NONLINEAR BEHAVIOR OF PIPELINE JOINTS

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SUMMARY

Experimental and analytical investigations performed on buried and unburied jointed pipelines have been summarized and indicate bilinear and multi-linear mechanical relationships for rubber gasketed joints subjected to axial, torsional and bending deformations, respectively. "Slip" limits which define the inception of the non-linear behavior have been quantified. A modified seismic joint detail which allows larger joint freedom is provided. Pipe network configurations are examined for the effects of a flexible pipe joint.

INTRODUCTION

Underground as well as above ground pipelines are commonly used to transport various liquids. Several types of joints are currently in use. For water carrying utility pipelines, the most common joint type is the flexible rubber gasket joint. Damage to pipelines due to earthquakes has been documented by several authors in Reference 1. In the design of above ground pipelines and facilities, the inertia effects are of major consideration. However, in buried pipelines, where the pipe moves with the surrounding soil, the effects of inertia forces due to the pipe are not recognizable. It is the relative motion of two points on a buried pipeline, due to the differential ground motions, which provides the governing design criteria. In buried jointed pipelines, this differential ground motion is sustained by the pipe barrel as well as the flexible joints. Above ground tests have been performed on several different diameter pipelines to obtain data for the load/reload type of nonlinear behavior including "slip" characteristics for the rubber gasket joints. Buried tests were performed to obtain the barrel interaction data with the surrounding soil at different burial depths. Analytical expressions have been obtained which are based on the known geometry of the rubber gasket and the pipe joint which adequately reproduce the experimental data. The primary purpose of this research work is to establish relationships between various parameters which control the nonlinear behavior of buried jointed pipelines and to provide "slip" and "failure" characteristics of the flexible joints which could be used in checking the adequacy of pipelines in a seismic environment. The joint geometry most commonly used in water distribution pipes at the present time could use some improvement to handle axial compressive and bending deformations.

RUBBER GASKETS AND PIPE JOINTS

Rubber gaskets are used in ductile cast iron pipelines to provide water tightness of the joint. All gaskets are confined in an annular space and are manufactured to have a circular main body and a trapezoidal outer body.

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Interestingly, the plot of engineering stress (load/original area) vs engineering strain (change in length/original length) for both main and outer parts of the rubber gasket turns out to be linear. The plots of true stress vs true strain, however, do follow the typical nonlinear diagram for the rubber material.

Equations (1) and (2) taken from Reference 2 represent the linear behavior of the rubber gasket, as follows:

for main circular body; $\sigma = 360\ \varepsilon$ (1)

and, for outer trapezoidal body; $\sigma = 790\ \varepsilon$ (2)

where σ and ε are engineering stress in psi (1 psi = 6.9 KPa) and engineering strain, respectively. Poisson's ratio (ν) was found to be 0.50. The geometry of the rubber gasket as defined by symbols in Figure 1 is shown in Table 1. The geometry of the most commonly used water distribution pipeline joint is defined by symbols in Figure 2 and is shown in Table 2.

Table 1. Geometry of Rubber Gaskets

Nominal Pipe	Dimensions (Inch) - see Figure 1				
Diameter (in.)	A	B	C	D	E
4	.60	.71	.35	.2	.13
6	same as for 4 inch pipe				
8	.72	.79	.39	.26	.17
10	.72	.98	.39	.26	.17

(Note: 1 inch = 25.4 mm)

Table 2. Geometry of Ductile Pipe Joint

Joint Dimensions-Inches-(see Figure 2)							
a	b	c	d	e	f	g	ϕ
7.22	1.08	4.91	3.15	5.64	1.357	4	4.8
9.47	1.15	7.01	3.38	7.74	1.357	6	6.9
12.0	1.32	9.17	3.69	9.98	1.759	8	9.1
14.2	1.38	11.22	3.75	12.03	1.963	10	11.1

