CAU2013

CAESAR II

Concepts in Buried Pipe Modeling

Buried Pipe Analysis – What are we looking for?

- Our focus is on pipe strain
  - Thermal strain rate may be small but pipe is long
  - Deadweight is not an issue in properly-prepared trenches

Buried Pipe Analysis – What are we looking for?

- Generally, pipe safety is assured by construction rules rather than analysis
  - Trench preparation – carry dead weight
  - 5-D bends and/or vaults – limit moments & stress
  - Thrust blocks – limit growth out of ground

Buried Pipe Analysis – What are we looking for?

- Generally, pipe safety is assured by construction rules rather than analysis
  - When properly installed, pipeline failure is usually caused by non-operational forces – e.g. a backhoe hitting the line

Buried Pipe Analysis – What are we looking for?

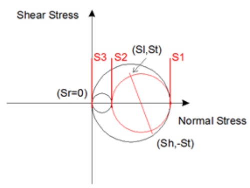
- CAESAR II analysis can evaluate strain-induced bending stress at bends and tees
- CAESAR II analysis can estimate pipe growth at soil entry and exit points

Piping Code Approach

- Again, it's construction, not analysis
  - The piping codes do not establish analysis rules for modeling the soil/pipe interaction
- Compression's role
  - Pipe stresses are typically based on maximum shearing stress with a focus on <u>tension</u>

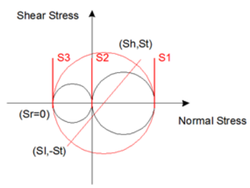
Piping Code Approach

- Compression's role



- With both hoop and longitudinal stress positive, the maximum shearing stress can be established without referencing the hoop term:

$$S_E = \sqrt{{S_b}^2 + (2S_t)^2}$$



- But with longitudinal stress compressive, the diameter of this Mohr's Circle and the maximum shear stress can no longer be estimated independent of the hoop stress.

Piping Code Approach

- The US Transportation Codes (B31.4, B31.8) provide different stress calculations for "Restrained" and "Unrestrained" pipe
  - Stress calculations for unrestrained pipe are similar to the typical B31 stress formula
  - B31.4 has a different maximum shear stress theory equation for restrained pipe:

$$S_{eq} = 2\sqrt{[(S_L - S_H)/2]^2 + {S_t}^2}$$

- B31.1 Appendix VII also has a non-mandatory appendix addressing buried piping

Piping Code Approach

- A note on B31.1 Nonmandatory Appendix VII
  - Title: Procedures for the Design of Restrained Underground Pipe
  - The closed form solution provided in the appendix does not suit an automated, system-wide evaluation
  - See Robert Robleto's PVP paper titled Modeling Underground Pipe with Pipe Stress Analysis Program (PVP2002-1271) for a comparison with CAESAR II
    - Conclusion – "By adjusting the friction factor and lateral spring rates to match those derived in B31.1, an accurate underground model can be simulated by [CAESAR II]."

Soil Restraint on Piping

- Bearing – pipe pushing soil
  - Lateral
  - Vertical
    - Different Up & Down
- Friction – pipe slipping in soil
  - Axial
  - F=mu*N

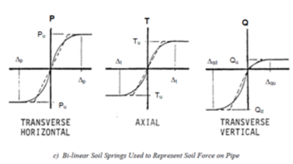


Figure B.1 Pipeline Modeling Approach from ALA's Guidelines for the Design of Buried Steel Pipe

- Soil response is nonlinear
  - Elastic deflection limit
  - Ultimate load (in load per unit length)

CAESAR II Issues – Point Restraints

- Soil load/restraint is continuous
  - Soil acts like a continuous restraint (foundation)
  - CAESAR II has point restraints

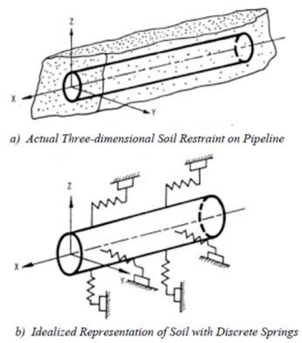


Figure B.1 Pipeline Modeling Approach from ALA's Guidelines for the Design of Buried Steel Pipe

CAESAR II Issues – Point Restraints

- What happens with pipe weight if soil is modeled as individual point supports?
  - If soil below pipe is represented by a group of point restraints, then
    - The pipe weight will deflect the soil down
    - The pipe weight will develop bending moments (and stress) around these point supports
  - Assume that the trench bottom will carry pipe weight
    - Dead weight deflection (downward) is eliminated
    - Dead weight bending is removed

