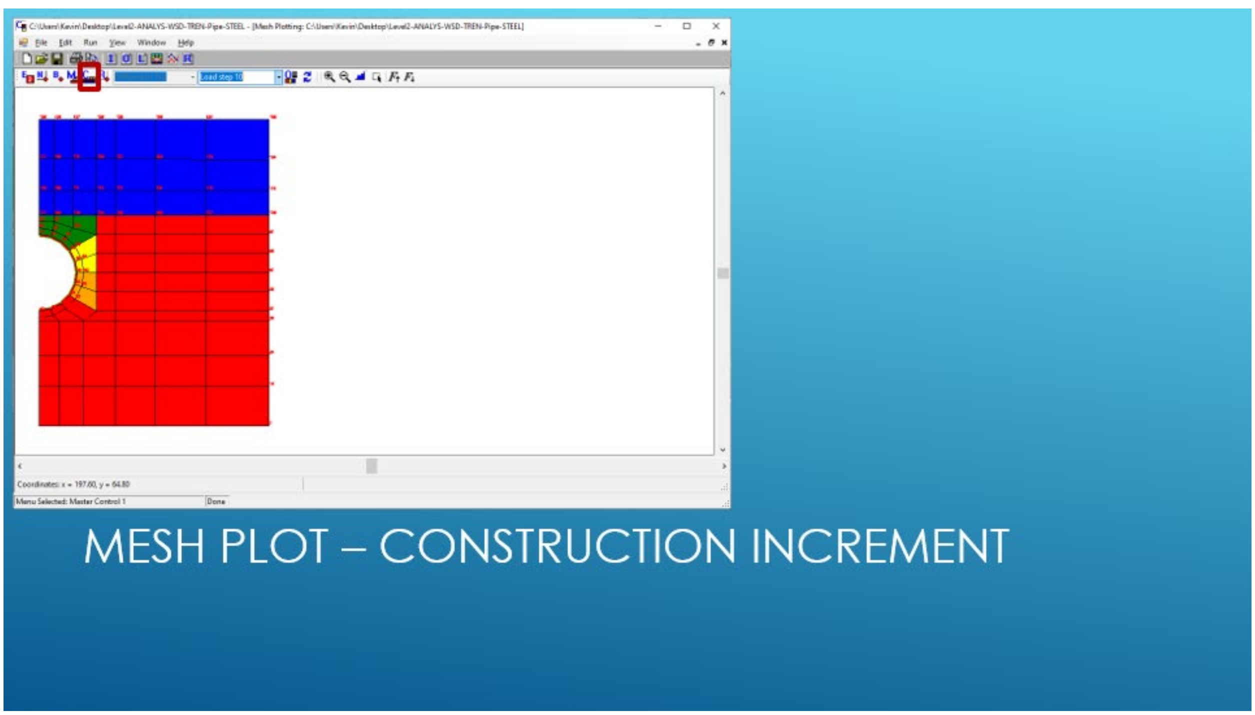

Running CANDE C:\Users\Kevin\Desktop\Level2-ANALYS-WSD-TREN-Pipe-STEEL
Stop
Pause
Clear
Close
5 0 5
6 -1 1
6 -1 2
6 -1 3
6 -1 4
6 0 5
7 -1 1
7 -1 2
7 -1 3
7 -1 4
7 0 5
8 -1 1
8 -1 2
8 -1 3
8 0 4
9 -1 1
9 -1 2
9 -1 3
9 0 4
10 -1 1
10 -1 2
10 -1 3
10 1 4
* * * * NORMAL EXIT FROM CANDE * * * *
Analysis complete
CANDE Analysis complete.
Close the Analysis window to return to the CANDE interface.
OK

