

The Benefits of Nonlinear Pipe Stress Analysis Methods

A Bentley White Paper

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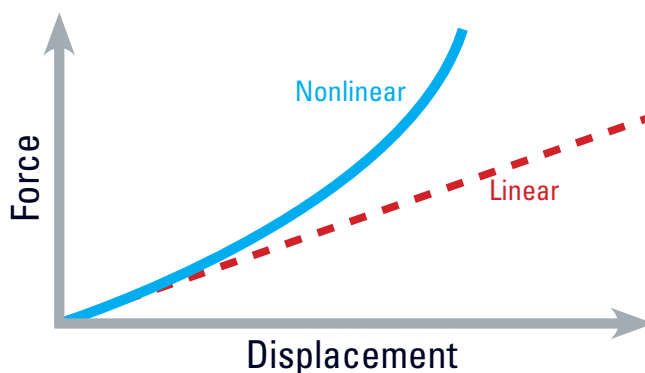


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A linear analysis is characterized by constant pipe properties, small deflections, and elastic deformation when the pipe reverts to its original shape. For example, for every pound of force applied one inch of displacement is created. Initial states are not required for the analysis – all gaps are assumed closed; friction is ignored; linear soil properties are used; and soil yielding is not considered.



Linear vs Nonlinear

A nonlinear analysis is characterized by changes in pipe properties over time, large deflections, and plastic – or permanent – deformations. The analysis is called nonlinear because the amount of force that creates a given amount of displacement is variable. It is important to run a nonlinear analysis because supports that have gaps and friction do not behave in a linear manner. Users gain significant benefits from a nonlinear analysis method. For example, a nonlinear analysis gives project teams the ability to better engineer designs by analyzing more realistic models. State-of-the-art nonlinear analysis engines use tangent stiffness and secant stiffness methods – both of which are found in finite element analysis (FEA) programs such as ANSYS and Abaqus – to handle piping models.

Tangent Stiffness vs. Secant Stiffness Strategies

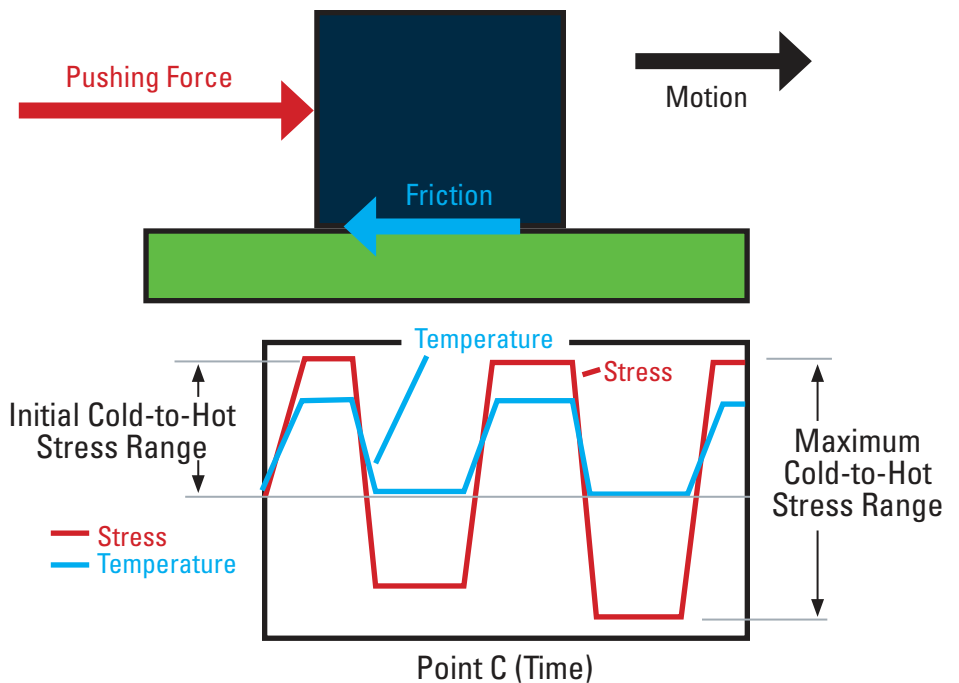
A tangent stiffness strategy, which handles all the supports and their gaps, involves performing a linear analysis for the nonlinear supports. The starting point equation for the analysis is an initial state. If the support gap in that direction doesn't close after the initial load case, the support in that direction is ignored. If the gap does close, the specified stiffness is used for the entire analysis.