AXIAL, BENDING AND TORSIONAL BEHAVIOR OF A PIPE JOINT

Experimental Data

Axial pull-out, bending and torsion tests have been performed on 4 (101.6), 6 (152.4), 8 (203.2) and 10 inch (254 mm) pipeline joints. These tests have been discussed in detail in References 3 and 4. A summary of results based on over 50 axial tests is shown in Figure 3. The axial pull out loads for 4 (101.6), 6 (152.4), 8 (203.2) and 10 inch (254 mm) pipes are 46, 69, 333 and 386 pounds (1 lb = 4.45 N), respectively. On the average, slip begins to take place at approximately 0.15 inch (3.81 mm) pull out, and at 1.2 inch (30.5 mm) the pipe is completely out of the bell of the joint. A summary of over forty bending tests is shown in Figure 4. The maximum moment sustained by the joint for 4, 6, 8, and 10 inch diameter (1 in = 25.4 mm) pipes are 63, 138, 396 and 764 lb-in (1 lb-in = 113 N-mm), respectively. The joint begins to slip at 0.26 degrees joint rotation, and "metal-to-metal" joint binding takes place at approximately 4 degrees joint rotation. Similarly, a summary of over thirty torsion tests is shown in Figure 5. The maximum torques sustained by a "rubber gasket" joint for 4, 6 and 8 inch diameter pipes are 206, 367 and 1210 lb-in, respectively. The joint begins to slip after 0.17 degree rotation in torsion.

Analytical Expressions

Theoretical expressions which are based upon the mechanical and material properties of the rubber gasket, the geometry of the joint and the basic principles of mechanics have been obtained and summarized here from Reference 5. Equation (3) can be used to predict the maximum pull out load (P_{max}):

$$P_{max} = \frac{5}{24} \Pi^2 \mu E_1 A \phi [A - \frac{e-\phi}{2}]/(e-\phi) \tag{3}$$

where E_1 (= 360 psi) is the initial modulus for the "main-body" of the gasket, μ is the friction coefficient between pipe and gasket (= 0.10), A is the diameter of the rubber gasket, and e and ϕ (Figure 2) are the parameters of the details of the pipe joint. The values for "A" for various diameter pipes are given in Table 1, and the values for "e" and "ϕ" are given in Table 2.

The maximum bending moment (M), which can be sustained by the joint without any slip, can be predicted by Equation (4). This equation is valid up to 0.26 degree rotation, beyond which the joint begins to slip, and the stiffness drops by a factor of seven. For $\theta \ngtr 0.26$ degrees:

$$M = \frac{4 \Pi \phi E_1 f^3}{9(e-c)} \theta \tag{4}$$

where c, e and f are defined in Figure 2 and Table 2.

The maximum torque (T) that the joint can sustain prior to slip can be obtained from Equation (5). This equation is valid up to 0.17 degrees beyond which the joint begins to slip. For $\theta \ngtr 0.17$ degrees:

$$T = \mu \Pi g^2 \frac{A}{2} E_1 [1 - \frac{D_2}{(A^2 - D_2^2)^{1/2}} \cdot \sin^{-1} (\frac{[A^2 - D_2^2]^{1/2}}{A})] \tag{5}$$

where $D_2 = \frac{e-\phi}{2}$, and g is the nominal pipe diameter (see Figure 2).

Correlation

Equations (3), (4) and (5) along with basic geometrical data from Tables 1 and 2 give predicted axial pull out force, bending and torsional capacities within the same "range" as the experimental values. The individual test values vary due to the variation in the coefficient of friction (e.g. μ ranges between 0.10 and 0.50 for lubricated gaskets).

