Understanding Non-Linear Load Sequencing

Typical loadings are Deadweight applied then pressure then system heated up. i.e. Gr -> P1 -> T1. Many pipe stress programs lump all these loadings together. AutoPIPE non-linear analysis applies these loadings in a sequence with Gravity always first as expected.  
Note: There is no load sequencing for a Linear analysis.

- AutoPIPE non-linear engine from Prof. Emeritus (UC Berkeley) for friction, gapped supports and soil
- Realistic loading with load sequencing e.g. Gravity then pressure then Temperature then Seismic
- Apply friction to any loadcase. Building codes like UBC, design with no friction in Seismic load cases

AutoPIPE load sequence
GR -> P1 -> T1 -> E1

Caesar 1 load vector
GR + P1 + T1 + E1

Lets look at Loading Sequencing

© Bentley Systems Inc 4/20/2007 Load_Sequencing5.doc
Example 1
No friction, load sequence = OP1 for occasional loads like Seismic, Wind, User etc
OP1 = hot operating condition GR -> T1, since no pressure analysis. So case E1 is applied in the hot condition after Gravity and temperature are applied.
Create User combination: GrE1 = Gr + E1 [This is to illustrate how this combination is inconsistent with the load sequence]

<table>
<thead>
<tr>
<th>Point/Connect/Load</th>
<th>LOCAL</th>
<th>GLOBAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supp. ID</td>
<td>Type</td>
<td>Combination</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>-----------</td>
</tr>
<tr>
<td>A04</td>
<td>Guide</td>
<td>left</td>
</tr>
<tr>
<td>A04 1</td>
<td>Guide</td>
<td>left</td>
</tr>
<tr>
<td>Stiff</td>
<td>RIGID</td>
<td>left</td>
</tr>
<tr>
<td>T1</td>
<td>down</td>
<td>0.000 X</td>
</tr>
<tr>
<td></td>
<td>left</td>
<td>0.200 Y</td>
</tr>
<tr>
<td></td>
<td>forw</td>
<td>0.737 Z</td>
</tr>
<tr>
<td>E1</td>
<td>down</td>
<td>0.000 X</td>
</tr>
<tr>
<td></td>
<td>rght</td>
<td>0.306 Y</td>
</tr>
<tr>
<td></td>
<td>forw</td>
<td>0.000 Z</td>
</tr>
<tr>
<td>GT1</td>
<td>down</td>
<td>0.000 X</td>
</tr>
<tr>
<td></td>
<td>left</td>
<td>0.200 Y</td>
</tr>
<tr>
<td></td>
<td>forw</td>
<td>0.737 Z</td>
</tr>
</tbody>
</table>
Notice default non-code combination is GT1E1 which is consistent with the load sequence.

Inconsistent User Combination GrE1

2. Thermal Loading (GT1)

T1, Dz = -0.2", gap is closed so load generated = 232 lb

3. Seismic E1 Loading (GT1E1)

E1, Dz = 0.306", Seismic load moves the pipe in the opposite direction. However, gap is not closed on +Z side since did not travel 0.4" (2 x gap = 0.2")

Hence GT1E1 = 0

However notice User combination GrE1 = Gr + E1, GrE1 Load at A04 guide, Fz = 232lb. However this does not make sense because the load sequence was Gr then T1 then E1, so this combination GrE1 does not consider movement due to T1. It thinks the E1 is applied after Gravity case which is not correct. If it was for E1, expect Dz = 0.2” instead of 0.306” and gap closed.

Note: Gr -> P1 -> T1 -> E1 gives the same result as Gr -> T1 -> P1 -> E1
Also refer to Analysis Summary

ANALYSIS SUMMARY

Current model revision number : 6

Static - Date and Time of analysis ............. Apr 16, 2007   9:46 AM
Model Revision Number ....................... 6
Number of load cases ....................... 3
Load cases analyzed ....................... GR  T1  E1
Gaps/Friction/Soil considered .............. Yes
Tolerance - Force, Displacement .......... 1.00 lb   0.0162 in
Friction - Scale Factor, Tolerance ....... 1.00   0.10
Ignore friction for cases E1,E2,E3 ....... Yes
Ignore friction for gravity case ...... No
Hanger design run ......................... No
Cut short included ......................... No
Thermal bowing included .................... No
Include Bourdon rotational effect ..... No
Pipe radius for Bourdon calculation ... Mean
Occasional load analysis type .......... Nonlinear
Non-linear analysis summary file ...... LOADSEQ_1.LOG
Use default load sequence ............... Yes
Base load cases for nonlinear analysis