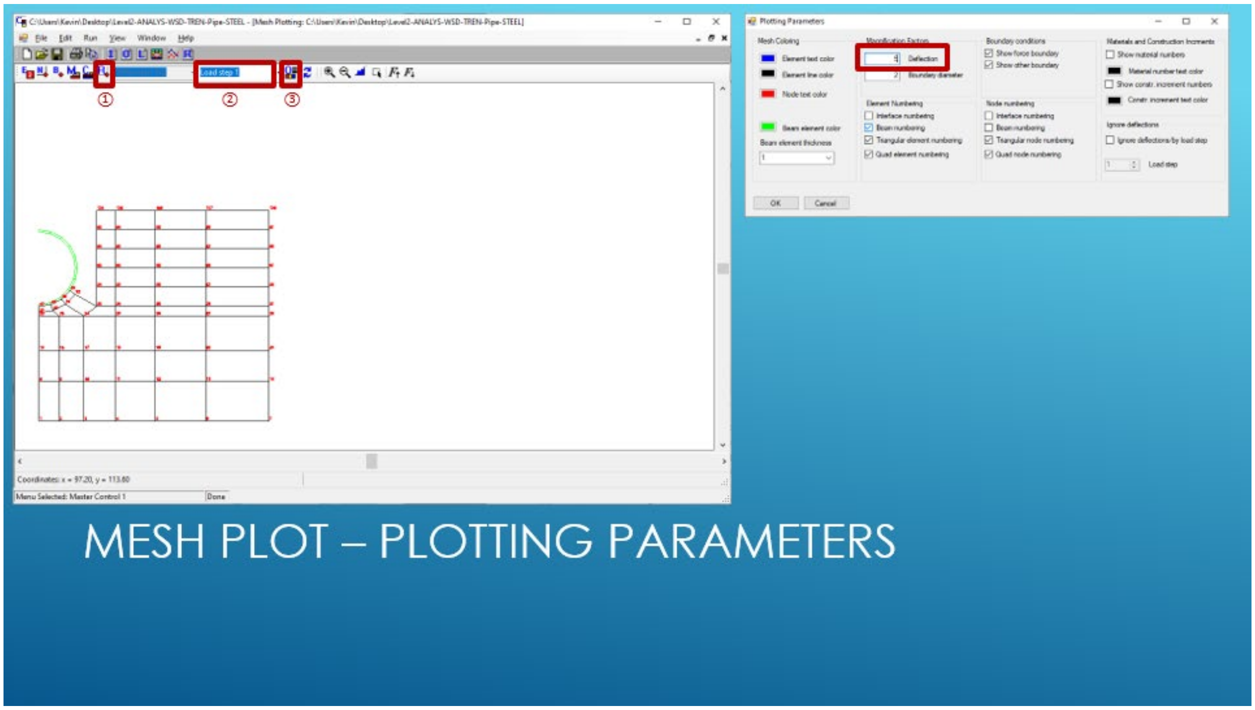
POST PROCESSING - RESULTS

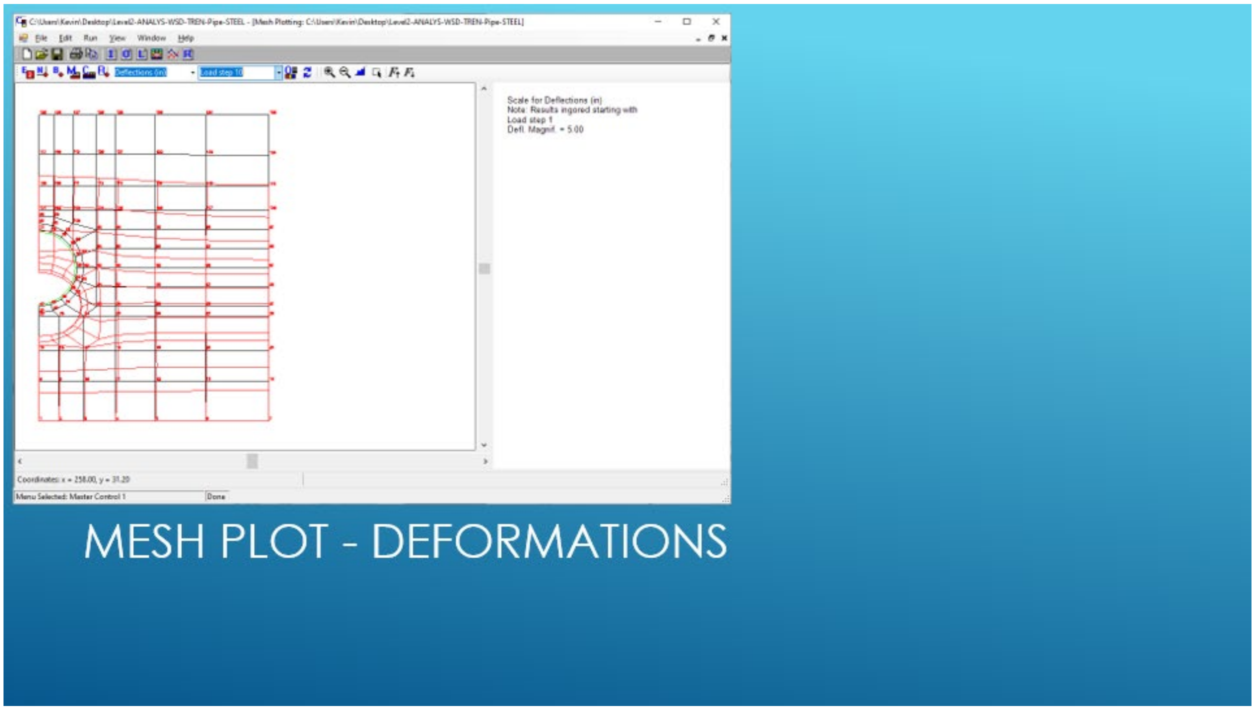


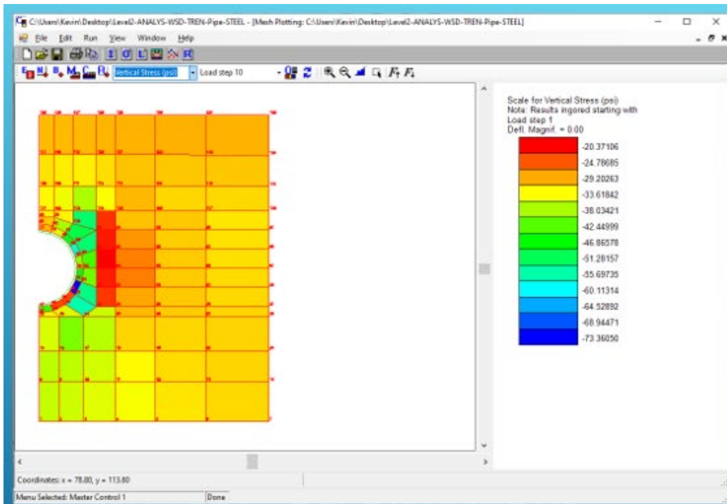
VIEW MESH PLOT


MESH PLOT - MATERIALS

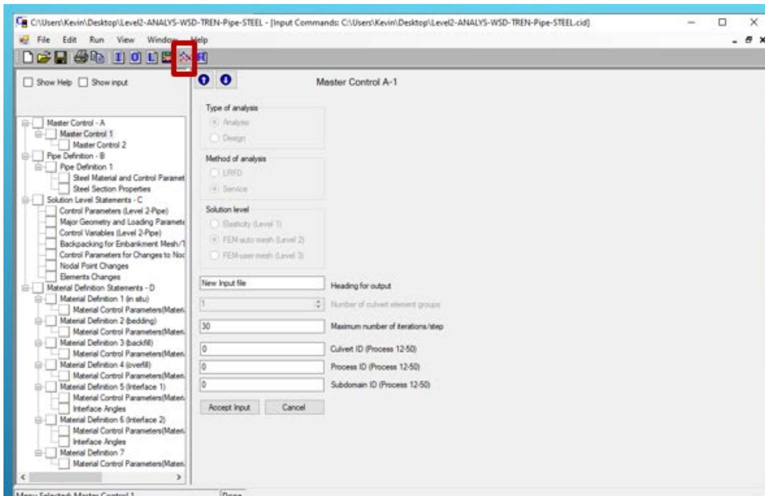

