FATIGUE DAMAGE CALCULATIONS FOR A DENTED AND OVALLED SECTION OF THE TRANSALASKA PIPELINE SYSTEM AT THOMPSON PASS

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ABSTRACT

During the summer of 1996, the TransAlaska Pipeline System (TAPS) experienced vibrations in a section of the pipeline near Thompson Pass, north of Valdez, Alaska. Alyeska Pipeline Service Company, operator of TAPS, initiated an extensive investigation, and determined that the vibrations were caused by pressure pulses originating near a slackline-packline interface. The pressure pulses are thought to have been caused by the collapse of vapor bubbles trapped in the flow. The vibrations occurred only when the interface was positioned near a terraced portion of the pipeline topography on the downstream side of the pass. This knowledge allowed Alyeska Pipeline to control the vibrations by back-pressuring the pipeline to move the slackline-packline interface well above the terrace location.

1. OVERVIEW

This paper describes a framework for fatigue damage calculations that was applied to a dented and ovalled section of TAPS pipe buried in the terraced section that was apparently triggering the pressure pulses below Thompson Pass. The main concern at this location was that, as each pressure pulse passed, the ovalled and dented pipe section tended to "re-round" itself, causing the pipe wall to flex a small amount. Since the pulses occurred as often as 20 times per minute, there was a concern for possible fatigue damage to the pipe.

The unique features of this investigation included (a) the use of pressure pulse measurements at remote gate valves (RGVs) downstream of the terrace location, (b) the use of pipeline geometry and corrosion data from smart pigs that are regularly run through the pipeline, (c) detailed finite element models of the dented and ovalled pipe including the effect of soil restraint to estimate the maximum stress range due to pressure changes, (d) incorporation of historical pipeline operation (flow) data to establish reasonable histograms of past and projected future pressure pulse activity, and (e) fatigue damage calculations using design and decision level S-N curves. The results from this investigation were used to help Alyeska make decisions about the integrity of the pipeline. The same method can be applied to pipelines in general, considering a variety of different stress raisers and considering stress cycling due to normal operation.

The section of pipeline subjected to pressure pulses extended essentially from the top of Thompson Pass to the top of Keystone Canyon (a distance of about 8 miles). Most of this section of the pipeline has a 48-inch diameter and a 0.462-inch wall thickness. Based on a review of the TAPS as-built data base and smart pig data for this section, most areas of the pipeline between Thompson Pass and Keystone Canyon were cleared from a structural integrity point of view. However, specific pipeline "anomalies" were identified for more detailed investigation. In addition to dented and ovalled sections of pipe, the anomalies included fillet welded sleeves that were added to the pipeline since construction. The focus of this paper is an ovalled and dented section of pipe at Station 40959+40 which, because of its location and geometry, was considered the governing location for fatigue analysis.

Recent research on pressure cycling of dented pipe (Alexander, et al. 1997a, Alexander, et al. 1997b, Fowler 1993, Fowler, et al. 1995, Keating & Hoffmann, 1996, Kiefner, et al, 1996, Maxey, et al, 1993) documents the potential for fatigue damage in dented pipe subject to pressure cycling. Unfortunately, the dent research did not appear to be directly applicable to the situation at Thompson Pass. This paper describes the overall framework of the fatigue damage calculations we used to help Alyeska Pipeline make decisions about the integrity of the pipeline. Key components of the fatigue calculations are discussed in the following sections.

2. PRESSURE PULSE INTENSITY AT DENT

The first step in the process was to identify the location of the critical dent and to establish the pressure pulse intensity based on the measured pressure pulse data. The dent is located at pipeline mile post 775.8 (Station 40959+40) which is located directly in a bench-like terrace location on the south side of Thompson Pass. As described in detail in Baskurt (1998), the pressure pulses were measured at remote gate valves (RGVs) 121, 121A and 123, (at Stations 41007+56, 41117+37, and 41400+45). These locations are located roughly 5000, 16000 and 44000 feet, respectively, downstream of the lower terrace location. Based on the measured attenuation of the pressure pulses between these locations, extrapolation was used to estimate the amplitude of the pulses at locations other than RGV 121. Based on the data, the pressure extrapolation factor between RGV 121 and the critical dent is estimated to be about 1.13 (i.e., a 100 psi pulse at RGV 121 scales up to a 113 psi pulse at the dent location). More details regarding the attenuation of pulses traveling downstream from Thompson Pass are presented in Baskurt (1998).