CAESAR II Issues – Point Restraints

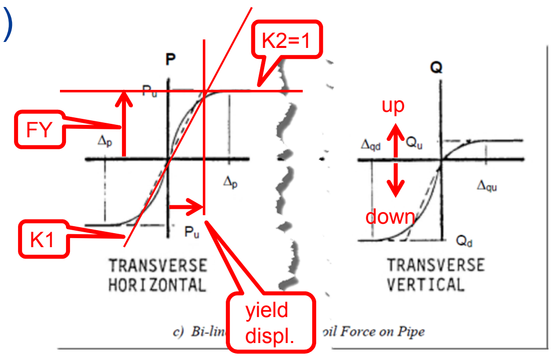
- What happens with pipe weight if soil is modeled as individual point supports?
  - CAESAR II will eliminate all pipe weight on all pipe that "it buries"
  - Again, our focus in analysis is the evaluation of pipe strain in the vicinity of bearing
  - Not addressed by this approach (by CAESAR II):
    - Subsidence
    - Traffic load

CAESAR II Issues – Bearing

- Ultimate load is based on area
  - Area is a function of pipe diameter times pipe length
  - Consider it like pressure – as distance between point restraints increases, so does the magnitude of ultimate soil load for that segment of pipe

CAESAR II Issues – Bearing

- Create bilinear restraints (per unit length) based on ultimate load (FY) and elastic deflection (yield displ.)



from ALA

CAESAR II Issues – Bearing

- Modeling bearing restraint
  - Several nearby (point) restraints are required to knock out bending and eliminate pivoting

CAESAR II Issues – Bearing

- Modeling bearing restraint
  - The magnitude for each soil restraint (stiffness and soil ultimate load) is based on the length of pipe between these soil springs

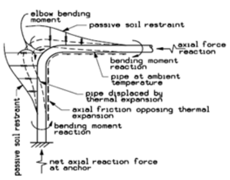
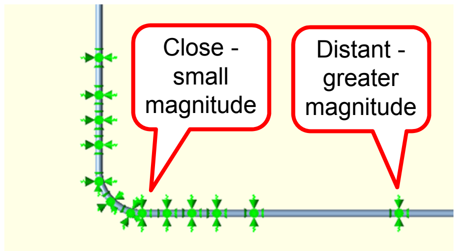


Figure 7.1-1 Bending Moment at Buried Pipe Bend Due to Constrained Pipe Expansion



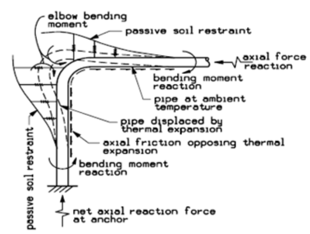
ALA Figure 7.1-1

CAESAR II Issues – Friction

- This is axial
- It is a force which accumulates along the pipe – once again, a force per unit length
- With no normal load (no weight) in the buried segments, regular friction cannot function
- Instead, create bilinear restraints (per unit length) based on ultimate friction load and elastic deflection

CAESAR II Issues – Friction

- Bending is not a straight run issue in modeling friction
  - Friction on one side of a bend will affect bearing response on the other side of the bend
  - Unlike a bearing model, many, close restraints are not required
  - Without buckling, a single (but very large) force can prevent axial motion



ALA Figure 7.1-1

CAESAR II Issues – Model Termination

- Models of above ground systems typically terminate at well-defined boundaries
  - Field anchor
  - Imposed motion (e.g. pump nozzle or vessel connection)
- The “end” of a buried pipe model is not as definite as a field anchor

CAESAR II Issues – Model Termination

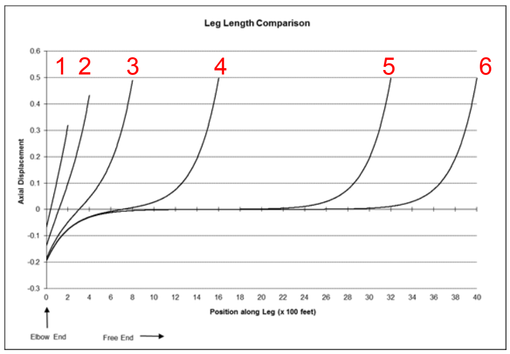
- But with sufficient buried straight pipe, the soil friction can isolate an upstream segment from the downstream segment
  - The pipe has a fixed amount of axial load due to thermal strain and pressure
  - There is no other load!
  - The longer the buried straight run, the more friction accumulates.
  - If sufficient straight run friction exists, the upstream and downstream segments will be isolated and these two segments can be analyzed independently.