A secant stiffness strategy, which handles friction, derives the initial stiffness from the ratio of support forces – i.e., the friction force – to the support deformation – i.e., the amount of friction slip – and also starts with an initial state. There is some question, however, about whether or not friction should be considered for seismic loads.

According to design codes such as the Uniform Building Code (UBC) and the international Building Code (IBC), friction ought to be ignored – a situation that’s only possible with incremental load case analysis engines. The total load approach offered by most pipe-stress software vendors fails to understand either boundary conditions or how the direction of the pipe movement can change the bearing force. That kind of change can possibly double the stress and load range when, for example, the magnitude of the friction force from an operating condition stays the same when the pipe returns to ambient conditions, yet operates in the reverse direction. Instead, it is better to do an incremental analysis to ensure that no extreme load is overlooked – and to conform with American Society of Mechanical Engineers (ASME) code philosophy.

Path Dependent Friction Finds True Stress Range

When the pipe system returns to ambient conditions after an operating condition, friction forces reverse sign but maintain magnitude, possibly doubling the stress and load ranges during cool down.



Incremental Analysis Approach

Achieving Convergence with Piping Models

Once users understand the basics of nonlinear analyses, they can learn how to converge their piping models.

There are some possible answers to the problem:

- The support can be modified or removed, depending upon the location and type of error.
- Soil properties and or the “Maximum Soil Spacing” setting can be modified in models with soil.
- By unchecking the “Gaps/Friction/Soils” in order to run the model as a static analysis, users can look for support reactions for abnormally large values that are fighting each other.
- Nonlinear analysis tolerance settings – the displacement tolerance, force tolerance, friction tolerance (which is a ratio), or the friction scale factor – can be modified.

There are other convergence remedies available for buried piping that involve using nonzero K2 values to avoid unlimited displacements. Temporarily using larger K2 values – where $K2 = K1$ divided by about 1,000 – allows users to determine if P1 values are sufficient by checking displacements. Setting K1, K2, and P1 to 0.01 and 0.0001 should make the model converge with no problem. It might be necessary to add a concentrated or distributed weight to submerged pipe to prevent it from uplifting; in some cases, concrete mats are added. Another option is using V-stops at a spacing that will allow the piping to pass the sustained stress test. Friction factors as large as 0.5 or even 1.0 may be necessary for these supports.

Load sequencing performed by an advanced nonlinear analysis program yields significant benefits.

Effective Load Sequencing

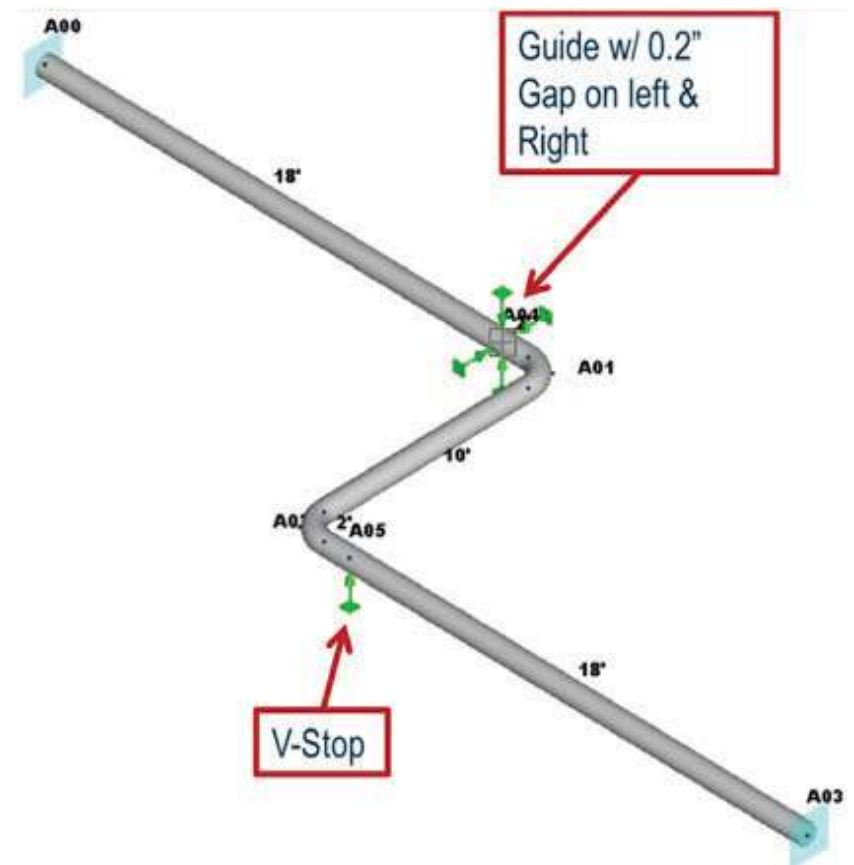
Load sequencing is the preferred method of a nonlinear analysis because it presents a real-life scenario for progressions. Load sequencing performed by an advanced nonlinear analysis program yields significant benefits. Before addressing those benefits, some background is necessary.