TESTS ON UNDERGROUND PIPES

Tests have been performed by burying pipe segments with a joint in between in a specially designed sand box which was strong enough to develop adequate soil pressures and large enough to eliminate any "edge effects" in the test. These tests are discussed in detail in References 3, 4 and 6. For axial pull out tests on 8 inch diameter pipe, the pull out force over a sixteen foot buried pipe length increased from an unburied value of 333 lbs. to 675 lbs. when the pipe was buried to a depth of 18" from the pipe centerline (see Figure 6). The main influence of the soil is to provide additional friction forces against joint slippage. These tests were performed in a dry Monterey sand with an internal friction angle of 38.3° and a unit soil weight of 98.1 lb/cu ft. Buried bending tests also increased the moment capacity due to soil resistance. The equivalent (Reference 6) modulus of soil from the bending tests was found using a computer program developed in Reference 7. Similarly, the torsion buried test indicated a linear relationship between the depth of burial and the torque capacity. For a cohesionless soil, the torque capacity can be predicted by Equation (6). For underground pipelines (see Reference 6):

$$T = \frac{\pi}{6}\,[\gamma(2+k_o)z - \frac{\pi}{4}\,\phi\gamma + .279]\;\phi^2\;\tan\beta \tag{6}$$

where γ is the unit soil weight (=98.1 lb/cu ft), z is the depth of burial to the pipe centerline, ϕ is the outside pipe diameter (Figure 2), and β is the soil angle of friction (38.3°), and,

$$k_o = 1 - \sin\beta\;. \tag{7}$$

The above equation is valid for various pipe diameters, and Figure 7 shows a comparison of the experimental and predicted torque capacities for an eight inch diameter pipeline. For ductile cast iron pipe, the slip does not occur at pipe-soil interface, rather it occurs at a short distance away from the pipe between various soil particles, and thus a full angle of friction "β" is developed.

FAILURE IN PIPE LINES

Figure 8 shows potential scenarios which lead to severely high stresses. Initial position of a pipe is shown in Figure 8(a). Under bending strains, after a joint rotation of larger than 4 degrees, the joint binds at the locations identified by circles in Figure 8(b) causing very high stresses and possible failures. Under compressive axial strains (Figure 8(c)), pipe has a tendency to buckle or crush near the joint. High compressive stresses occur at about 1/8 inch (3.175 mm) motion of the barrel. Under tensile axial strain (Figure 8(d)), all ductile cast iron pipe joints get completely disassembled at an axial displacement exceeding 1.2 inches for each barrel length (i.e. ground strains exceeding .005). However, severe fluid leakage occurs at ground strains of about one third of strains leading to total collapse. At fault crossings, ground strains exceeding 2.5% are quite common and therefore special attention to joint details at fault crossings should be provided.

MODIFIED SEISMIC JOINT

Figure 9 shows a modified joint detail which provides additional "push-in" space (f in Figure 2) and much larger bending rotation capacities by changing the "shape" of space "d" in Figure 2 to Figure 9, thus preventing a "metal-to-metal" contact during axial and bending motions.

JUNCTION STRESSES IN BURIED JOINTED PIPELINE NETWORKS

Pipelines with flexible joints show a completely different stress pattern than continuous pipelines (viz welded joints). Axial, bending and torsional stiffness (or flexibility) coefficients are needed for a stress analysis of pipelines with flexible joints. Analytical expressions presented in this paper can be used to derive these joint stiffness coefficients as shown in Reference 7. For the pipe barrel, the stiffness coefficients can be obtained by using the beam on elastic foundation type of approach and by using appropriate unit displacement functions to define stiffness coefficients as done in Reference 7. Using this approach, three dimensional buried pipeline networks have been analyzed, and it is found that the moments in the intersecting pipelines can be reduced by suitable placement of flexible joints. Network effects influence the stress distribution in the inter-connecting pipelines within a predetermined distance from the junction point depending upon the properties of soil and inter-connecting pipelines (Reference 7).