CAESAR II Issues – Model Termination

- Examples of this separation:
  - For a given temperature, plot the axial growth for a variety of buried pipe lengths
  - For a given buried pipe length, plot the axial growth for a variety of pipe temperatures

CAESAR II Issues – Model Termination

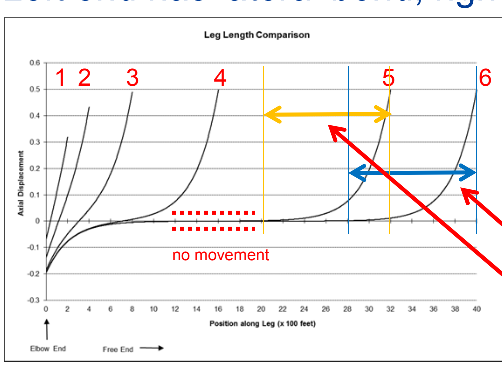
- For a given temperature, plot the axial growth for a variety of buried pipe lengths
- Left end has lateral bend, right end free



Length of free end:
1) 200 feet
2) 400 feet
3) 800 feet
4) 1600 feet
5) 3200 feet
6) 4000 feet

CAESAR II Issues – Model Termination

- For a given temperature, plot the axial growth for a variety of buried pipe lengths
- Left end has lateral bend, right end free



Length of free end:
1) 200 feet
2) 400 feet
3) 800 feet
4) 1600 feet
5) 3200 feet
6) 4000 feet

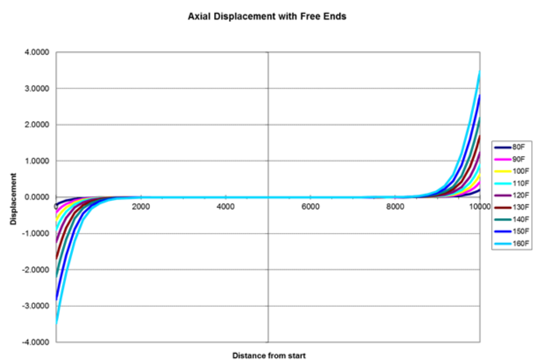
continuous

separation

Both 5 & 6 require the same length of pipe to accumulate enough friction to balance the thrust load.

CAESAR II Issues – Model Termination

- For a given buried pipe length, plot the axial growth for a variety of temperatures
  - Vary temperature for a 1000 foot run (ends free)



CAESAR II Issues – Model Termination

- For a given buried pipe length, plot the axial growth for a variety of temperatures
  - Right end detail:

As temperature increases, so does the amount of friction required to balance thermal load – so too, the length of moving pipe increases.

CAESAR II Issues – Model Termination

- This "sufficient buried pipe length" whose friction will balance the pipe thrust can be called a Virtual Anchor Length (VAL)
- When the distance between two adjacent bearing points (e.g. bends or tees) exceeds the VAL, these two bearing points cannot interact and they need not be in the same model

CAESAR II Issues – Model Termination

- Do not define an anchor at the end of this length of pipe in your CAESAR II model!
  - The soil model, itself, will provide the isolation
  - In fact, if the (isolated) upstream and downstream segments are modeled separately, this straight run between the two bearing points can appear in both models

CAESAR II Issues – Model Termination

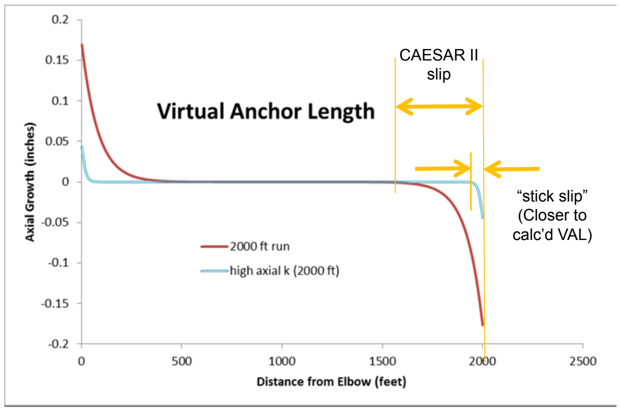
- How long is this isolating length, this VAL?
  - What are the thrust loads?
    - Thermal load $= A_{xs}E\alpha$
    - Pressure end thrust= PA_{in}
    - Poisson effect (shortening due to hoop load)= $-\nu(2PA_{in})$
  - What is the restraining load?
    - $= Length * (Pipe\&Soil\ Friction\ Load/Unit\ Length)$
  - What length of buried pipe is required to balance the thrust?
    - $A_{xs}E\alpha + PA_{in} - \nu(2PA_{in}) = Length * (Fric/Len)$
    - $Length = VAL = \frac{A_{xs}E\alpha+(1-2\nu)PA_{in}}{(Fric/Len)}$

