PERFORMANCE OF A PIPELINE AT A FAULT CROSSING

John M. Eidinger[1], Michael O'Rourke[2], Jeff Bachhuber[3]

Abstract

The 1999 Izmit (Turkey) earthquake subjected a number of welded steel pipelines to fault offset. In this paper, we examine the actual performance of a 2.2 meter diameter welded steel pipeline that was subjected to about 3 meters of right-lateral fault offset of the North Anatolian fault. The pipe had been installed just a year prior to the earthquake, and is part of the Thames Water Company's water treatment and transmission system.

During the earthquake, the pipe suffered leaks at the fault crossing, and managed to stay in service during the immediate post-earthquake hours and days. After a few days, the pipe was shut down, excavated and drained in order to assess and make repairs at the fault crossing location. It was found that the pipe had suffered wrinkling and tears at three locations. The pipe was temporarily repaired and put back into service. About 6 weeks after the earthquake, field geologists investigated the pipeline at the fault crossing location. Soil samples were taken and subsequently lab tested in California. A survey was done of the displaced pipeline at the fault crossing location.

This paper presents the findings from the field investigations. The paper also presents structural analyses of the pipeline to simulate the field conditions. Using suitable structural analyses, we can predict the mode and location of pipeline failure within a reasonable degree of accuracy. Finally, observations are presented as to design implications for pipelines at fault crossings.

Pipeline Performance

The Thames pipeline crosses the Sapanca segment of the North Anatolian fault between the towns of Kullar and Izmit. Figure 1 shows a map of the pipeline at and near the fault crossing. The actual crossing is at latitude N40° 43.174' longitude E29° 58.098'. Except for a short shut down for emergency inspections and repairs, this pipeline was maintained in service for 7.5 months following the earthquake before final repairs were made. For more details as to the response of Thames Water facilities in this earthquake, see (Parker, 2000) and (Tang 2000).

A small surface leak was visible where the pipe crossed the fault. A decision was made not to investigate the damage and undertake repairs in the immediate days after the earthquake; instead,

[1] G&E Engineering Systems Inc., 6315 Swainland Rd., Oakland CA 94611 eidinger@earthlink.net
[2] Rensselaer Polytechnic Institute, 110 8th Street, Troy NY 12180 orourm@rpi.edu
[3] Lettis & Associates, 1777 Bothelho Drive, Suite 262, Walnut Creek, CA 94596 bachhuber@lettis.com

it was decided to keep the pipeline in service in order to continue supplying water to the rest of the system.

Within a few days after the earthquake, the 2200 mm diameter pipeline was exposed in the area of the fault to allow a better understanding of the nature and extent of damage to the pipe. Soil was excavated from the top of the pipe, to expose about one-quarter of the depth of the pipeline. After draining the line, a manhole was cut into the pipeline at the excavation to allow for access into the pipeline (the cut steel plate can be seen at the invert of the pipe in Figure 2). Damage was observed at three locations: stations 1+320, 1+337 and 1+349 (see Figure 4 for station numbers). The damage consisted of three wrinkled locations. The wrinkles at stations 1+337 and 1+320 (Figures 2 and 3) were folded to a depth of typically 200 mm or more; in other words, the steel was folded into the main pipeline. This caused a reduction in net cross sectional area of the pipeline, with a corresponding reduction in flow capacity due to the increased friction losses at higher flow rates. The only leakage occurred at a crack in the steel at one of the major wrinkles (some reports suggest a larger leak at one major wrinkle, and a smaller leak at the other major wrinkle). The pipeline was losing less than about 1% of its flow at the larger leaking wrinkle (perhaps on the order of 1,000 gpm). There was no life safety concern due to this leak.

