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SEISMIC AND THERMAL ANALYSIS OF BURIED PIPING

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ABSTRACT

Buried pipelines are principally subjected to seismic and thermal loads. Their responses to earthquakes are affected predominantly due to the differential soil movement and wave propagation effects. A simplified analytical method described in the ASCE guidelines to assess the wave propagation effects, based on approximate and generally conservative assumptions, is evaluated and compared with a proposed rigorous analysis approach based on the finite element method. Specialized pipe elements capable of handling large displacements and ovalization effects at bends are employed. The inelastic soil interaction is modeled with nonlinear spring elements. A numerical example of practical significance is used to determine the response of a quasi-static model of a pipeline with a 90° elbow subjected to compression waves and to investigate the behavior at or near the elbows. Special consideration is given to the bend flexibility. The extension of the analysis method to accommodate thermal expansion effects is discussed. The proposed finite element based approach generally avoids undue conservatism, and has the versatility to be useful for numerous practical design situations.

KEYWORDS

Buried Pipeline, Seismic Analysis, Thermal Effects, Finite Element Modeling

INTRODUCTION

The design of pipelines used for the transportation of energy, i.e., oil and gas, for the effects of earthquakes, has been studied extensively as a part of lifeline earthquake engineering. The designation ‘lifelines’ for oil and gas pipeline systems signifies that their operation is essential to maintain public safety and well-being. Basic considerations for the seismic design of oil pipeline systems have been discussed by various investigators (e.g., Hall and Newmark, 1978, Kennedy et al., 1977). The American Society of Civil Engineers (ASCE) published a unified set of guidelines (1984) to include rationale for making decisions regarding the design, construction, operation, maintenance and upgrading of equipment and components of pipeline systems.

Both onshore and offshore pipelines are typically buried to provide protection and support. During earthquakes, a buried pipeline may experience significant loading as a result of two effects: (1) large relative displacements of the ground along its length, and (2) the propagation of a seismic wave relative to the pipeline length. For evaluating the wave propagation effects, conservative simplified methods based on classical mechanics are adopted in practice (Goodling, 1983) and have been referenced in the ASCE

Guidelines. The purpose of this paper is to present and compare the simplified method proposed in the ASCE Guidelines with a finite element approach to analyze buried pipelines subjected to seismic wave propagation. Since it is well known that dynamic amplification does not play an important role in the response of buried pipelines, a quasi-static model of a pipeline with a 90° elbow, which takes into account the ovalization of the pipeline as well as the nonlinearity of the surrounding soil, is used to investigate the behavior at or near elbows. Special consideration is given to bend flexibility/ovalization. The extension of the analysis method to accommodate thermal expansion effects is discussed. Large deflection effects associated with a pipeline crossing a fault are not addressed in this study.