3. DENT GEOMETRY

The next step was to determine the geometry of the critical dented and ovalled section of pipe based on smart pig caliper data. Alyeska regularly monitors TAPS using sophisticated smart pigs, including the NOWSCO GEOPIG (NOWSCO, 1995) and the VETCO deformation pig (VETCO, 1995). For the purposes of this study, the most important data is obtained from calipers that measure the radial deformation of the pipe wall cross section. The GEOPIG uses rings of sonar calipers to measure the cross section while the VETCO pig uses spring loaded metal calipers in contact with the pipe wall. A review of the VETCO and GEOPIG caliper data highlighted the dent at Station 40959+40 as the largest in the area, with a maximum vertical diameter reduction of about 1.9 inches. Representations of the dent geometry based on the GEOPIG data are as shown in Figure 3.1. The figure illustrates that the majority of the diameter reduction is due to the ovality rather than the dent.

One key aspect of the investigation was the use of pig data recorded at the dent under different pressure conditions. During some of the GEOPIG runs, the backpressure was intentionally increased, in order to provide tightline conditions at Thompson Pass. This prevents the pig from "free falling" down the steep hillside, which has a maximum pitch of 50 degrees. One consequence of the increased backpressure is that the static pressure at the critical dent location was approximately 450 psi when the pig passed. This is approximately 400 psi higher than the estimated 50 psi static pressure at this location during typical operating conditions. As the next step, therefore, we studied data from a number of VETCO pig runs made under slackline conditions in great detail and compared them to GEOPIG runs made under tightline conditions. This effort indicated that the vertical diameter change (ΔD) between slackline and tightline conditions appears to be on the order of 0.23 inches for a pressure change (ΔP) of 390 psi.

4. FINITE ELEMENT MODEL OF DENT

Industry research on pressure cycle testing of dented pipe is usually focused on dents that are deeper (typically 5% to 20% of the pipe diameter) than the dents in this study (the maximum dent plus ovality is about 4% of pipe diameter). The pressure cycles are also generally larger (typically 500 to 1000 psi) than those in this study (maximum 200 psi). The number of cycles in the experiments are lower than those anticipated for the present study (most experiments are stopped after roughly 100,000 cycles). Very little of the dent research has been conducted on pipe with TAPS D/t ratios (D=48 inches, t=0.462 inches, D/t=104) or with X65 pipe materials. Unfortunately, most of the experiments do not include the effect of radial soil restraint on the behavior of the dent. Soil restraint is known to have a significant effect on the behavior of the cross section. Some of the more recent experiments on dented pipe have attempted to address the issue of restraint of the dent (Keating, 1996). The results indicate that with all other factors being equal, restrained dents have a substantially longer fatigue life than unrestrained dents.

Faced with these limitations, the project team decided to utilize finite element analysis models of the dented region to further investigate the integrity of the pipe at this dent. Finite element models of a pipe stub containing the dented region were developed based on detailed GEOPIG sonar measurements of the dent geometry. The FACTS (SSD, 1991) program was used to conduct the analyses. The dented stub models are based on three-dimensional shell elements with eight nodes, four at the inner surface of the pipe and four at the outer surface of the pipe, with three degrees of freedom (DOFs) per node. This element, which is applicable to thin and moderately thick shell elements, allows for thickness variations and accounts for large deformations. More details regarding this element can be found in Kanoknukulchai (1978). Any point in the shell is assumed to be in a state of plane stress, considering in-plane normal stresses and membrane shear stresses. The element has the capability to include a nonlinear material model, however, elastic material was assumed for the purposes of estimating the stress range. An example mesh for a FACTS stub model is shown in Figure 4.1.

In addition to the shell elements, the FACTS models included various patterns of small spring elements distributed around the pipe circumference to simulated the effect of external soil restraint on the pipe section. These horizontally and vertically oriented springs connected each node on the outside surface of the stub mesh to fixed "ground" reference points surrounding the pipe. Examples of assumed soil spring patterns are illustrated schematically in Figure 4.2. In order to obtain soil restraint assumptions that were consistent with the smart pig measured pressure and diameter changes (ΔP and ΔD), the approach that we used was to assume physically reasonable soil support patterns and vary the soil spring stiffness for different patterns to find the stiffness for which the calculated diameter change for a 390 psi pressure change is about 0.23 inches. Typically, we performed enough analyses to bound the desired diameter change fairly closely, then interpolated to obtain both the soil stiffness and the stress range. If the required soil stiffness value is reasonable, we conclude that the assumed soil support pattern is a possible one. If the required soil stiffness is clearly too high or too low, that pattern was excluded from consideration.