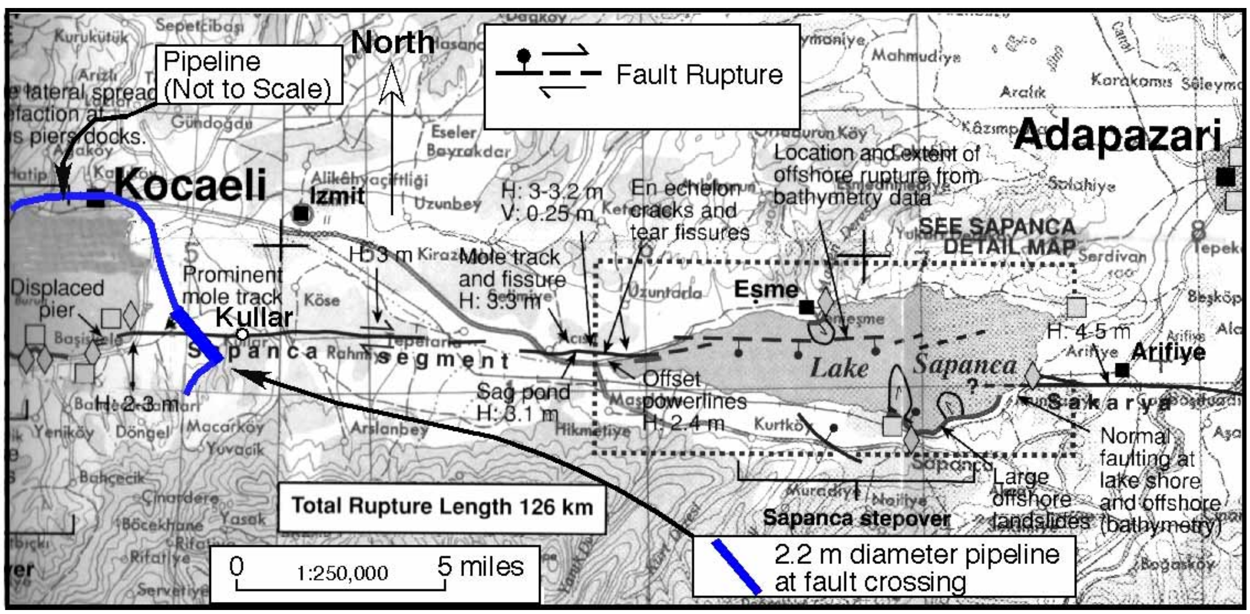

Figure 1. Map of Pipeline and Fault

As the extent of the wrinkling in the pipeline was discovered, it became apparent that sleeving the deformed joints and encasing the pipeline in concrete would not be a suitable repair strategy. The extent of the wrinkles suggested that the internal diameter had been "necked" down to about 1400 mm diameter at two of the wrinkles.

Figure 4 shows the plan view of the pipeline at the fault crossing location. Key features are as follows: The plan is drawn to scale. The outline of the pipeline is based on a post-earthquake survey of the damaged pipe. Elevation contours are shown using 1 meter contour lines. Seven survey points were made at the top of the pipeline. Station numbers were assigned to the seven survey points, each denoted with a station number. The sheet pile walls and excavation pit were installed as part of the emergency repair process. Each survey point is for the top center of the pipeline. The survey was to the top of steel (there is an epoxy coating system).