STRUCTURAL MODEL OF BURIED PIPELINES

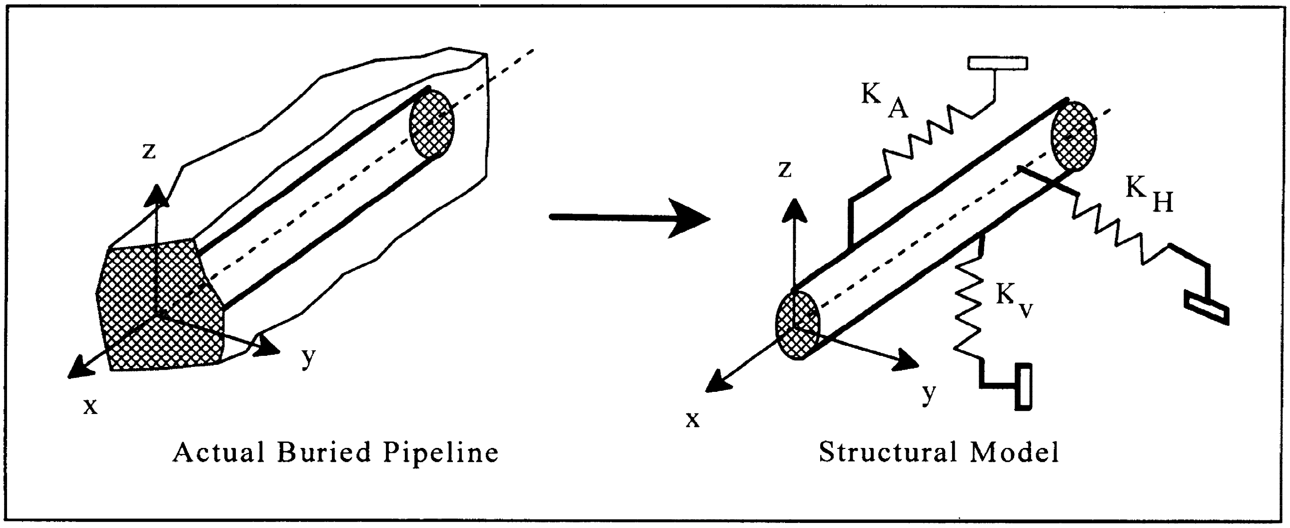

Fig. 1. Idealized Structural Model for Buried Pipeline

A buried pipeline consists of straight runs of piping or bends and is modeled as structural beam. The soil-pipeline interaction is generally represented by soil spring components in the axial (or longitudinal), transverse horizontal and transverse vertical directions, as schematically represented in Figure 1. The amount of restraint or load exerted on the pipeline is a nonlinear function of the amount of relative soil-pipeline displacement. As shown in Figure 2, the three-dimensional soil restraint can be schematically represented by a series of discrete springs whose load-deflection characteristics are denoted as t-x, p-y and q-z curves. These springs represent the nonlinear, stress-dependent behavior of the soils in the axial, transverse horizontal, and transverse vertical directions, respectively. For large relative displacements (greater than x_u, y_u and z_u), the soil loads are assumed to reach a constant ultimate value (t_u, p_u, q_u).

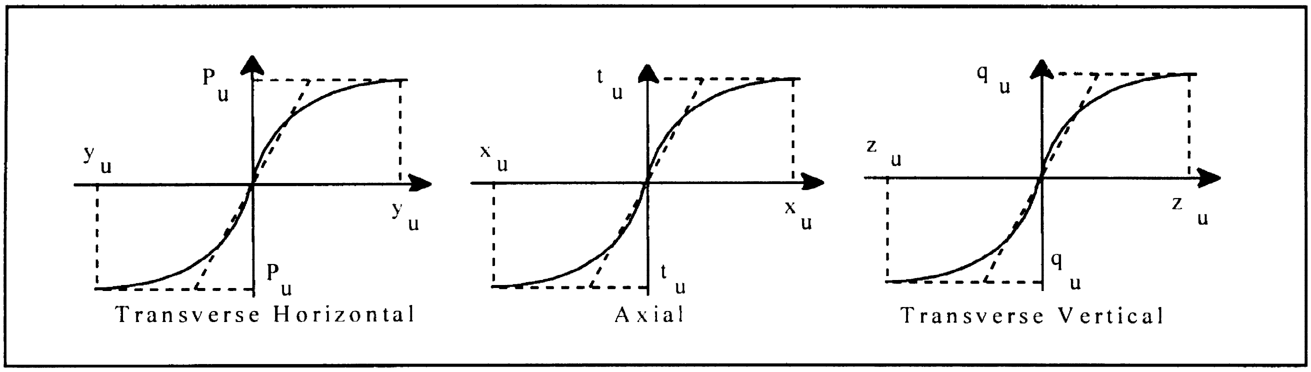

Fig. 2. Soil Load Deformation Relationship

The maximum soil friction force per unit length of the pipe in the axial direction, t_u, for a fully buried pipeline and the transverse horizontal force per unit length, p, are expressed as (ASCE, 1984):

$$t_u = \frac{\pi D}{2} \gamma H (1 + K_o) \tan\delta, \quad p = \frac{y}{A' + B' y} \tag{1}$$

Here K_o is the coefficient of soil pressure at rest, H is the depth from the ground surface to the center of the pipeline, D is the external diameter, γ is the effective unit weight of soil, y is the horizontal displacement and δ is the interface angle of friction between the soil and the pipeline. Additionally, $A' = 0.15\, y_u/p_u$, $B' = 0.85/p_u$, $y_u = 0.02$ to $0.03\,(H + D/2)$ for dense sand, $p_u = \gamma H N_{qh} D$ and N_{qh} is the horizontal bearing capacity factor