Since we did not know the actual in-situ support conditions, it was necessary to consider a number of reasonable patterns, and to use the pattern giving the largest stress range for the fatigue life calculations. For each pattern, the key variable is the uplift soil stiffness. In all cases, the bearing and lateral stiffnesses were assumed to be multiples of the uplift stiffness. Based on initial studies, we estimated that a reasonable value for the uplift stiffness is around 20 lb/in^2 per inch. We consider required values larger than about 80 lb/in^2 per inch or smaller than about 5 lb/in^2 per inch to be unreasonable. Case D, which was determined to be the key pattern, is described as follows:

Case D: Uplift support over entire top half of the pipe; horizontal support over the entire side of pipe with a stiffness 32 times the uplift stiffness; and bearing support over the entire bottom of the pipe with a stiffness equal to 50 times the uplift stiffness.

Each of the assumed soil support patterns included a very stiff "footprint" of springs near the bottom of the pipe section centered on the dent region. This pattern was selected because the evidence suggested that the dent was caused by the pipe bearing down on a "hard spot". The hard spot was thought to be either a rock or a piece of timber cribbing that was left in the trench under the pipe when it was backfilled during construction.

The analysis approach implemented involved an elastic analysis of the dented stub model for a simulated internal static pressure increase of 100 psi. Since the geometry of the pipe cross section changes as the pressure changes, the analysis accounts for large displacement effects. The key result from each analysis was an estimate of the elastic circumferential and axial stress changes that occur on the inner and outer surfaces of the pipe due to the 100 psi pressure increase. This approach avoided the difficulties associated with successive trials of loading models with an initially circular cross section into the ovalled and dented cross section, which could in general require that nonlinear material behavior be considered. We believe that this is an appropriate and practical approach since the key result for fatigue calculations is an elastic stress range. Even if some local yielding of the pipe wall occurred in order to obtain the buried dent geometry, the response to the relatively low amplitude pressure pulses will shake-down to elastic behavior. The pressure induced stress changes were decomposed into a vector (S) of longitudinal and circumferential membrane and bending components for use in the fatigue damage model.

5. HISTORICAL FLOWRATE DATA

The pressure pulse data recorded during the Thompson Pass slackline tests (Baskurt, 1998) indicated that, under normal backpressure conditions, the pulses only occurred when the flowrate dropped below about 1.4 MMBPD. For almost the entire time period between 1980 and 1995, the TAPS flowrate was above 1.4 MMBPD, and there were no reports of pressure pulses. Flow rates were below 1.4 MMBPD from startup through October, 1979, and they have also been below this value in recent years, as the amount of oil flow has progressively declined. The longest periods of relatively low flow occurred prior to 1980.

Using flow rates based on extrapolation of existing flows into the near future and re-constructions of pre-1980 data, the length of time that the pipeline operated at any given flow rate during any one year period was computed.

6. FLOWRATE-PULSE INTENSITY RELATIONSHIPS

In order to conduct fatigue damage calculations at the dented and ovaled section of pipe, a relationship between pressure pulse intensity and flow rate is required for a range of flow rates covering past and future operating conditions.

As described in Baskurt (1998), the relationship between pulse pressure and frequency of occurrence can be represented using a lognormal statistical distribution. A pulse intensity histogram was developed based on a combination of 8 individual events recorded at RGV 121. The pressures were scaled by an extrapolation factor to obtain the pulse histogram at Station 40959+40. This distribution is completely defined by a mean pulse pressure and a standard deviation from the mean. The distribution has a lower bound of zero and, in theory, no upper bound. Two key values that can be calculated for this distribution are (1) the mean pressure and (2) a "97.7% confidence" pulse pressure. No more than 2.3% of the pressure values will exceed this "confidence" pressure. For each event recorded the log-normal distribution was computed and plots of the mean and 97.7% confidence pulse pressures as a function of flow rate were developed at Station 40959+40.

As shown in Figure 6.1, two relationships between flow rate and pulse intensity were considered.

(1) *Relationship 1*. This relationship is based on the conservative assumption that the pulse intensity is the same for all flow rates ranging from zero to 1.4 MMBPD.
(2) *Relationship 2*. This relationship assumed smaller pulse intensities at the ends of the range. For flow rates between zero and 0.3 MMBPD, and between 1.2 and 1.4 MMBPD, we assumed uniform steps to reduced (e.g., 2/3 or 1/3) pulse intensities.