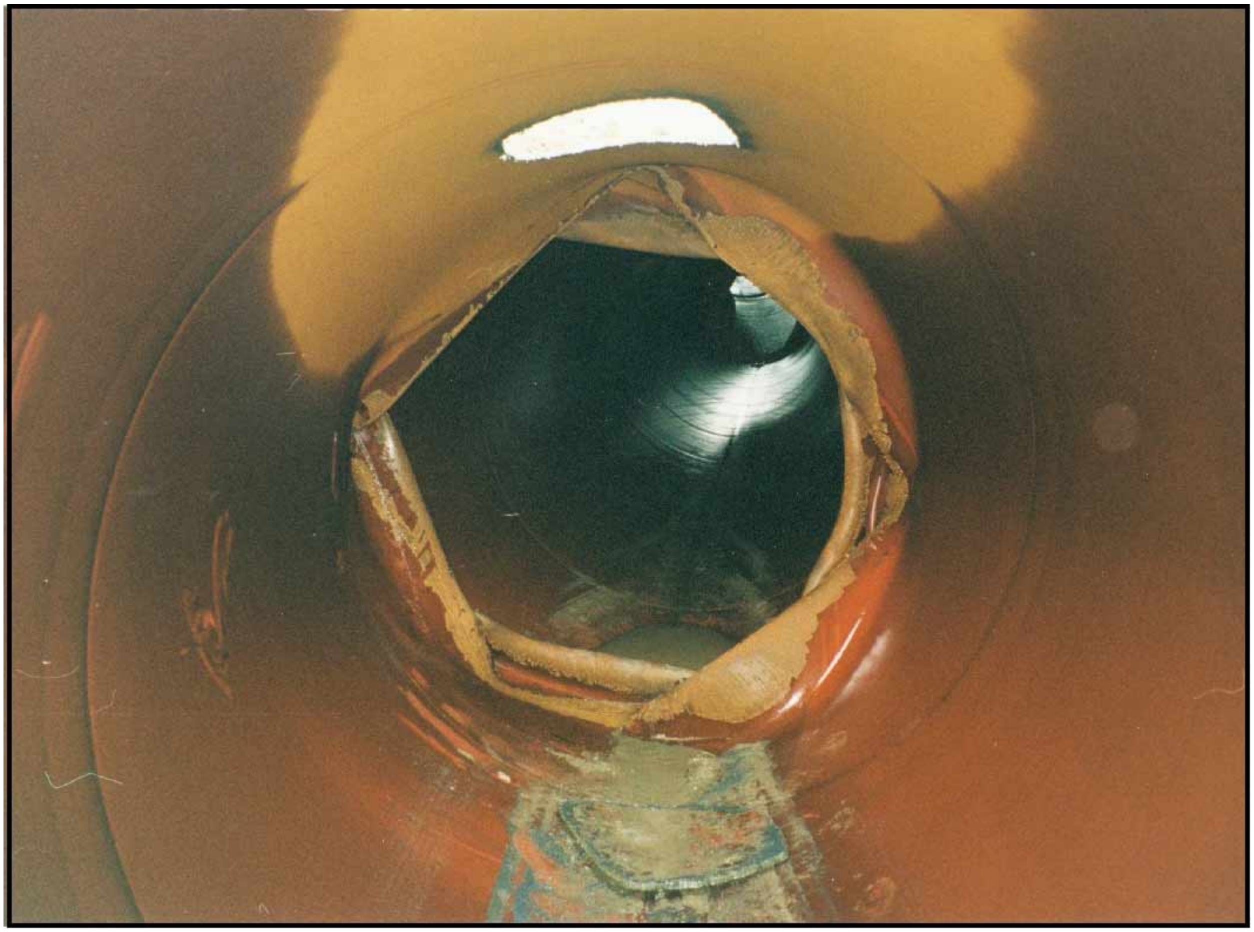

Figure 2. Major Wrinkle. Note Steel Plate at Invert from Manhole

Figure 5 also shows the pipeline in its post-earthquake configuration. Angles are shown for various segments of the pipeline. As drawn, each segment is straight, but this is not necessarily true. Assuming that the fault moved in a purely strike-slip fashion, then the pipeline was subjected to 1.70 meters of shortening and 2.47 meters of transverse offset.

The fact that the Thames Water Pipeline was damaged at the North Anatolian fault crossing is not surprising given the nature of the fault offset and the design aspects of the pipeline. The pipeline crossed the fault at a 50° to 55.5°± angle, putting the pipe into compression as the fault moved in right lateral offset.

The distance between the two large wrinkles, either side of the fault, is about 17.6 meters. If the pipe were shortened just between the wrinkles closest to the fault (it did not – some took place in the wrinkles, some in the pipe between the large wrinkles, and some in the pipe beyond the large wrinkles), the average compression strain between the two wrinkles would reach 9.7% (=1.70 / 17.6). This greatly exceeds the yield capacity of the steel. The theoretical compressive stress to reach onset of wrinkling for a perfect cylinder (Timoshenko and Gere 1961) is:

$$\sigma_{classical} = \frac{1}{\sqrt{3(1-\mu^2)}} \frac{tE}{R}$$

where μ is Poisson's ratio and E is Young's modulus, t is the pipe wall thickness, and R is the radius of the pipeline. For μ = 0.3, this formula becomes:

$$\varepsilon_{theory} = 0.6\frac{t}{R}$$

For a non pressurized cylinder with imperfections, a lower bound estimate of the onset of wrinkling is:

$$\varepsilon_{onset} = 0.175\frac{t}{R}$$

Figure 3. Major Wrinkle. Remaining Flow Diameter is 1400 mm

For this pipeline, with t = 18 mm and R = 1100 mm, the theoretical strain to reach onset of wrinkling for an imperfect cylinder is 0.00286, or an compressive stress of 85 ksi. The specified material for the pipeline is API Grade B steel or better, with minimum specified yield stress of 241 N/mm^2 (35 ksi). Clearly, this pipe had to wrinkle, and wrinkle it did!