The ASCE and finite element methods discussed in the following sections are applied in conjunction with the example pipeline layout shown in Figure 3, which depicts two straight segments of a pipeline connected by a bend, which may be treated as either rigid or flexible. It is assumed that the seismic wave propagates in a direction parallel to the longitudinal leg of length, l_2. The bend radius is r_o and the transverse leg has length l_2. The pipeline is assumed to be anchored at the ends of these legs. S_1 is the shear in the transverse leg at the bend, and thus is also the axial force in the longitudinal leg at the bend. Similarly, S_2, is the shear in the longitudinal leg and also the axial force in the transverse leg. The moment, M, acts at the interfaces of the bend and the two legs. The distance, L′, is the effective slippage length over which the friction force, t_u, acts.

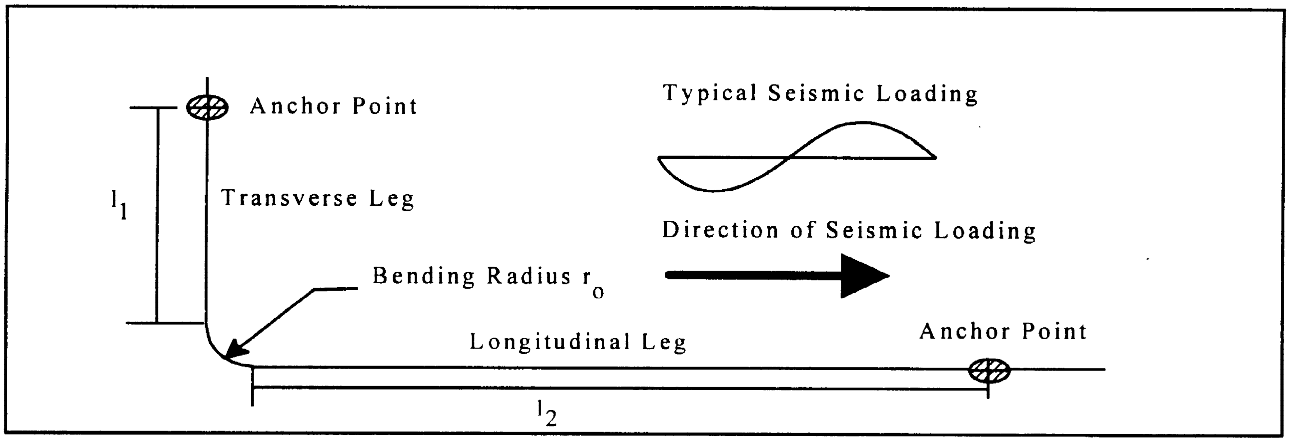

Fig. 3. Example Pipeline Elbow

ASCE METHOD

The salient features of the ASCE method (based on Shah and Chu, 1974; Goodling, 1983) are summarized below. Two alternative assumptions of the bend elastic properties are considered, viz. rigid and flexible.

Rigid bend analysis

The displacement caused by slippage, Δ, is computed as the difference between the displacement of the pipe element and the displacement of the soil and is expressed as:

$$\Delta = \epsilon_{max} L' - \frac{S_1 L'}{A E} - \frac{t_u L^2}{2 A E} \tag{2}$$

where A is the pipe wall cross-section area, E is the initial modulus of elasticity of the pipe and ϵ_{max} is the maximum axial strain in the pipe. Further, the shears and moment are evaluated by:

$$S_1 = \epsilon_{max} A E - t_u L', \quad S_2 = \frac{S_1}{3}, \quad M = \frac{S_1}{3 \lambda} \tag{3}$$

Here λ is a parameter for beam on elastic foundation. The rigid bend analysis can result in extremely conservative estimates of bending stresses.

Flexible bend analysis

Goodling (1983) proposed the following relations based upon the analysis of bending in thin-walled curved tubes.

$$\Delta = \frac{\epsilon_{max} L' - \dfrac{t_u L^2}{2 A E}}{1 + \dfrac{k_o L^2}{2 \lambda A E} + \dfrac{2 \lambda^2 L' I k^*}{\pi A r_o}} \tag{4}$$

$$S_1 = \frac{k_o \Delta}{2 \lambda} + \lambda M, \quad M = \Delta \frac{2 \lambda k^* E I}{\pi r_o} \tag{5}$$

where r_o is the bend radius, k^* is a dimensionless constant related to the flexibility of the elbow and k_o is the modulus of subgrade reaction.