Figure 6.1 compares the assumed pressures with the measured pressures as a function of flowrate, using the mean and 97.7% confidence pressures at Station 40959+40. This figure indicates that the assumed relationship between flow rate and pressure pulse intensity is conservative for essentially all flow rates.

7. DAMAGE CALCULATIONS

Using the relationships described in the previous sections, the fatigue damage calculation steps are as follows.

(1) As described in Section 2, identify the location of the dent, and establish the pressure pulse extrapolation factor required to scale the pressures recorded at RGV 121 to the dent.

(2) Determine the geometry of the dent (as described in Section 3). As described in Section 4, construct finite element models of the dented region, for various soil restraint assumptions. Use static finite element analysis, calculate the maximum stress range for a 100 psi internal pressure increase.
(3) Choose a range of flow rates and for the flow rate at the middle of this range, obtain a relative pulse intensity value as illustrated in Figure 6.2.
(4) Using the relative pulse intensity value, and using statistical distribution of pressure pulses, process the probability density function to obtain a histogram of pulse pressure versus number of occurrences per hour for the chosen flow rate. The number of occurrences can be scaled to any other time period, for example one year. We refer to each pressure range in the histogram as a "bin". For each bin we have a pulse pressure (at the midpoint of the bin) and a number of pulses per hour. The width of each bin is 5 psi pulse pressure.
(5) Convert the pressure histogram to a stress range histogram, using the analysis results from Step (2). For example, if the pulse pressure for a given bin is 80 psi, the stress range is the calculated 100 psi stress range from Step (2) multiplied by 80/100. This calculation assumes that the stress range is proportional to pressure. This was confirmed by analysis for pressures in the range 50 to 150 psi.
(6) Using the pipeline flowrate data described in Section 5, consider each year of pipeline operation. Choose a one year time period and estimate the number of days that the pipeline operated at the flow rate chosen in Step (3). Convert the stress range histogram to this number of days. The histogram now gives stress range (S) versus number of cycles (N) for the chosen flow rate and year.
(7) Using a S-N fatigue curve, calculate the cumulative damage for the chosen flow rate and year. The details of the multi-axial fatigue calculations are summarized in Stevick (1998). The cumulative damage for any bin in the histogram from Step (6) is the number of stress cycles in the bin divided by the number of cycles to crack initiation given by the S-N curve. The cumulative damage for the chosen flow rate and year is the sum of the damage values over all bins.
(8) Repeat from Step (6) for each year of operation. This can include projections for future years.
(9) Repeat from Step (3) for a different flow range, ultimately covering all flow rates for all years of pipeline operation.
(10) Sum the cumulative damage values for each year of operation.
(11) Sum the cumulative damages for all years of operation up to any given year, to obtain the cumulative damage at the end of that year.

The steps described above were applied to investigate the effect of the slackline induced pulses on the dented and ovalled pipe at Thompson Pass. However, the general analysis framework is valid for analysis of the fatigue capacity of other anomalies (such as dents) in other pipelines subject to operational cycles.

8. OBSERVATIONS AND CONCLUSIONS

The calculated stress ranges vary with the assumed soil support conditions. Since we did not know the actual in-situ support conditions, it was necessary to consider a number of reasonable patterns, and to use the pattern giving the largest stress range for the fatigue life calculations. Our "best estimate" soil support cases are referred to as Cases D1 and D2. We believe that Case D2 is definitely conservative, and that Case D1 is probably conservative.

Calculated fatigue damage also depends on (a) the relationship between flow rate and pulse intensity, and (b) on whether a "design" level or "decision" level S-N curve (see Stevick, 1998 for more details) is used. We first considered a design level S-N curve, to draw conclusions on whether or not the pipe satisfies the type of design criteria that might be used for new pipeline design. We then considered a decision level S-N curve, to draw conclusions on what short term measures needed to be taken to ensure the structural integrity of the pipe. We chose what we believed to be the most reasonable set of results for decision making.

Table 8.1 presents the calculated cumulative damage through the end of 1996 without flow management and without any backpressure modifications, for two S-N curve types, two estimated relationships between flow rate and pulse intensity, two assumptions for the relative pulse intensity for years before 1980, and support cases D1 and D2. In each case the calculated cumulative damage is shown through the end of 1996, and beside it, in parentheses, the percentage of this damage incurred through the end of 1979. The following observations can be made.