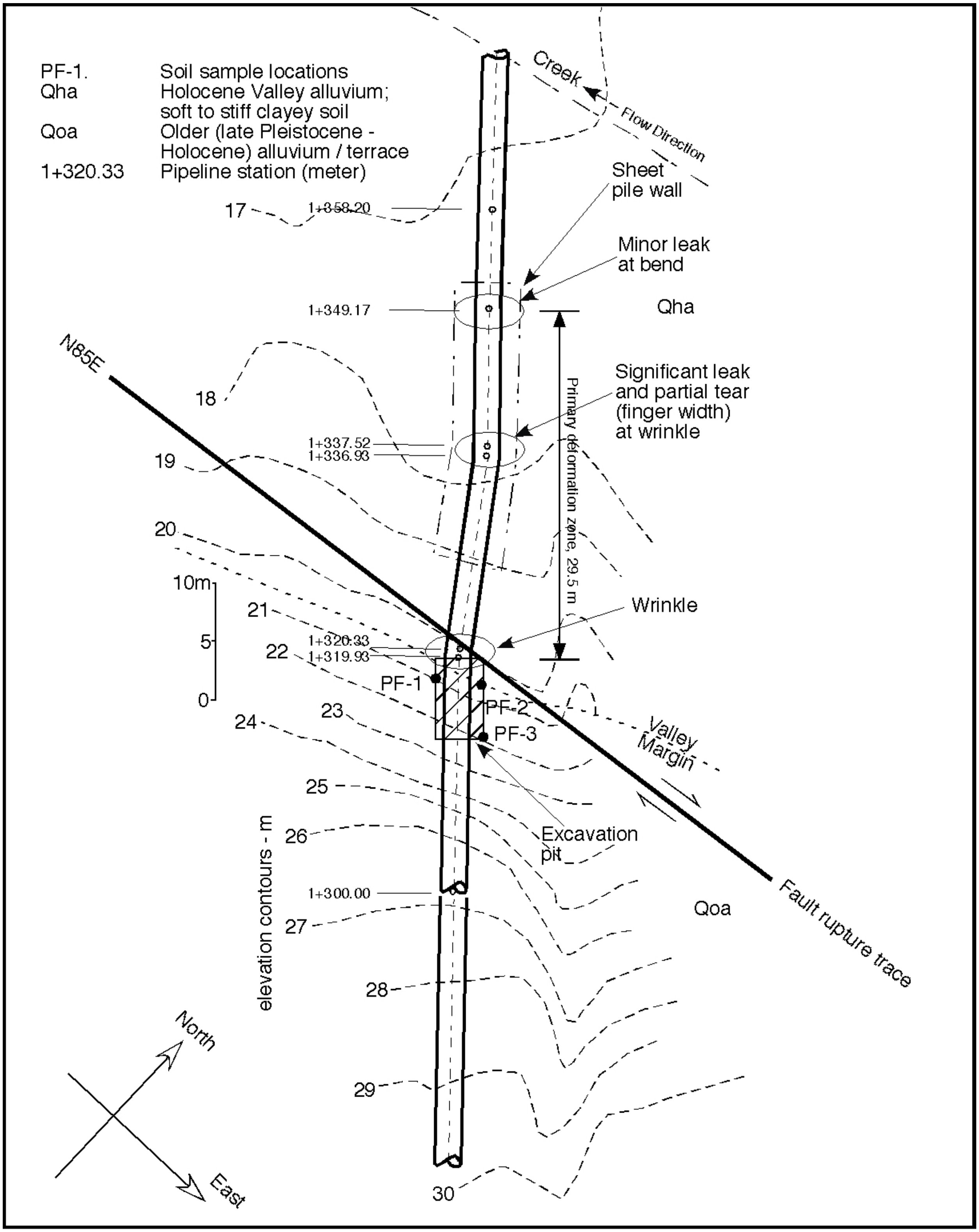

Figure 4. Pipeline and Fault Location After Earthquake.