FINITE ELEMENT ANALYSIS

The primary requirements in obtaining an accurate assessment of stresses in a buried pipeline are:

- Realistic modeling of the mechanism for the transfer of ground strain patterns during a seismic event to strain patterns in the pipe,
- Accurate representation of the soil nonlinearities associated with friction effects and slippage resulting from axial strains along the longitudinal pipe leg and with soil compliance and yielding effects resulting from strains perpendicular to the pipe axis along both longitudinal and transverse legs, and
- Appropriate representation of the pipeline elastic properties, including pipe bend flexibility due to ovalization of pipe section subjected to bending moment.

A finite element analysis inherently meets the above requirements. Modeling the surrounding soil by a series of soil springs at the appropriate discretization in spacing simulates the distributed soil support to any desired level of accuracy. Specifying nonlinear soil springs simulates both the frictional and yielding properties of soil. The wave propagation effects for various wave types and various wave front incident angles can be simulated by applying appropriate quasi-static displacement patterns. Consideration of the effects of ovalization has a predominant effect on the predicted stress in the pipeline, and can be accommodated by special finite elements. For the type of bend in Figure 3, special pipe finite elements were used. Typical pipe elements are 2- or 4-noded. The 2-noded element uses a beam element formulation and has six displacement degrees of freedom per node. The 2-noded element yields satisfactory results for linear analysis. The 4-noded element uses a shell formulation and is capable of handling problems involving ovalization and warping, these effects being activated by assigning 3 to 6 ovalization/warping nodal degrees of freedom. This element can also take into account the effects of stiffening due to internal pressure and large displacements. The element matrices and force vectors are evaluated using 3-point Gaussian integration in the radial direction, 2-point integration through the thickness of the pipe wall and 12-point integration along the circumference for in-plane ovalization effects. This element yields satisfactory results for both, linear and nonlinear analyses, and a wide variety of practical buried piping configurations.

EXAMPLE PROBLEM.

The following example utilizes the pipeline configuration shown in Figure 3 with the following properties:

Pipe Data:	l_1 = 800 ft, l_2 = 800 ft, r_0 = 7 ft for the 90° bend Outside diameter = 42 inches, Thickness = 0.562 inches Pipeline assumed to be anchored at the ends
Soil Data:	Overburden depth = 3 ft, unit weight = 130 pcf Angle of friction = 33° Angle of Interface = 28° Coefficient of soil pressure = 0.5
Seismic Data:	Compression wave in the direction of the longitudinal leg Frequency = 5 Hz, Velocity = 3500 fps Maximum ground acceleration = 113 in/sec^2 Maximum ground velocity = 16 in/sec

METHODS OF ANALYSIS

The example problem illustrates the effect of joint flexibility on the bending stresses computed in the elbow. Both the rigid and flexible approaches are presented for comparison of the ASCE method to the finite element method.

ASCE method

The ASCE method described earlier was programmed using Mathcad. Some key parameters obtained are as follows:

Ultimate axial resistance (t_u)	2.708 k/ft
Ultimate transverse horizontal resistance (p_u)	17.3 k/ft at ultimate displacement of 1.56 in
Modulus of subgrade reaction	6160 psi
Effective slippage length	1724 inches
Maximum soil displacement	0.378 inches

Finite element method

The finite element model (FEM) of the buried pipeline was reduced to two dimensions since the loading is in the form of applied displacements in the horizontal plane. The pipeline was discretized using 2-noded and 4-

noded straight and bend elements. The soil was modeled using nonlinear springs in both the directions, longitudinal and transverse to the pipe alignment. The displacements were applied to the nodes at the bend and along the longitudinal leg of the pipeline, as axial displacements (in the x-direction) in the form of a half-wavelength pattern. The finite element analysis used three alternative assumptions for the elastic behavior at the bend: (1) Rigid bend (bend elements given an arbitrarily large stiffness value), (2) Flexible bend without ovalization, and (3) Flexible bend with ovalization.

COMPARISON OF RESULTS

The comparison of the results from the ASCE method and the finite element method are given in Tables 1 and 2 for a rigid bend and flexible bend, respectively.