MESH PLOT – CONSTRUCTION INCREMENT


MESH PLOT – PLOTTING PARAMETERS

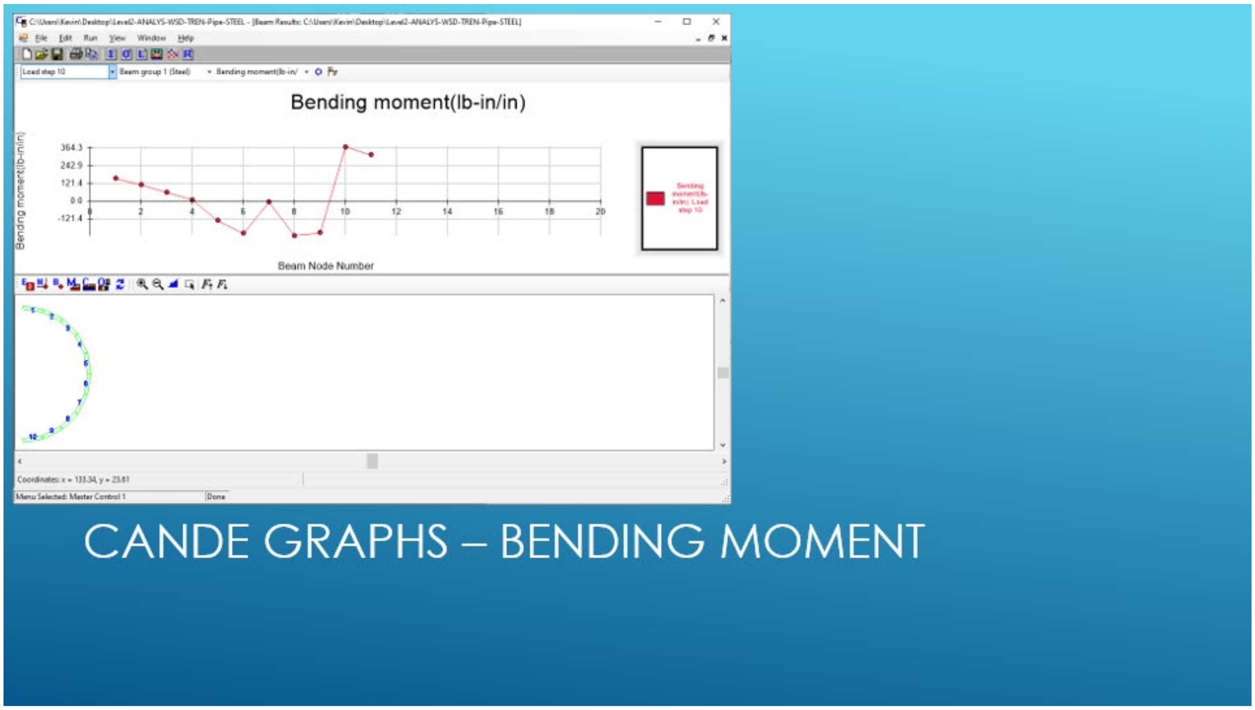

MESH PLOT - DEFORMATIONS

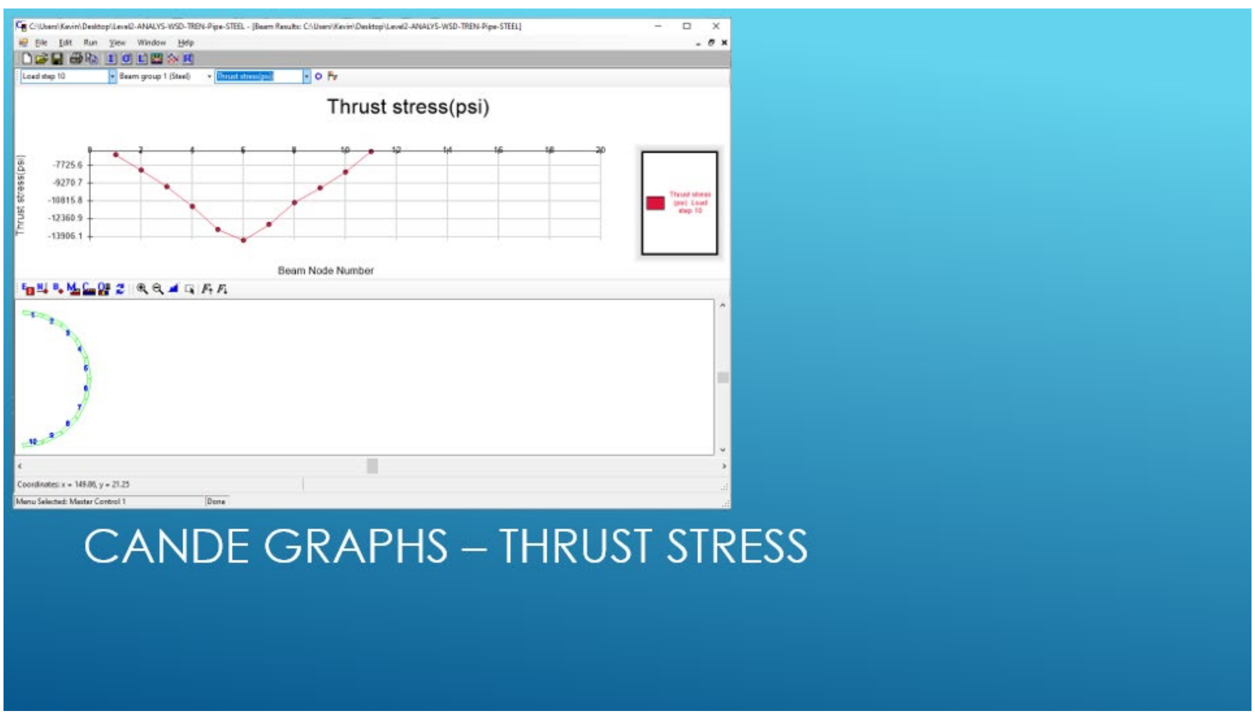


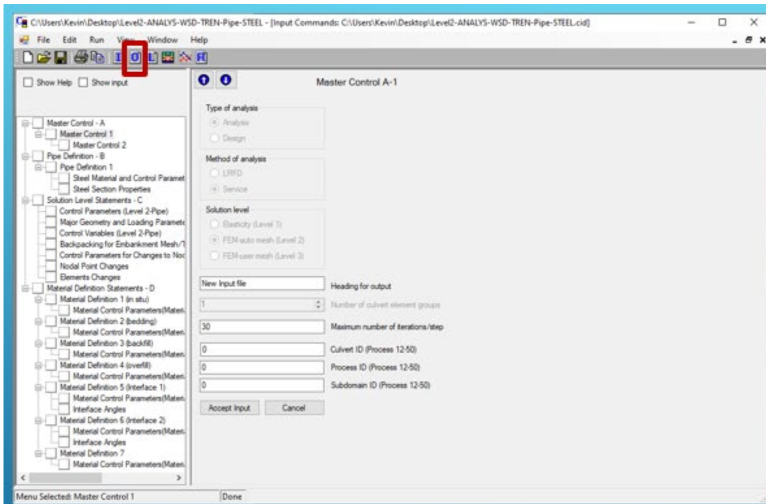
MESH PLOT – VERTICAL STRESS