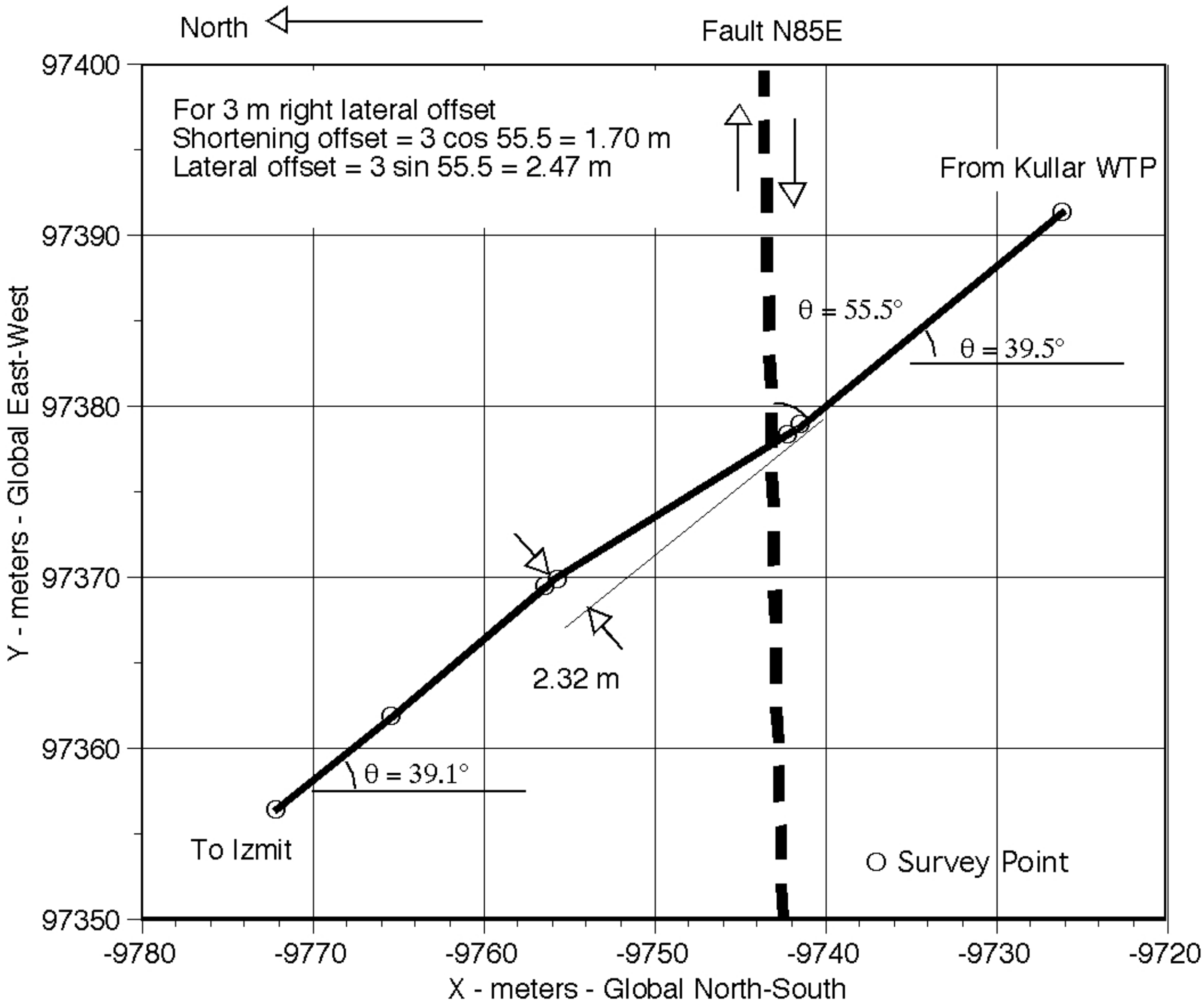

Figure 5. Pipeline and Fault Geometry

The location of the fault and the two closest observed wrinkles is expected. If a continuous welded steel pipeline is at 90 degrees to the fault (right angles to the fault), then large fault offset will produce high bending moments in the pipeline at a moderate distance either side of the fault. The sense of the bending moments would be opposite, as the pipe takes on a "S" type shape across the fault. The high bending moments impose high compressive strains in the outer fibers of the pipeline, and with enough fault offset, the high strains would initiate two wrinkles.

For this pipeline, there were actually two major wrinkled locations and one minor bend location (see Figure 4). The two main wrinkles are those at stations 1+320 and 1+337. The third bend (wrinkle) at station 1+349 is due to sufficiently high bending moments even at that location.

The distance between the two main wrinkles is about 17 meters. Given that the pipeline has nominal diameter of 2.2 meters, this puts the spacing between the wrinkles at about 8 pipe diameters. Stress analysis of a buried pipeline subject to fault offset would show that for a given pipe diameter, the thicker the pipe wall, the wider the location between the two wrinkles, whereas for a higher soil stiffness surrounding the pipeline, the shorter the location between the two wrinkles.

From stations 1+320 to 1+349, the pipe was described to have undergone "broad bending". This bending could not be observed during the reconnaissance of September 30, 1999.

The pipeline crosses the fault at a break-in-slope between an older alluvial terrace or ridge slope and a small active alluvial valley. Surficial geologic units are denoted Q_{oa} and Q_{ha} in Figure 4.