(1) We believe that the "uniform" relationship between flow rate and pulse intensity is too conservative, and that the "stepped" relationship is more reasonable.
(2) We believe that soil support Case D2 is too conservative, and that Case D1 is more reasonable, but probably also conservative.
(3) Considering factors such as viscosity, volatility and operating temperature, we believe it is reasonable to assume that the pulses were relatively less intense in the years prior to 1980 than for the same flow rates in 1996.
(4) Using the "design" level S-N curve, cumulative damage ratios exceeding 1.0 are calculated only for the cases with the most conservative assumptions.
(5) For the same pulse intensity prior to 1980 as in 1996, a conservative estimate of the cumulative fatigue damage at the end of 1996, using the design S-N curve, is 1.18, with 91% of the damage occurring prior to 1980. For this value of accumulated damage, there is a very small probability that a crack has initiated at the critical dent location.
(6) For a reduction in pulse intensity to 90% prior to 1980 (with the same pulse frequency of occurrence), the calculated damage at the end of 1996 using the design S-N curve reduces from 1.18 to 0.57, with 82% of the damage occurring before 1980. For a reduction to 80%, the calculated damage reduces to 0.18, with 38% occurring before 1980.
(7) For the "decision" level S-N curve, the calculated damage values are one fifth to one sixth of the values for the "design" curve. The calculated damage is no more than 0.21 for any reasonable cases.

Our "best estimate case" was based on a stepped relationship between flow rate and pulse intensity (Relationship 2), soil support Case D1, and a 10% reduction in relative pulse intensity for years prior to 1980.

For these assumptions, the cumulative fatigue damage at the end of 1996 for the design level S-N curve is 0.57. This means that at the end of 1996, the pipe at the critical dent satisfies the type of design criteria that might be used for the design of a new pipeline. The results at the end of 1996 were the most important since this was the approximate time when backpressure modifications were installed at Valdez to eliminate the pressure pulses at Thompson Pass. Additional calculations were performed to increase the cumulative damage beyond that calculated at the end of 1996 to consider normal period operational shutdown-startup pressure cycling with the backpressure system installed. The analysis suggested that with the pressure pulses stopped, the pipe has an effective remaining design life of about 63 years at this location.

If the pulses were allowed to continue without flow management and without any backpressure modifications, the corresponding "best estimate" of cumulative fatigue damage at the end of 1997 for the design level S-N curve was 0.79. Similarly, using the "best estimate" assumptions, the cumulative fatigue damage at the end of 1998 for the design level S-N curve was 1.52. Using the same set of assumptions with a "decision" level S-N curve, the corresponding cumulative damages at the end of 1997 and 1998 are 0.13 and 0.26, respectively. These values are one fifth to one sixth of the values for the "design" curve.

We put forward the following conclusions at the completion of the project in January 1997.

(1) For reasonable assumptions about the amount of soil restraint and the pulse intensities, the cumulative fatigue damage for the design level S-N curve was no more than 0.6. This is based on the stepped relationship between flow rate and pulse intensity, soil support Case D1, and a 10% reduction in relative pulse intensity for years prior to 1980. For this case the calculated damage was 0.57. This means that at the end of 1996, the pipe at the critical dent satisfied the type of design criteria that might be used for the design of a new pipeline.

(2) In order to get a cumulative fatigue damage value larger than 1.0 for the "decision" S-N curve, it was necessary to make extremely conservative assumptions (a uniform relationship between flow rate and pulse intensity, soil support Case D2, and no reduction in pulse intensity for years prior to 1980). This means that there was no need to consider immediate excavation and repair of the pipe.

(3) For a cumulative fatigue damage of 0.6, the static strength of the pipe is essentially unimpaired. This means that if the pressure pulses were stopped in the near future as planned, the pipe at the critical dent location was essentially undamaged for future operating conditions.

A technical peer review by the Joint Pipeline Office, a joint federal/state oversight agency, confirmed the analysis performed by Alyeska and supported Alyeska's conclusions.

9. FOLLOW UP FIELD INVESTIGATION

Although the pipe was deemed to be stable and safe from the integrity analysis, Alyeska elected to perform an inspection of the ovaled and dented area at pipeline milepost 776 to verify the fatigue analysis and to confirm, by testing, some of the key assumptions made in the computer model about pipe support and geometry. The site was excavated in July 1997. The excavation also allowed investigation of the cause of dent and allowed Alyeska to make repairs if necessary.