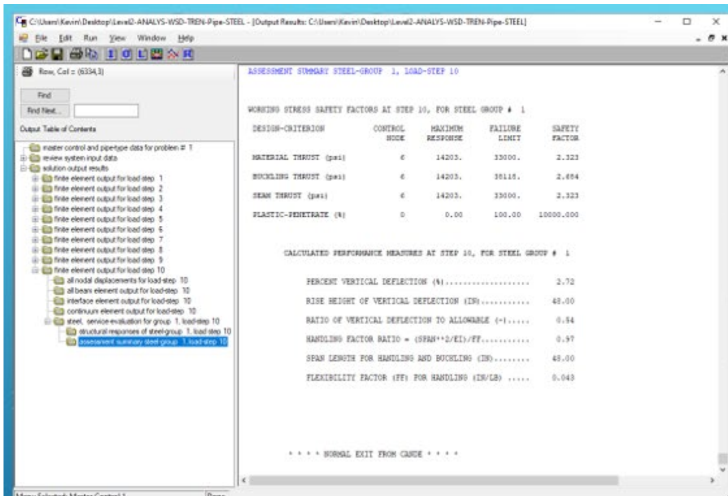
VIEW CANDE GRAPHS


Bending moment(lb-in/in)
Bending moment(lb-in/in)
364.3
242.9
121.4
0.0
-121.4
0 2 4 6 8 10 12 14 16 18 20
Beam Node Number
Load step 10
Beam group 1 (Steel)
CANDE GRAPHS – BENDING MOMENT


Thrust stress(psi)
Thrust stress(psi)
-7725.6
-9270.7
-10815.8
-12360.9
-13906.1
0 2 4 6 8 10 12 14 16 18 20
Beam Node Number
Load step 10
Beam group 1 (Steel)
CANDE GRAPHS – THRUST STRESS



VIEW CANDE OUTPUT



CANDE OUTPUT