At the fault crossing (i.e., between stations 1+320 and 1+349), the pipe is underlain by Holocene alluvium. Native soils exposed at the excavation pit (Figure 4) consist of medium stiff, dark brown clay and silty clay. When visited, there was some standing water at the bottom of the excavation pit, which may represent either groundwater, pipe leakage or recent rainfall accumulations. In any case, groundwater is likely to occur at shallow depth in the small alluvial valley at the fault crossing. Laboratory testing was performed on three hand collected samples from the excavation pit to document the main soil conditions near the pipeline: Native clay soil (clay to silty clay with sand and fine gravel); Compacted backfill (mixed native clay soil and bedding); Granular bedding (well graded gravel with silt and sand).

Results from the lab testing show that the native soils immediately south of the fault crossing consist of medium stiff, fat clay (CH) to silty clay with sand and fine gravel, and have a Plasticity Index of 52% to 38%. A three point direct shear test was performed on the native clay soil sample, and indicates peak shear strength of about 44 kPa (= 920 psf) at a normal stress of 29 kPa, and effective stress parameters of $\phi' = 30 – 32°$ and c'=28 to 31 kPa (= 585 to 650 psf). Pocket penetrometer soundings in the trench wall and backfill clay soil indicated unconfined compression strength values of between 38.6 kPa to 76.5 kPa.

Pipeline Structural Analysis

A series of structural analyses were performed to simulate the performance of the pipeline at the fault crossing. A comprehensive treatment of the analyses is provided in (Eidinger 2001). The ANSR-III computer program was used. Major features of the model were as follows: The total length of pipe in the model was 1,400 feet. Each segment of the pipeline was modeled using 3-dimensional distributed plasticity ANSR type 6 elements. In the transverse and axial directions, the soil was modeled using 3-dimensional nonlinear truss ANSR type 1 elements. The elements use bilinear load deflection curves. In the vertical direction, the soil was modeled using 3-dimensional nonlinear 2-node, 1-degree-of-freedom gap ANSR type 5 elements. Two elements were used to model the upwards and downwards motions, reflecting the differences in soil behavior in those directions. Large geometry effects were included in the analyses.

The maximum displacement imposed on the south side of the model was +3 meters (=118.08 inches). The north side moves easterly and southerly relative to the south side. X (pipe axial direction in pre-earthquake alignment) movement = 118.08 cos 55° = -67.728 inches. Z (direction transverse to the pipe axial direction) movement = 118.08 sin 55° = -96.676 inches. The analysis was run as a static nonlinear displacement loading. The total ground offset of 118.08 inches was applied in 1,000 to 3,900 equal steps, using equilibrium iteration.

Soil springs were attached to each pipeline element. The spacing of the soil springs was based upon the length of the pipeline element. Formulations for the soil properties are provided for the three orthogonal directions. These soil properties were incorporated into the model using the bilinear (or trilinear) soil spring models following methods described in (ASCE 1984).

To establish soil springs for the analytical models, some assumptions were made about the in-situ soils and soil failure planes. For transverse loading of the pipeline it was assumed that the native clay type soils beyond the pipe trench would fail in a triangular shape; and that an average undrained shear strength of that clay soil could be based on the field data for native alluvial clays of c = 4.6 psi and $\phi = 30°$. These soil properties were taken from an excavated location where the pipeline begins to slope up rather steeply, and this soil condition might not be applicable to the soils in the flat creek basin. Assuming a soil density of 120 pcf, and 6.33 feet of cover, then the undrained shear strength of the clay is S_u = 1,540 psf. Lower and upper bound shear strength properties are taken as 1,000 and 2,000 psf, respectively.

The depth of cover of soil above the top of the pipe was not measured in the field, but was designed to range between 1.335 to 1.775 meters per the design drawings.

Based on the field survey, it was apparent that the soils in creek bottom area were softer than those in the southerly terrace area. Native soil properties in the creek bottom area were assumed to be one-half those in the terrace area.

Results from 4 analytical models are presented in Table 1. A note of explanation is needed to understand the meaning of the predicted peak pipe strains and distance between wrinkles, listed in Table 1. By "peak pipe strain", it is meant the predicted strain in the pipe, assuming that the pipe does not wrinkle. In other words, we present the simplified predictions, ignoring the complicating effects of wrinkling. In actuality, the nominal strain at which this particular pipeline would wrinkle is in the range of –0.3% to –1.0% (perhaps even slightly higher). Once the first wrinkle begins to form, the pipe bending moment will be limited or in fact unload, as the pipe section sheds stiffness due to the formation of the wrinkle. The actual strain within the wrinkle will be substantially higher than that listed in Table 1, owing to large bending in the wrinkles. It is maximum tensile strain within the wrinkle that actually causes tearing of the pipe.