Rigid bend analysis

Figures 4 and 5 show the deformed shapes of the bend using the 2-noded and 4-noded finite elements, respectively. The maximum soil displacement applied was 0.378 inches. The resulting displacement at the bend (Table 1) was calculated to be 0.152 inches using the ASCE method. A 2-noded finite element model gives the corresponding displacement of 0.163 inches. The result from the 4-noded element analysis (0.152 inches) shows excellent agreement with the ASCE solution. The 4-noded element models the bend effects more realistically than the 2-noded element and hence its estimates of stresses and displacements are more accurate.

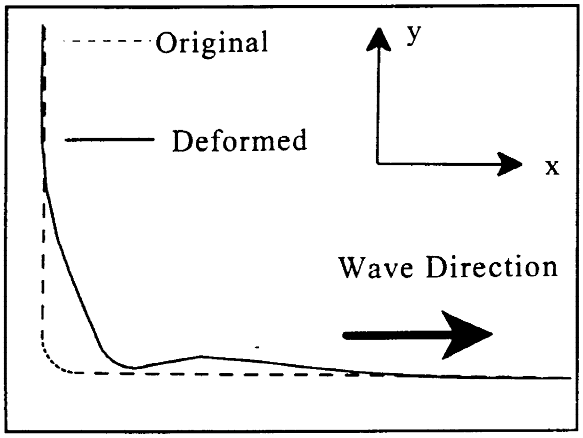

Fig. 4. 2-Noded Element Analysis

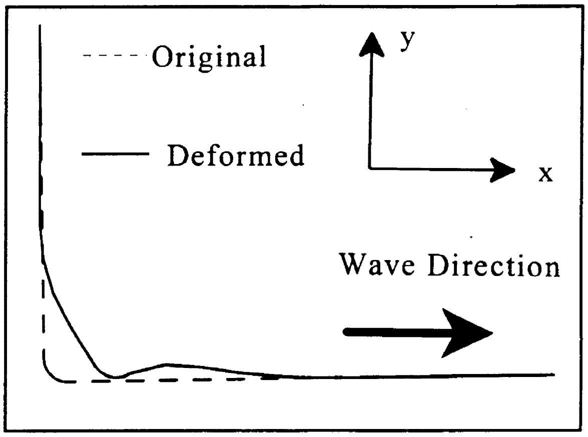

Fig. 5. 4-Noded Element Analysis

The ASCE method and computer solution confirm the inherent conservatism in the ASCE simplified procedure. With the more accurate 4-noded element, the finite element method predictions are 24% and 53% less than the ASCE method for transverse leg axial force and bending moment, respectively. With the bend displacements agreeing closely, the longitudinal leg axial forces are expected to also agree.

Table 1. Rigid Bend Analysis

Quantity	ASCE	2-Noded Elem	% Diff	4-Noded Elem	% Diff
Bend Displacement (inches)	0.152	0.163	+7	0.152	---
Axial Force Long. Leg (lb)	92,180	78,260	-15	95,812	+4
Axial Force Trans. Leg (lb)	30,730	26,995	-12	23,433	-24
Moment at Bend (lb-in)	4.03×10^6	2.10×10^6	-48	1.89×10^6	-53

Flexible bend analysis

Only 4-noded finite elements were used for the flexible bend analysis, with the bend elastic properties specified at realistic values instead of being given an arbitrarily large stiffness value. The ASCE method/computer solution comparison further emphasizes the conservatism in the approximations of the ASCE method, which is formulated on a rigid bend assumption. While the bend displacements and longitudinal leg axial forces still agree closely, the transverse leg axial forces, and bending moments are each further reduced from the rigid bend case, being 26% and 69% less than the ASCE method, respectively.

Table 2. Flexible Bend Analysis

Quantity	No Ovalization			With Ovalization		
	ASCE	FEM	% Diff	ASCE	FEM	% Diff
Bend Displacement (inches)	0.152	0.154	+1	0.167	0.156	-7
Axial Force Long. Leg (lb)	92,180	92,094	----	74,150	88,347	+19
Axial Force Trans. Leg (lb)	30,730	22,758	-26	24,720	23,629	-4
Moment at Bend (lb-in)	$4.03\text{x}10^{6}$	$1.24\text{x}10^{6}$	-69	$0.90\text{x}10^{6}$	$0.35\text{x}10^{6}$	-61

Flexible bend analysis using ovalization

The finite element analysis was extended to allow for ovalization, and for this case, the deformed cross-section of the pipe is shown in Figure 6. For comparison, the ASCE method with the Goodling (1983) modification to account for ovalization was used. The most interesting observation that can be made from this comparison is that while the Goodling modification makes a remarkably good approximation to the reduction of bending moment as a result of ovalization effects, the end results are still conservative relative to the finite element results, and slightly more so (61% less versus 53% less) than the case in which both methods ignored the ovalization effects.