CAESAR II Issues – Model Termination

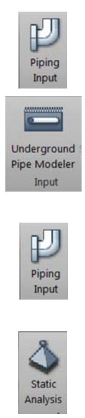
- CAESAR II calculates this VAL.
- But the CAESAR II model for friction does not have rigid stiffness for K1 (in the K1, K2, Fy model provided by the bilinear axial restraint)
- K1 is based on ultimate axial load and a given elastic displacement limit – it is not rigid
- Therefore – I recommend you double this calculated VAL

CAESAR II Issues – Model Termination

- I recommend you double this calculated VAL



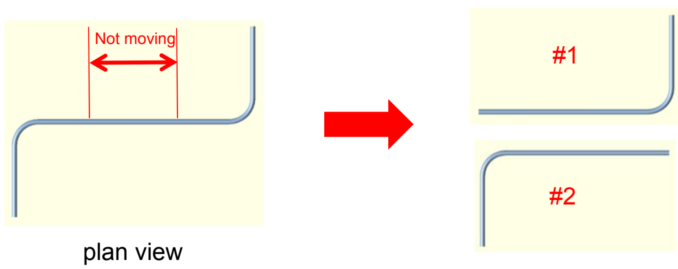
The CAESAR II Process



1) Build the model ignoring soil
2) Define soil properties
3) Build the soil restraints into the piping model
4) Add any additional underground restraints (e.g. thrust block)
5) Review and analyze the buried model

The CAESAR II Process

1) Build the model ignoring soil
   - Models can be separated into independent analyses when runs between bearing points is greater than the VAL. The straight run that doesn't move should be included in both models.



plan view

The CAESAR II Process

2) Define soil properties
   - Unique soil models are based on soil mechanics and buried depth of pipe.
     - Up, down, lateral & axial
     - As soil characteristics change along the line, so can the soil models
     - Model accuracy is dependent on local soil characteristics (provided by civil engineering group) and number of sample sites (Is this art? Is this science?)

The CAESAR II Process

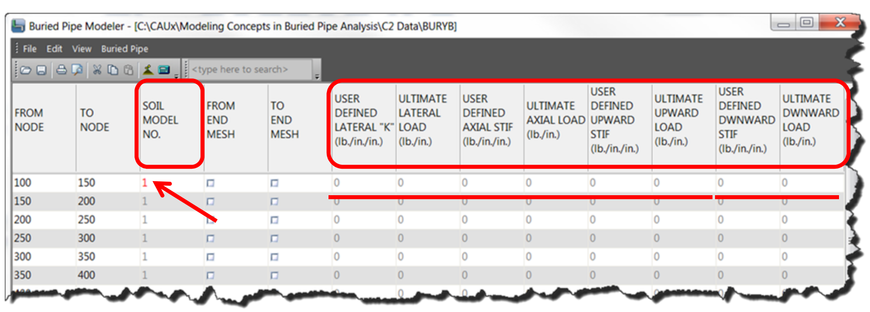
2) Define soil properties

- ☐ Two methods of defining soil response in CAESAR II
  1. User-defined data (identified as Soil Model #1).
     - o Bilinear stiffness (K1, K2) and ultimate load (Fy) are explicitly entered by the user
       - Ultimate soil bearing load or maximum friction load (Fy) can be used with a maximum elastic displacement to set K1. K2 (essentially plastic) response is set as 1.
       - Like other CAESAR II data, these values remain the same through the list until changed – they "carry-forward"
       - Values are entered "per length of pipe"

The CAESAR II Process

2) Define soil properties

- ☐ Two methods of defining soil response in CAESAR II
  1. User-defined data (identified as Soil Model #1).