Table 1. Analytical Models 1, 2, 3 and 4, and Actual Observations

Model	Soil Stiffness	Cover	Soil Properties along Length	Peak Pipe Strains	Distance Btw Wrinkles
1	Lower Bound	Average	Constant	+2.6% / -9.8%	33 feet
2	Upper Bound	Average	Constant	+4.7% / -14.6%	27 feet
3	Lower Bound	Lower bound	Constant	+2.5% / -9.5%	39 feet
4	Lower Bound	Lower bound	Asymmetric	+3.0% / -9.6%	45 feet
Actual			Asymmetric		55 feet

Figure 6 shows the variation of bending moment along the length of pipeline nearest the fault, from model 4. The asymmetric location of the points of highest bending moment conform approximately to the observed locations of wrinkles of the actual pipe at stations 1+320 and 1+337. Model 4 predicts a distance between major wrinkles of 45 feet. The actual distance between major wrinkles was 55 feet. Adjustments to the computational model (modifying soil properties downward, adjusting pipeline strength properties upwards) would allow "perfect" agreement of the distance between the wrinkles.

Figure 7 shows the variation of tensile and compressive longitudinal strains in the pipeline, as predicted from model 4. Strains above yield are limited to about 130 feet either side of the fault. The model shows that there should be secondary points of high bending moment and strains either side of the fault. In the actual pipe, there was a minor wrinkle at station 1+349, or about 40 feet from the wrinkle at station 1+337. The analytical model would predict a wrinkle forming about 58 feet away from station 1+337.

More detail modeling of the pipeline could be done to demonstrate the post-wrinkled behavior of the pipeline. This is easily accomplished using "pipe" type nonlinear elements by inserting a suitable moment unloading element into the complete pipe model, being activated just at the point where initial wrinkling occurs. The formulation of such an unloading element and evaluation of the actual tensile strains within the wrinkle can be done using three dimensional finite element models, described in (Eidinger 1999).