Leak detection and environmental monitoring equipment were installed at the area of concern in November 1996 and continued to operate until the pipe excavation commenced. No indications of a hydrocarbon release were detected except for abnormal readings recorded in November 1996, which resulted in a contingency response and subsequent determination that the elevated readings were a false alarm. No evidence of an old spill or leak was detected during the excavation in July 1997.

The pipe was found to be resting on bedrock in two areas. This apparently was the cause of the dents. The rock was removed by hand and jackhammer to provide at least 18 inches of clearance for pipe inspection and re-application of epoxy coating for corrosion protection.

Static pressure in the line at the dig site was increased from approximately 150 psi to approximately 450 psi during the excavation to minimize vibrations and to facilitate re-rounding of the ovaled and dented areas. The pipe is rated to be operated at 901 psi. Over the course of the excavation, the pipe almost completely rebounded to a circular cross section.

The pipe was examined by wet fluorescent magnetic particle methods that could reveal microcracks on the outside surface of the pipe and also by non-destructive ultrasonic methods that examine the interior of the pipe wall for crack features. No evidence of fatigue damage or cracking was found, confirming the main conclusions of our analyses.

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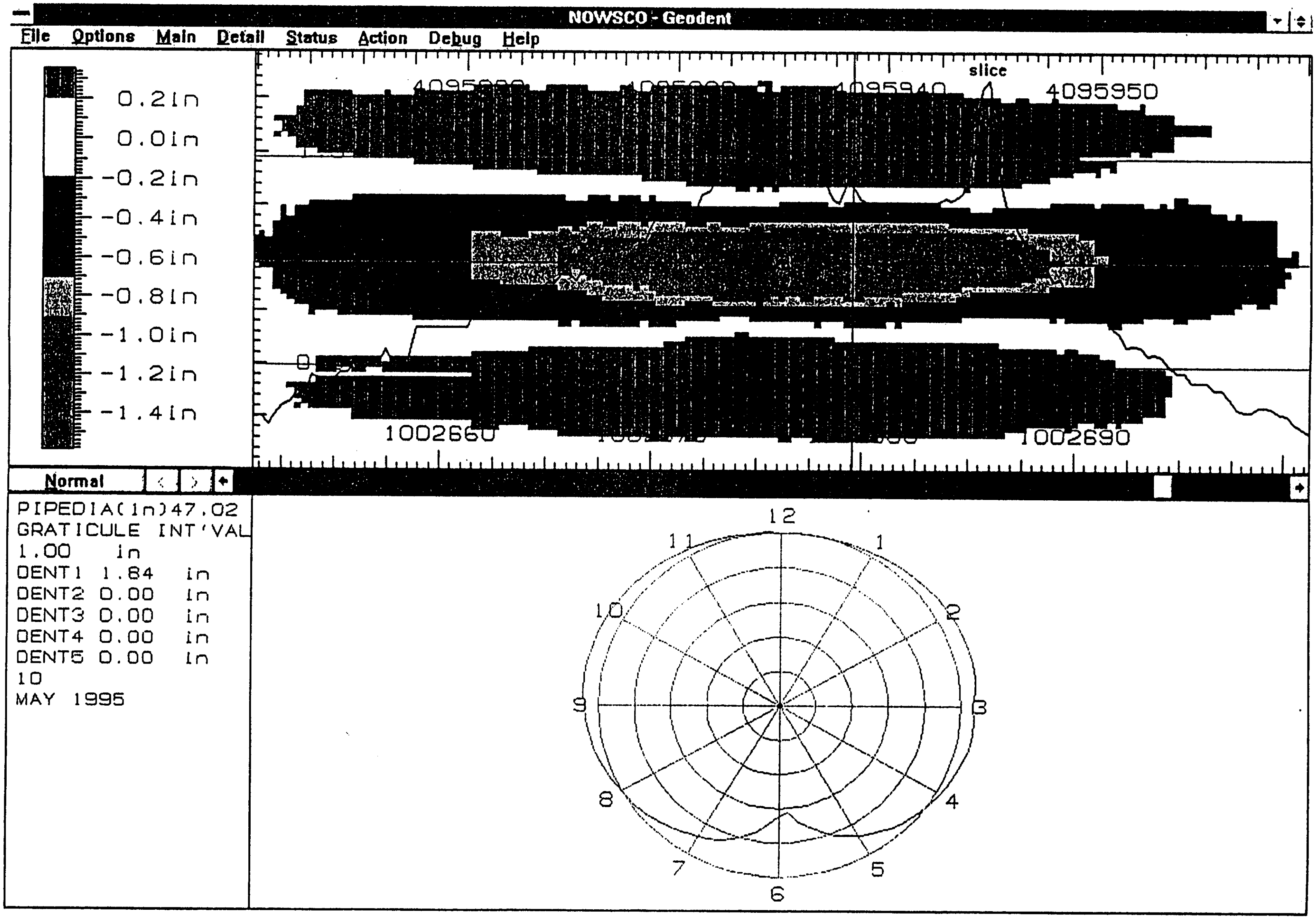
Table 8.1 Calculated Cumulative Fatigue Damage Through 1996 Dent/Ovality at Station 40959+40