FROM NODE	TO NODE	SOIL MODEL NO.	FROM END MESH	TO END MESH	USER DEFINED LATERAL "K" (lb./in./in.)	ULTIMATE LATERAL LOAD (lb./in.)	USER DEFINED AXIAL STIF (lb./in./in.)	ULTIMATE AXIAL LOAD (lb./in.)	USER DEFINED UPWARD STIF (lb./in./in.)	ULTIMATE UPWARD LOAD (lb./in.)	USER DEFINED DWNWARD STIF (lb./in./in.)	ULTIMATE DWNWARD LOAD (lb./in.)
100	150	1	☐	☐	0	0	0	0	0	0	0	0
150	200	1	☐	☐	0	0	0	0	0	0	0	0
200	250	1	☐	☐	0	0	0	0	0	0	0	0
250	300	1	☐	☐	0	0	0	0	0	0	0	0
300	350	1	☐	☐	0	0	0	0	0	0	0	0
350	400	1	☐	☐	0	0	0	0	0	0	0	0

The CAESAR II Process

2) Define soil properties

- Two methods of defining soil response in CAESAR II
  2. Data derived by CAESAR II (Soil Model Type)
     - User supplies general soil properties
     - CAESAR II estimates bilinear restraint values using:
       - CAESAR II Basic Model
       - American Lifelines Alliance
     - These models are identified as Soil Models 2, 3, 4…

The CAESAR II Process

2) Define soil properties

- CAESAR II Basic Model

- This approach is defined in an article published in the May 1978 issue of Pipe Line Industry magazine by Liang-Chaun Peng entitled: Part 2 – Soil-pipe interaction / Stress analysis methods for underground pipe lines. http://www.pipestress.com/papers/UnderGrd-2.pdf
- CAESAR II provides some additional control of the calculated values
  - Overburden Compaction Multiplier (a bearing adjustment)
  - Yield Displacement Factor (adjust limit on elastic response)

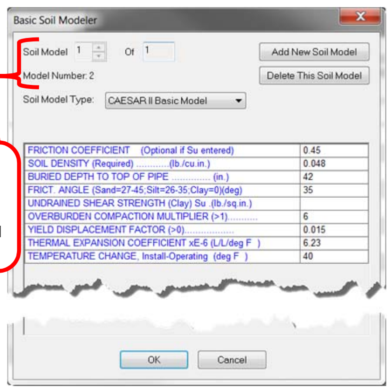
INTERGRAPH

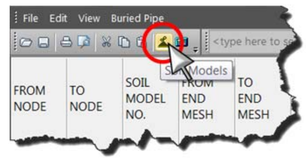
The CAESAR II Process

Underground Pipe Modeler Input

2) Define soil properties

- CAESAR II Basic Model





- For granular soils (sand)
  - Specify friction coefficient
  - Specify friction angle
- For cohesive soils (clay)
  - No friction coefficient required
  - Friction angle = 0
  - Specify Undrained Shear Strength
- Last two values here are used to calculate VAL

INTERGRAPH

The CAESAR II Process

Underground Pipe Modeler Input

2) Define soil properties

- American Lifelines Alliance

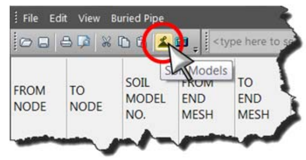
- This approach is defined in a publication by the American Lifelines Alliance: Guidelines for the Design of Buried Steel Pipe. http://www.americanlifelinesalliance.com/pdf/Update061305.pdf
- Appendix B: Soil Spring Representation provides the method to set the bilinear spring models in CAESAR II
  - While the guideline provides blended values for a sandy-clay soil, CAESAR II accepts either sand or clay
  - The text provides estimates for elastic deflection limits
  - Up and down soil responses are unique

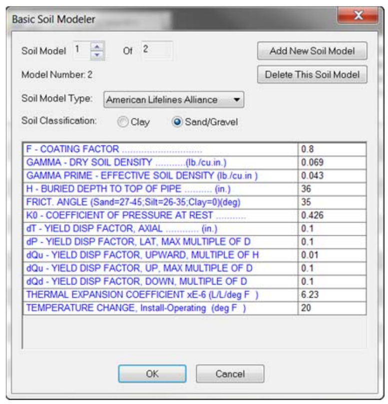
INTERGRAPH

The CAESAR II Process

2) Define soil properties

- American Lifelines Alliance



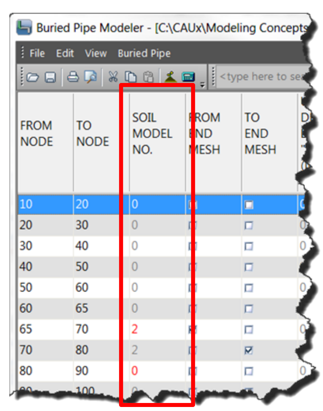


- Separate data sets for granular soils (sand/gravel) and clay (cohesive soils)
- Last two values here are used to calculate VAL