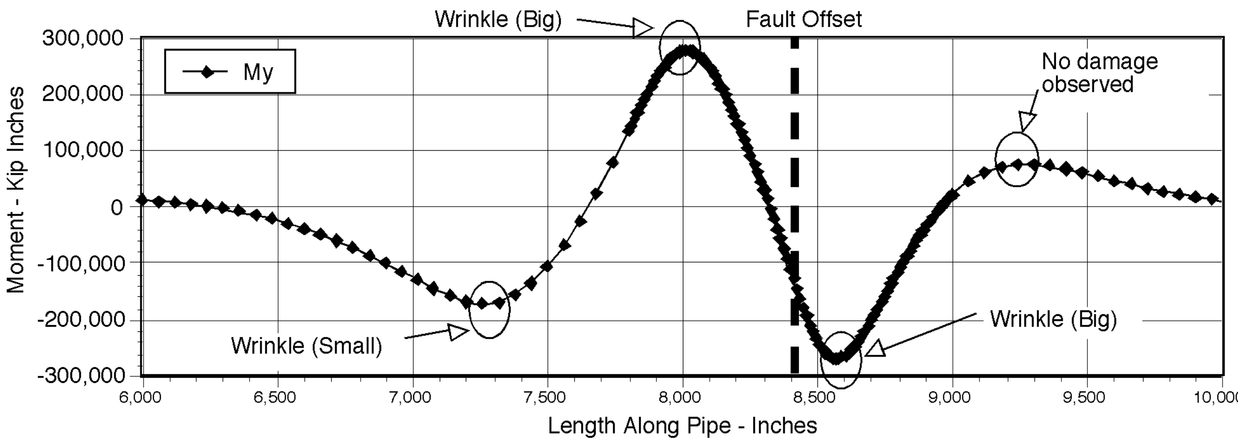

Figure 6. Variation of Bending Moment along the Pipeline Near the Fault, Model 4

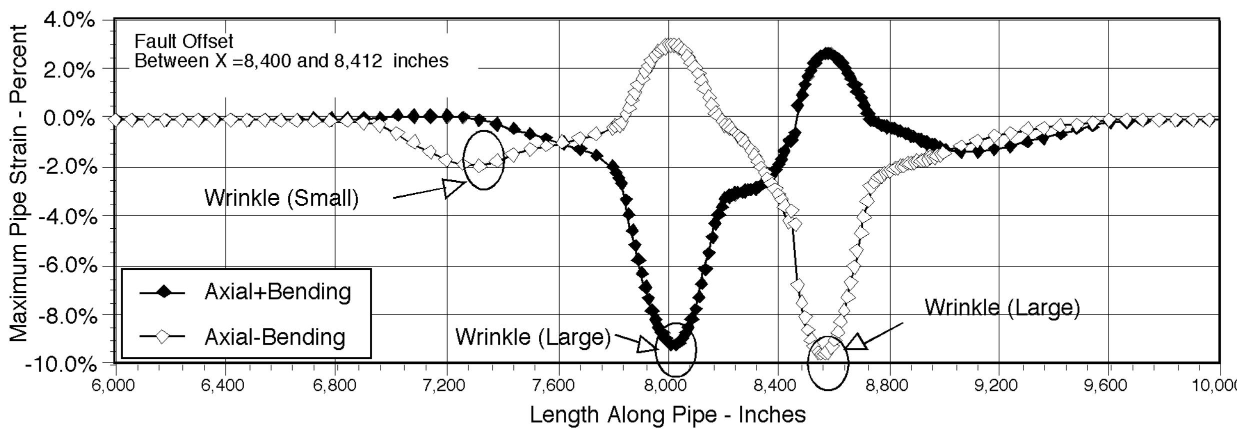

Figure 7. Variation of Strain along the Pipeline Near the Fault, Model 4

Design Implications

Pipeline alignment at a fault crossing is a top priority consideration for design. The pipe should be ideally laid out to create net tension (with very limited compression due to bending) within the pipe for the expected range of fault offset. This particular pipeline violated this principal.

The choice of pipeline material is also a top priority consideration. The use of prestressed concrete or other brittle pipe should be avoided at fault crossings. Damage to such pipe may be spectacular, resulting in total loss of flow, and possible serious inundation issues. Properly designed, mild steel pipe can withstand meters of fault offset without rupture of the pressure boundary. Use of "flex joints" at fault locations can be problematic: if the joints are placed too far apart, then the intermediate pipe will fail in bending; if the joints are placed too close together, the joints will "lock up" and fail at too small an offset; if the fault zone is more than 10 to 30 feet wide, many joints are needed to allow for uncertainties in the fault offset patterns.

If the acceptance criteria were to keep the pipe from initiating a wrinkle, then the Thames Water design for this fault offset fails. This type of acceptance criteria has sometimes been used for the seismic design of pressurized gas or oil pipelines where they cross faults.

Since the release of water from a water pipeline is usually not so hazardous as the release of gas (potentially explosive) or oil (severe environmental impacts), it might be prudent and cost effective to establish allowable criteria for water pipelines that allow for some level of wrinkling. This might allow that the amount of wrinkling be not so severe such that the tensile strains within the wrinkled section are limited to a percentage of the ultimate uniform strain of the steel. For probable earthquakes, this might be +5%, and for maximum earthquakes, this might be +10%. These tensile strain limits within the wrinkle reflect that it is desired to retain some factor of safety in the design to accommodate for uncertainties in the analysis, and possible flaws in the steel. The water system operator could allow strains above this point if the consequences of pipe failure were acceptable (like redundancy in the water system), or post-earthquake emergency response procedures (like rapid installation of bypass pipelines) were acceptable.

In practice, the 2200 mm pipeline did leak at a rate of about 1,000 gpm at one of the wrinkles. This flow rate is similar to that from a fire hydrant, and is not too serious in terms of life safety or erosion impacts to this particular fault crossing site. This level of pipeline performance might be considered "acceptable" for the circumstances in Turkey. However, a repeat impact of fault offset to this pipeline (or the replacement pipelines) would probably also cause wrinkles, and the amount of tearing at the wrinkles could be higher than what actually happened to the 2200 mm pipeline in the 1999 event.

Measures

Both US and SI units of measure are presented in this paper. Distances are described in meters, millimeters (mm), feet and inches. Flows are described in gallons per minute (gpm). Pressures and stresses are described in kips (kilo-pounds) per square inch (ksi), pounds per square inch (psi), pounds per square foot (psf), newtons per millimeter squared (N/mm^2), kilo pascals (kPa). Density is in pounds per cubic foot (pcf). Bending moment is in kip-inches. There is no preference for units, other than a desire to communicate information.

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