GR = None
T1 = GR
E1 = T1

Actual load sequence:

GR -> T1 -> E1
Example 2
No friction, load sequence = GR for occasional loads like Seismic, Wind, User etc
GR  = cold operating condition GR -> E1, since no pressure analysis. So case E1 is applied in the cold condition after Gravity so temperature is not considered.

Notice default non-code combination is GE1 which is consistent with the load sequence i.e. no temperature case considered.
Also refer to Analysis Summary

**ANALYSIS SUMMARY**

Current model revision number : 6

Static - Date and Time of analysis ............ Apr 16, 2007 9:14 AM
Model Revision Number ..................... 6
Number of load cases .................... 3
Load cases analyzed .................... GR T1 E1
Gaps/Friction/Soil considered .......... Yes
Tolerance - Force, Displacement .......... 1.00 lb 0.0162 in
Friction - Scale Factor, Tolerance .... 1.00 0.10
Ignore friction for cases E1,E2,E3 .... Yes
Ignore friction for gravity case ...... No
Hanger design run ...................... No
Cut short included ................... No
Thermal bowing included .............. No
Include Bourdon rotational effect .... No
Pipe radius for Bourdon calculation ... Mean
Occasional load analysis type ........ Nonlinear
Non-linear analysis summary file ...... LOADSEQ_1.LOG
Use default load sequence ............ No
Base load cases for nonlinear analysis

**Actual load sequence:**

**GR -> T1**
**GR -> E1**

Notice combined movement =0.2” in +Z direction, i.e. gap distance
### Summary

<table>
<thead>
<tr>
<th>Load Case</th>
<th>SEQ</th>
<th>LOAD</th>
<th>Disp (D2)</th>
<th>Reaction (Fz)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASE1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OP1 as initial state for E1</td>
<td>A</td>
<td>GR</td>
<td>0.000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Earthquake during operation</td>
<td>B</td>
<td>GR+T1</td>
<td>-0.200</td>
<td>-232</td>
<td>Gap closes due to T1</td>
</tr>
<tr>
<td>Actual case GT1E1</td>
<td>C</td>
<td>GR+T1+E1</td>
<td>0.106</td>
<td>0</td>
<td>Pipe moves 0.306 inches due to E1, no contact with gap support</td>
</tr>
<tr>
<td>User Cases E1 and GR+E1</td>
<td>C-B</td>
<td>E1</td>
<td>0.306</td>
<td>232</td>
<td>Displacement due to E1 alone in hot case</td>
</tr>
<tr>
<td>obtained by superposition</td>
<td>A+C-B</td>
<td>GR+E1</td>
<td>0.306</td>
<td>232</td>
<td>Conflicting results, movement (0.306&quot;) &gt; gap(2&quot;), smaller reaction and most likely larger stresses due to large displacement</td>
</tr>
</tbody>
</table>

E1=(GR+T1+E1) (GR+T1) (linear superposition)

SE1 estimated by linear superposition

<table>
<thead>
<tr>
<th>CASE2</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GR as initial state for E1</td>
<td>A</td>
<td>GR</td>
<td>0.000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Earthquake during cold case</td>
<td>B</td>
<td>GR+E1</td>
<td>0.200</td>
<td>450</td>
<td>Gap closes, Large reaction, smaller disp and stress</td>
</tr>
</tbody>
</table>

Actual GE1 case

Bottom line: When support conditions change, superposition leads to inconsistent and less accurate results

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### Recommendations

It is recommended to evaluate the maximum support loads and movements by analyzing both GR and OP1 default sequence. Also remember to include + ve and - ve Seismic and wind loadings for ‘worst-case’ evaluation of occasional loads and stresses.