“Pipe Stress Engineering” by L.C. Peng and Alvin Peng, published by ASME, stated that many pipe-stress software packages used incorrect analysis methods. It further stated three approaches to nonlinear analysis – the general, straightforward approach found in many general purpose FEA programs such as ANSYS and Abaqus; the algebraic subtraction method; and the operating condition approach, which the book’s authors recommended because – unlike the other two flawed methods – it conforms to ASME code philosophy and requirements.

The sequence of loads is important in a nonlinear analysis; specifically, the starting point for a load case is important, since the principle of superimposition is not applicable. In the most effective programs, the default load sequence is as follows: gravity is analyzed with no initial state; thermal load cases are analyzed with gravity as the initial load case; pressure load cases are analyzed with the corresponding thermal load case as the initial load case; and occasional load cases are analyzed with gravity as the initial load case.

This example using AutoPIPE demonstrates how an advanced load-sequencing non-linear analysis engine works.

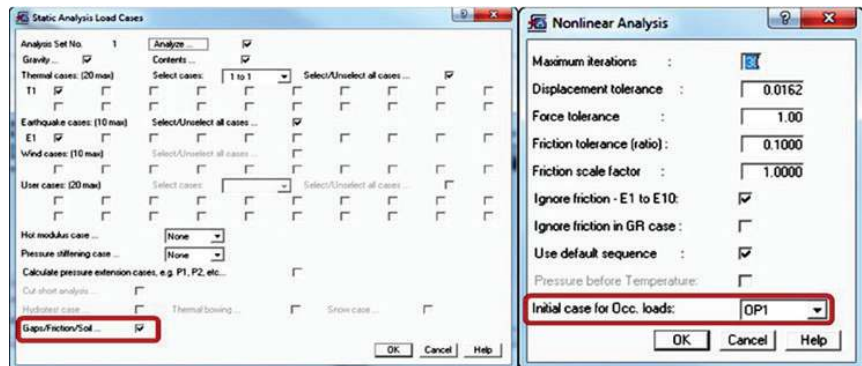
Load sequencing is the preferred method of a nonlinear analysis because it presents a real-life scenario for progressions.



Example of Load Sequencing

The AutoPIPE model displayed in the figure has a guide with 0.2-inch gaps on the left and right, and a user combination created for the model, called GRE, loads gravity and then the seismic load.

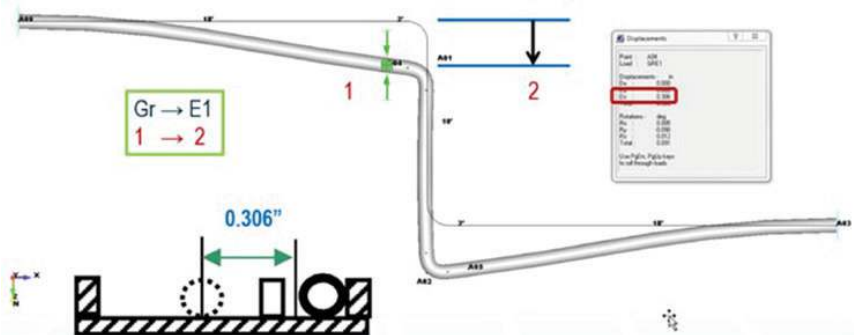
Running a nonlinear analysis with this model starts with turning on "Gaps/Friction/Soil" in the "Static Analysis Load Cases" dialog and then selecting "OK" to bring up the "Nonlinear Analysis" dialog. Next, the nonlinear tolerance setting is modified. This is where the "Initial Case for Occasional Loads" settings can be found, and for the first model run, the setting will be OP1.