CONCLUSIONS

For distribution type utility ductile cast iron pipelines with rubber gasket joints, the initiation of pipe-rubber slippage within the joint leading to a non-linear (multi-linear) behavior of the joint takes place at 0.15 in (.318 mm), 0.26 degrees and 0.17 degrees for axial, bending and torsional types of deformations, respectively. Analytical expressions have been provided which adequately predict the axial, bending and torsional capacities of joints for various diameter pipelines. For all ductile cast iron distribution pipelines (4 in through 12 in diameter), joint failures may occur at 0.125 in (3.175 mm) axial compression, or 1.2 in (30.5 mm) axial pull-out or more than 4 degrees bending rotation of the joint.

ACKNOWLEDGEMENTS

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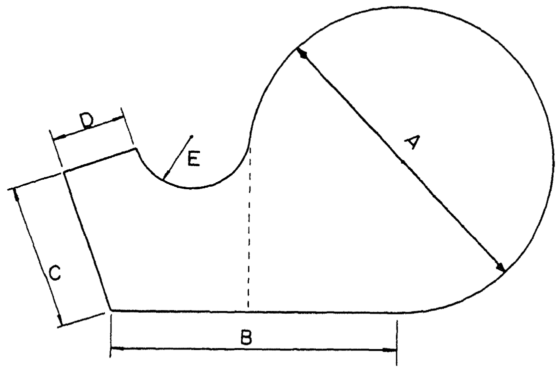