S-N Curve Type	Pulse Intensity vs. Flow Relationship	Pre-1979 Pulse Intensity	Post-1979 Pulse Intensity	Case D1 1996 (1979%)	Case D2 1996 (1979%)
Design	1 (Uniform)	1.0	1.0	4.40 (72%)	7.60 (72%)
	2 (Stepped)	1.0	1.0	1.18 (91%)	2.05 (91%)
		0.9	1.0	0.57 (82%)	1.02 (81%)
		0.8	1.0	0.18 (38%)	0.31 (42%)
Decision	1(Uniform)	1.0	1.0	0.80 (73%)	1.46 (72%)
	2 (Stepped)	1.0	1.0	0.21 (90%)	0.39 (90%)
		0.9	1.0	0.09 (78%)	0.17 (82%)
		0.8	1.0	0.03 (46%)	0.06 (42%)

Figure 3.1 Section Plot of Dent/Ovality Anomaly at Station 40959+40



```
PIPEDIA(in)47.02
GRATICULE INT'VAL
1.00   in
DENT1  1.84   in
DENT2  0.00   in
DENT3  0.00   in
DENT4  0.00   in
DENT5  0.00   in
10
MAY  1995
```

Figure 4.1a Thompson Pass Initial Dent Geometry (DRx5)

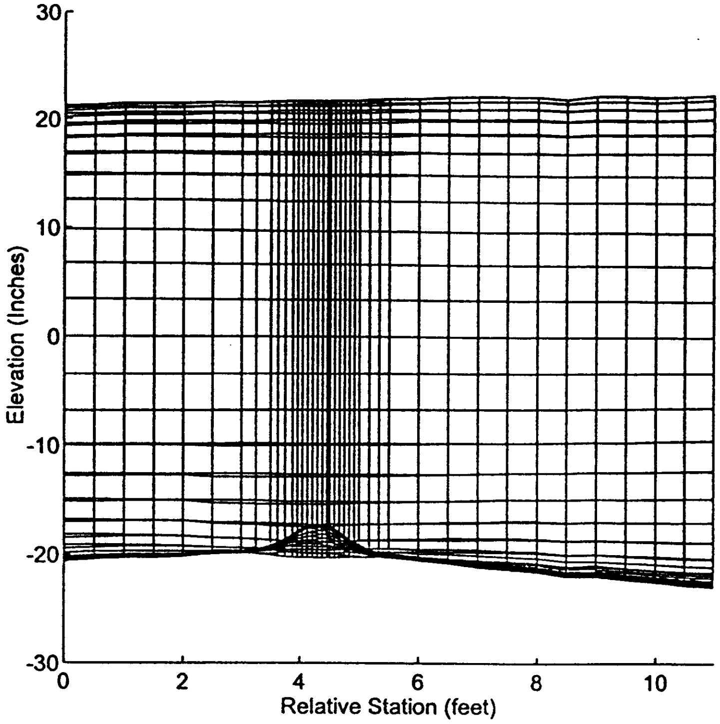
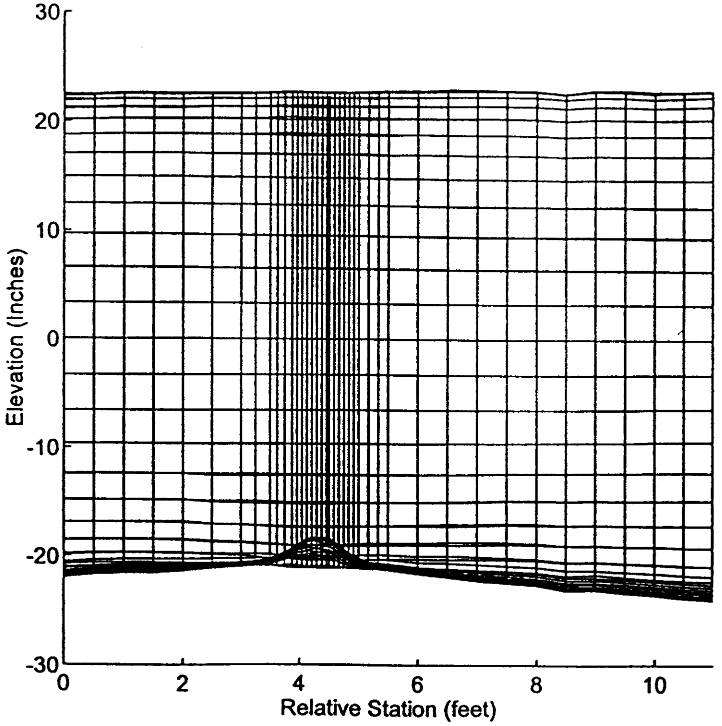