AutoPIPE Settings for Nonlinear Analysis

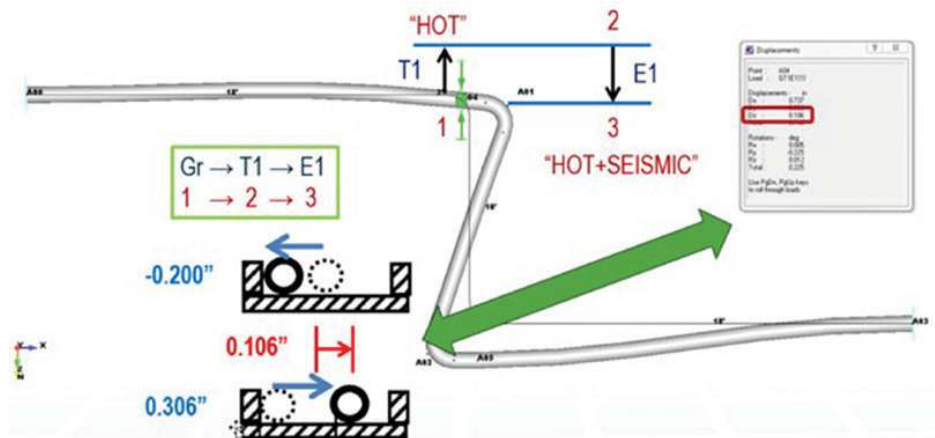
The objective here is to examine the model's "Support Forces" report and see how the program corrects for inconsistency.

The default non-code combination GT1E1 is consistent with the load sequence, which means it yields a physically possible result. But the GRE1 user combination that was created is inconsistent, since the 0.306-inch result it produces is larger than the 0.2-inch gap that had been set for the support.



Results of Load Sequencing

The thermal case shows that the pipe hits the support once it moves 0.2 inches from the gravity case in the negative Z direction to the thermal case. A look at the seismic case shows the pipe moving 0.306 inches from the gravity case in the positive Z direction to the seismic case. However, the correct load sequencing case shows the pipe starting with gravity, applying the thermal load case that hits the support gap, and then moving with the earthquake load to its final position – 0.106 inches in the positive Z direction.



Results of Load Sequencing

Fixing the seismic case involves changing the initial case for the occasional loads, a process that bypasses the thermal condition and moves from cold to seismic. The result is a consistent load case, where the pipe hits the support after it only moves 0.2 inches from the gravity case in the positive Z direction to the seismic case.

Nonlinear Methods for Buried Piping Analysis

An advanced nonlinear analysis program, such as AutoPIPE, can have tools to define nonlinear properties of buried piping systems to the modeling and analysis of those systems. For instance, the solution's model analysis can consider or ignore the nonlinear support properties of soil supporting a buried pipe, where the soil softens or stiffens as its load increases. Similarly, other properties can be defined for longitudinal soil resistance representing longitudinal cohesion, for transverse horizontal resistance, and for transverse longitudinal cohesion. Also, different upward and downward directional properties can be specified to account for differences in uplift and downward bearing behavior.

Users can define soil springs at closer spacing where a change in direction occurs – for example, at bends and tees. As the pipe moves away from the bends and tees, the soil spring spacing can be increased until a vertical anchor is approached. Beyond the point, soil springs may not be required.

Ideal advanced nonlinear analysis tools have a buried piping module recognized by the American Society of Civil Engineers (ASCE) and can handle static and dynamic loads. They also have advanced soil capabilities, including traffic loading, seismic wave propagation, and building settlement. Older technology products cannot analyze dynamic loads and have convergence problems with buried piping. Nonlinear analysis engines that are now available have the feature-set versatility to precisely analyze the broad spectrum of possible changes in piping properties.

To conclude, we discussed the importance of running a nonlinear analysis because of the way pipe supports act in real life. Bentley Systems' AutoPIPE runs a nonlinear analysis adhering to ASME codes. This paper provides you with examples of how to get your models to converge when issues arise.

For more, visit www.bentley.com/AutoPIPE

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