The CAESAR II Process

3) Build the soil restraints into the piping model

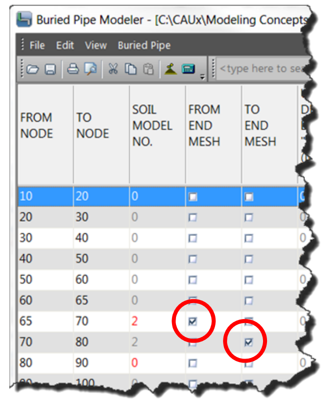
- Define which pipe elements are buried by entering a Soil Model Number
  - Here:
    - 10-65 is above ground
    - 65-80 is buried using Soil Model #2
    - 80-90 is not buried



The CAESAR II Process

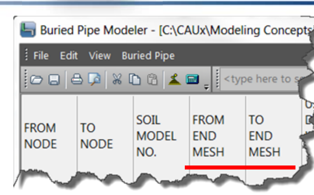
3) Build the soil restraints into the piping model

- □ Identify locations where bearing is a concern
  - Use From End Mesh & To End Mesh
  - Here, the entry point and exit point (nodes 65 and 80) require close spacing of soil restraints to provide a proper soil model to handle pipe lateral movement



The CAESAR II Process

3) Build the soil restraints into the piping model

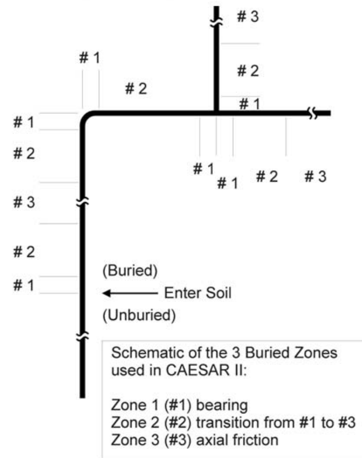


- □ A note on From End / To End Mesh
  - Closely-spaced soil restraints (i.e. fine mesh) are necessary to model the effects of bearing
  - These locations occur whenever strain pushes the pipe off it's axis
  - CAESAR II will automatically identify bends as fine mesh points
  - You are responsible for identifying other such bearing-sensitive locations – tees and entry/exit points

The CAESAR II Process

3) Build the soil restraints into the piping model

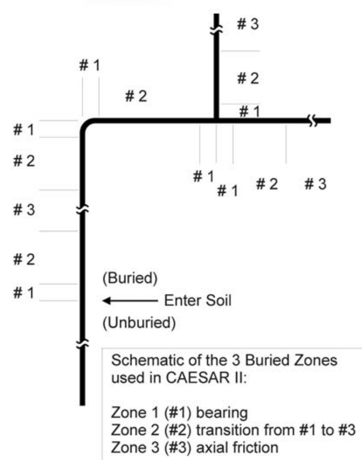
- CAESAR II Soil Zones
  - Zone 1:
    - Controlled by bearing
    - Declared using From/To End Mesh (automatic for bends)
    - Overall length set by Lateral Bearing Length (Lb)
    - $Lb = 0.75\pi\sqrt[4]{4EI/K_{tr}}$
    - 4 restraints in this Zone



The CAESAR II Process

3) Build the soil restraints into the piping model

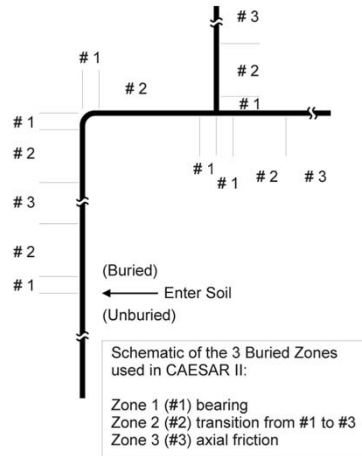
- CAESAR II Soil Zones
  - Zone 3:
    - Controlled by friction
    - Distance between Zone 3 soil restraints is 100*OD