Figure 4.1b Thompson Pass Dent Geometry With 100 psi Pressure (DRx5)



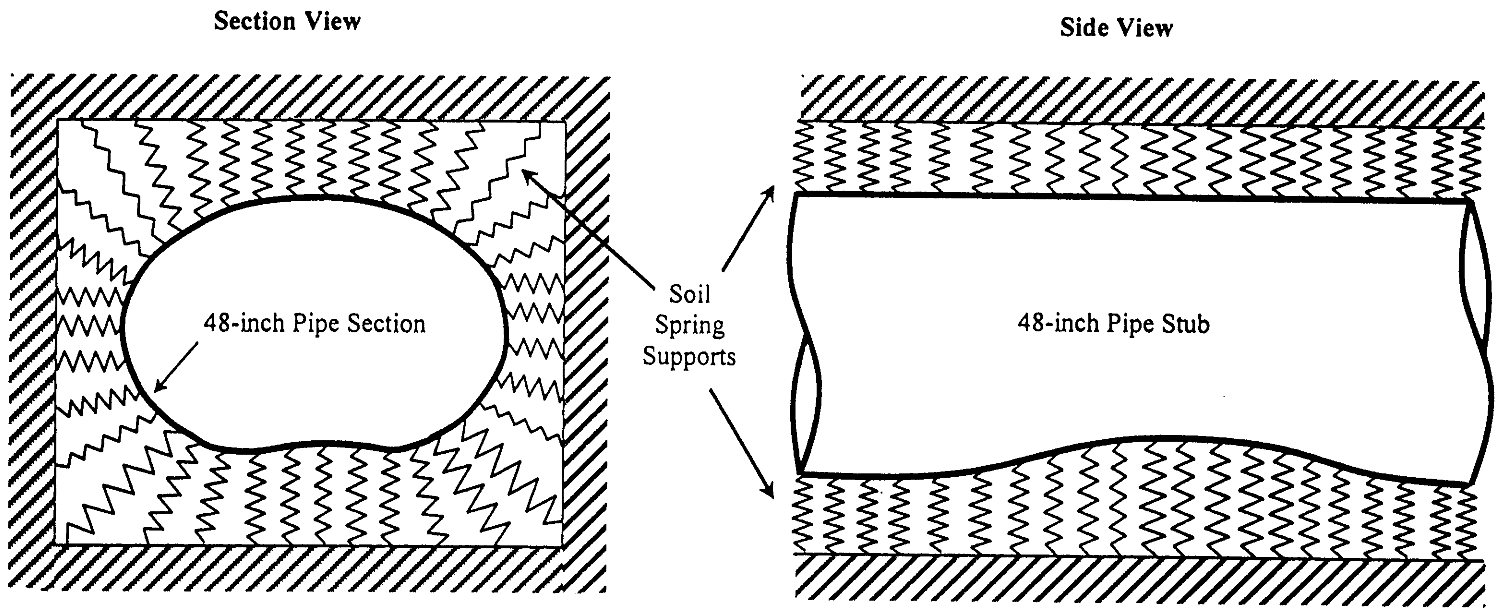


Figure 4.2 Schematic of Soil Springs Restraining Ovalled and Dented Pipe Stub