Figure 1
Geometry of a Rubber Gasket

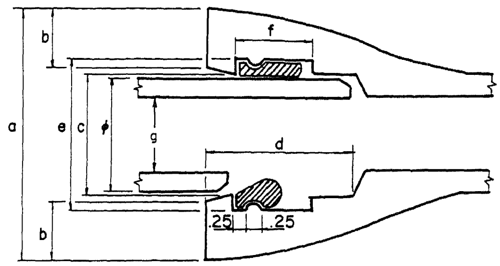

Figure 2
Geometry of a Pipe Joint

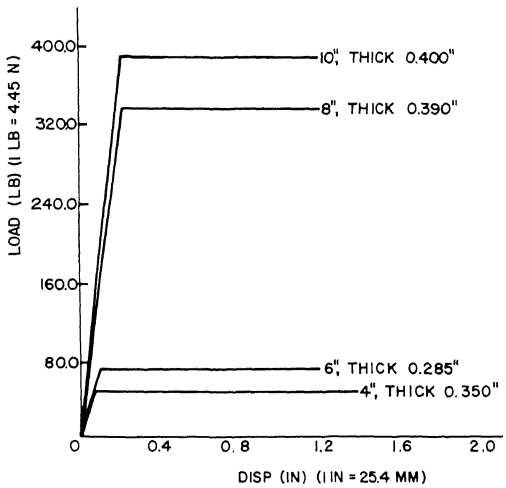

Figure 3
Axial Pull Out Joint Stiffness

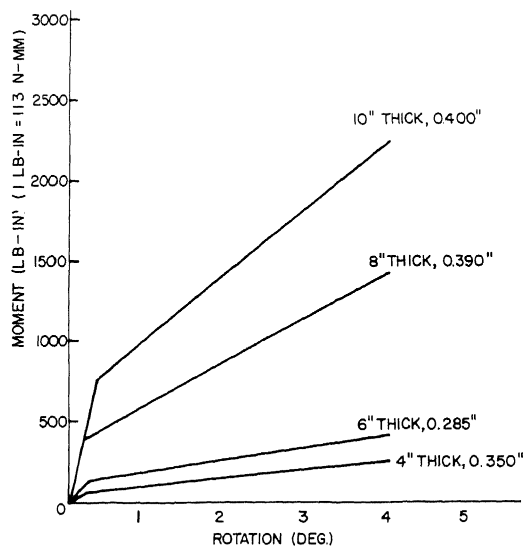

Figure 4
Joint Bending Stiffness

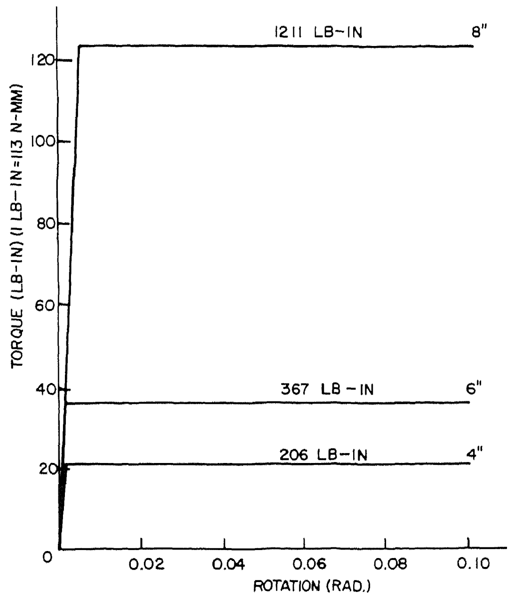

Figure 5
Torsional Joint Stiffness

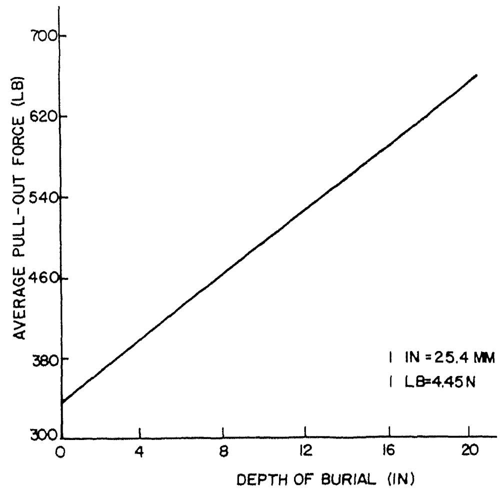

Figure 6
Effect of Depth of Burial
on Pull-Out Force

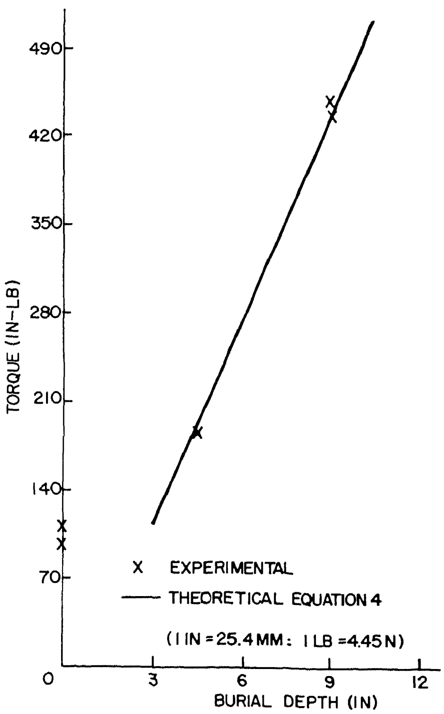

Figure 7
Failure Torque for 8" Diameter Pipe

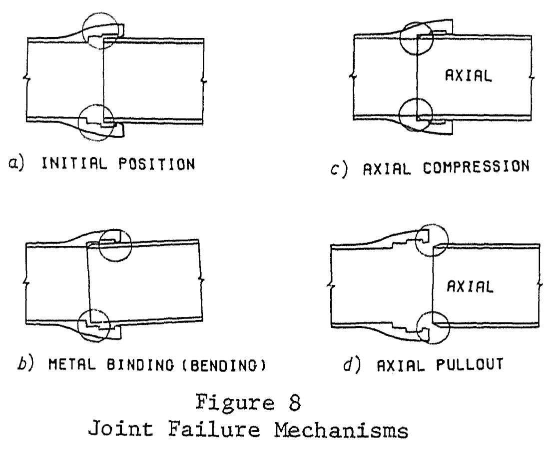

Figure 8
Joint Failure Mechanisms

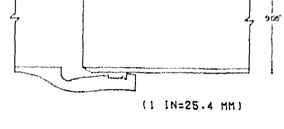

Figure 9
Joint Detail for 8" Pipe