The CAESAR II Process

Underground Pipe Modeler Input

3) Build the soil restraints into the piping model
- □ CAESAR II Soil Zones
  - ● Zone 2:
    - ○ Transition between Zones 1 & 3
    - ○ 4 elements, proportionally increasing in length from half of Lb to half of Zone 3 length

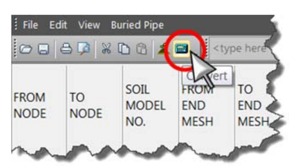


INTERGRAPH

The CAESAR II Process

Underground Pipe Modeler Input

3) Build the soil restraints into the piping model
- □ Push the button
- □ CAESAR II will display the stiffness and load terms calculated from the soil data and list the added nodes/restraints to “bury” the piping.



INTERGRAPH

The CAESAR II Process

Underground Pipe Modeler Input

3) Build the soil restraints into the piping model

- ☐ Result of this step is a new model

Restraints

	From Node	To Node	Restraint Node	Type	Stiffness lb./in.	Gap or Length in.	Mu or Fi (lb.)	Cnode
1	10	20	10	ANC				
2	10	20						
3	10	20						
4	10	20						
5	30	40	40	+Y			0.3000	
6	30	40						
7	30	40						
8	30	40						
9	65	66	65	X2 (-.92384, -.38276, 0)	59549.9063	1.0000	5954.9907	
10	65	66	65	Z2	16564.1113	1.0000	47704.6406	
11								
12								
13								
14								
15								
16								
17								
18								
19								
20	67	70	67	+X2 (-.19513, .980776, 0	28174.6582	1.0000	101428.7969	
21	70	71	70	X2	81865.5156	1.0000	8186.5518	
22	70	71	70	Z2	22771.3105	1.0000	65581.3750	
23	70	71	70	-Y2	15188.0117	1.0000	8201.5244	
24	70	71	70	+Y2	109225.9219	1.0000	393213.3125	
25	71	72	71	X2	135033.9063	1.0000	13503.3896	
26	71	72	71	Z2	37560.3711	1.0000	108173.8984	
[illegible]	71	72	71	Y2	[illegible]	1.0000	[illegible]	

Existing restraints

Added soil restraints

Node	Direction	K1	K2	Fy	
70	X2	81865.5156	1.0000	8186.5518	Axial
70	Z2	22771.3105	1.0000	65581.3750	Lateral
70	-Y2	15188.0117	1.0000	8201.5244	Down
70	+Y2	109225.9219	1.0000	393213.3125	Up

The CAESAR II Process

Underground Pipe Modeler Input

3) Build the soil restraints into the piping model

- ☐ Result of this step is a new model
  - JOBNAME.C2 becomes JOBNAMEB.C2
  - The data from the Buried Modeler Input is saved as JOBNAME.SOI and included in the JOBNAME.C2 data set

The CAESAR II Process

Piping Input

4) Add any additional underground restraints (e.g. a thrust block)

- CAESAR II removed them if they were entered before the model was "buried"

The CAESAR II Process

Piping Input Static Analysis

5) Review and analyze the buried model

- Note: all densities removed from buried sections

Elements

	From Node	To Node	Pipe Density lb./cu.in.	Fluid Density lb./cu.in.	Insulation Density lb./cu.in.	Cladding Density lb./cu.in.	Insul/Clad Unit Weight lb./in.	Refractory Density lb./cu.in.
1	10	20	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
2	20	30	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
3	30	40	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
4	40	50	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
5	50	60	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
6	60	65	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
7	65	66	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
8	66	67	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
9	67	70	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
10	70	71	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
11	71	72	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
12	72	79	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
13	79	80	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
14	80	90	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
15	90	100	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
16	100	110	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
17	110	120	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
18	120	130	0.28300	0.00000	0.00000	0.0000	0.0000	0.0000
19	130	131	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
20	131	132	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
21	132	133	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
22	133	134	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
23	134	135	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
24	135	136	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
25	136	137	0.00000	0.00000	0.00000	0.0000	0.0000	0.0000
26	137	138	0.00000	0.00000	0.00000	0.0000	0.0000	[illegible]