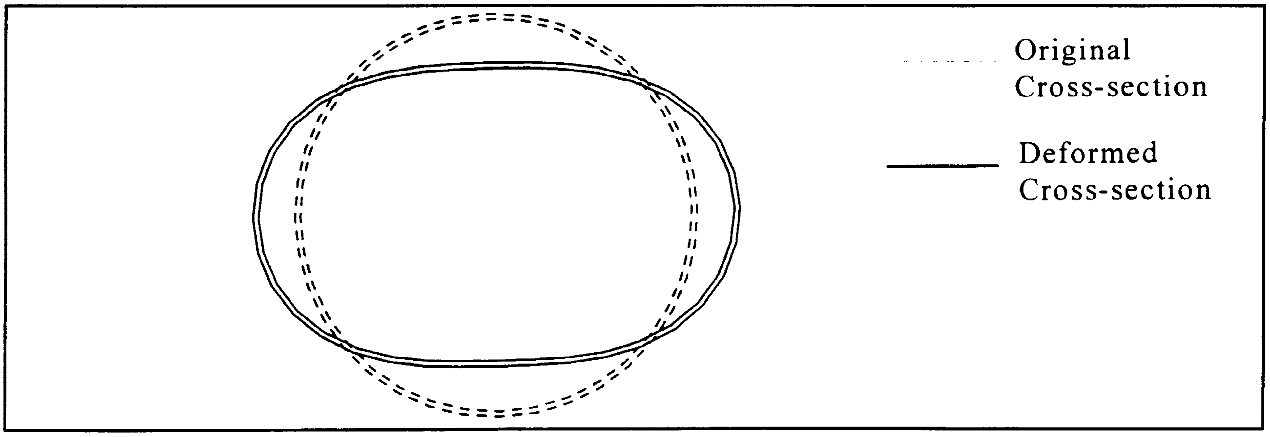

Fig. 6. Ovalization of the Pipe Elbow

THERMAL EXPANSION

In the case of thermal expansion effects of buried pipelines, the mechanism for transfer of strains between the pipeline and soil is different from for the seismic wave effects. The pipeline expands and imposes axial and lateral strains on the soil, which provides resistance through soil/pipe friction and lateral soil pressure effects, respectively. Unlike seismic analysis, where the seismic strain is assumed to act along the longest run at any given moment, the thermal strains may act along both the runs. However, despite the differences in load application, the mechanisms for transfer of the load between soil and pipeline, for simulating nonlinearities in the soil, and for reflecting the flexibility of the pipe bends, are as applicable and effective for thermal expansion analysis using the proposed finite element method based approach, as has been demonstrated for seismic analysis.

CONCLUSION

A simplified procedure for buried piping analysis proposed by the ASCE provides an effective method of qualifying the piping for seismic and thermal loading. The method is easy to program, conservative for pipeline elements such as bends and tees, and is a quick and convenient design qualification method for new pipeline layouts. Comparisons made between the ASCE method and finite element based procedures proposed by ARES indicate that the classical method is relatively conservative when the flexibility effects of ovalization at pipe bends are ignored in both methods and this relative conservatism increases when ovalization is accounted for in both methods.

The finite element based method proposed has considerable advantage in the following circumstances:

- For the qualification of existing buried pipelines to new or upgraded seismic criteria,
- For complex, three-dimensional pipeline layouts, in which the proximity of bends and tees to one another does not rationally permit isolating simple elements of pipe layout and assuming uncoupled behavior, and
- For situations where significant nonlinearities may occur within either the soil or the pipeline.

Lastly, the proposed finite element method may prove to be useful for analysis of multiple wave types and alternative wave incidence characteristics, which may be necessary in the design of critical and/or safety-related buried pipelines.

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