Here,

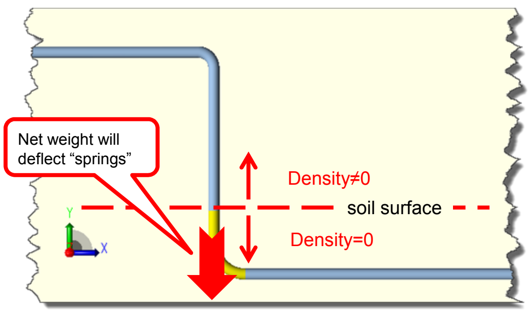
- 10-65 is not buried
- 65-80 is buried
- 80-130 is not buried
- 130 on is buried

The CAESAR II Process

Piping Input Static Analysis

5) Review and analyze the buried model

- Note: all densities removed from buried sections
- Watch out for vertical runs in soil (changing soil models) or vertical runs in or out of soil (weight)

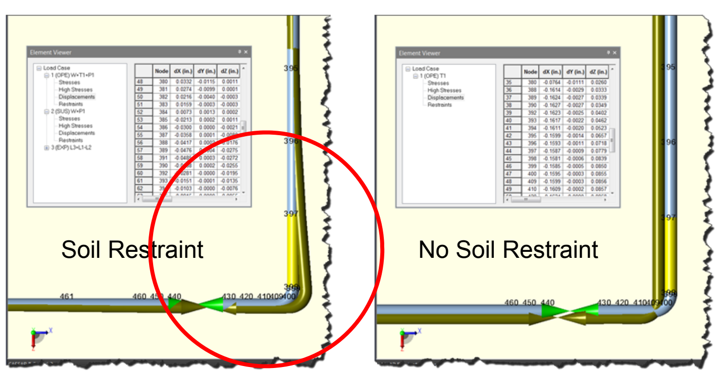


The CAESAR II Process

Piping Input Static Analysis

5) Review and analyze the buried model

- Check pipe deflection



The CAESAR II Process

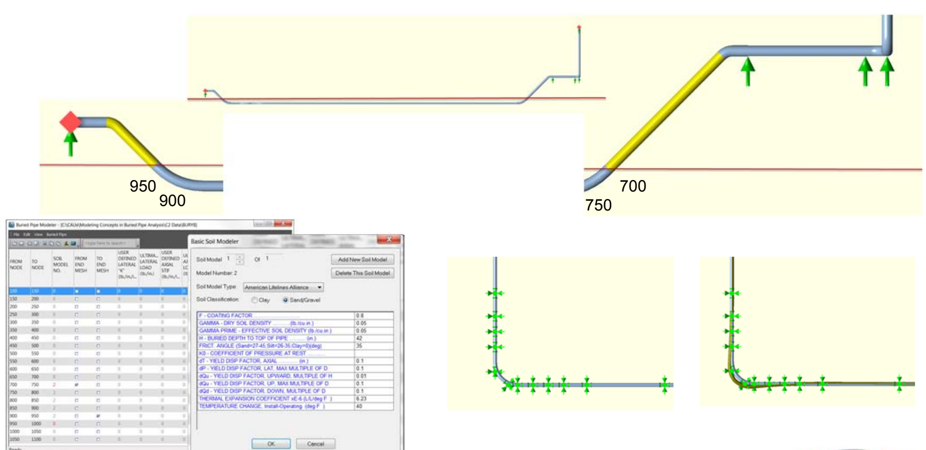
5) Review and analyze the buried model
- Check virtual anchor lengths; here:
  - 400 – 481 is a 980 foot straight run in X
  - Positive X growth: 400-473
  - Negative X growth: 474+
  - 471 & 476 move about .01”
  - 471-476 is 360 feet of pipe!

```
CAESAR II 2013 R1  Ver.6.10
Job Name: RENUMBER 470
Licensed To: ICAS TRAINING
DISPLACEMENTS REPORT: Noda
CASE 3 (EXP) L3=L1-L2
```

Node	DX in.
398	0.1715
399	0.1830
400	0.1848
409	0.1844
410	0.1834
420	0.1820
430	0.1806
440	0.1761
450	0.1747
460	0.1734
461	0.1679
462	0.1624
463	0.1571
464	0.1494
465	0.1307
466	0.1045
467	0.0764
468	0.0417
469	0.0226
471	0.0119
472	0.0057
473	0.0017
474	-0.0018
475	-0.0059
476	-0.0122
477	-0.0230
478	-0.0425
479	-0.0778
480	-0.1259
481	-0.1614

An example

- The User Guide layout with ALA sand



Concepts in Buried Pipe Modeling

- Questions? Comments?

CAU2013

Concepts in Buried Pipe Modeling

Thank You