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A UNIQUE PIPELINE FAULT CROSSING DESIGN FOR A HIGHLY FOCUSED FAULT

James D. Hart
President
SSD, Inc.
Reno, Nevada, USA

Nasir Zulfiqar
Project Engineer
SSD, Inc.
Reno, Nevada, USA

Chih-Hung Lee
Senior Consultant Engineer
Pacific Gas & Electric Company
Walnut Creek, California, USA

Frank Dauby
Senior Pipeline Engineer
Pacific Gas & Electric Company
Walnut Creek, California, USA

Keith I. Kelson
Principal Geologist
William Lettis & Associates, Inc.
Walnut Creek, California, USA

Christopher Hitchcock
Senior Geologist
William Lettis & Associates, Inc.
Walnut Creek, California, USA

ABSTRACT

This paper describes the development of a unique pipeline fault crossing design upgrade for a 22-inch (559 mm) diameter Pacific Gas & Electric Company (PG&E) gas transmission line where it crosses the Calaveras fault near Sunol, California. The new design is capable of withstanding significant levels of horizontal fault offset while minimizing the deformation demands experienced by the pipeline. This unique design concept is applicable to fault crossings with well defined fault locations and highly localized fault offset profiles (e.g., for this fault, 85% of the offset is expected to occur within ±5 feet (±1.5 m) from the center of the fault trace, which was precisely located by field trenching studies).

Relative to the original fault crossing design, the new design provides a more favorable "local" fault crossing angle "β" ($\beta=73^{o}$ for the original design vs. $\beta=95^{o}$ for the new design). The angle change is accomplished by installing an offset section of the pipeline adjacent to the fault such that the fault crosses the pipeline in the middle of a tangent section in the nearest offsetting leg. The four bends used to fabricate the offset section are cold bends with an average radius of 76.4 feet (23.3 m). The entire mitigated section of the pipeline is buried in a select sand trench. For this design configuration, right lateral fault motion results in (a) a "closing" action within the two adjacent cold bends located on either side of the fault and (b) a net tension force in the pipe (due to the obtuse β value) centered on the tangent section of the offsetting leg containing the fault crossing. The net tension force in the offsetting leg results in an "opening" action within the two adjacent cold bends on either side of the fault. By adjusting the local fault crossing angle β, the "bend opening" action that results from pipe extension across the fault can be made to nearly offset the "bend closing" action induced by the transverse component of the fault offset. The use of a select sand backfill in the retrofit section allows the bends to engage the soil with relatively low transverse and longitudinal resistance thereby enhancing the overall flexibility/compliance of the fault crossing design. Implementation of this unique design concept at the Calaveras fault crossing increased the amount of fault offset required to damage the pipeline from about 7 inches (18 cm) for the "as-built" design to well over 90 inches (2.3 m) for the retrofit.

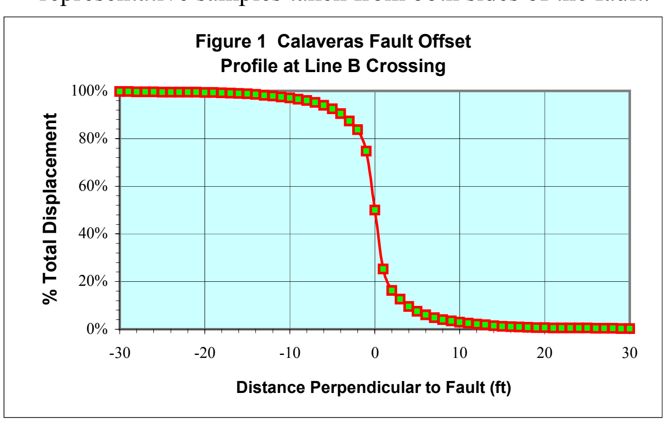
INTRODUCTION

PG&E's Line B is a 22-inch (559 mm) diameter gas pipeline that crosses the active Calaveras fault near Sunol, California. This fault crossing location was identified as a relatively high seismic hazard within PG&E's gas transmission system and was scheduled for a seismic upgrade. As part of the seismic upgrade effort, PG&E commissioned William Lettis & Associates, Inc. (WLA) to undertake a geological and geotechnical investigation at the fault crossing site. PG&E also commissioned SSD, Inc. (SSD) to perform pipeline deformation analyses to estimate the capacity of the as-built and as-modified pipeline designs to withstand significant fault offsets at this location. This paper describes our efforts in developing the seismic upgrade design and then extends the design concept for more general application.

GEOLOGIC CHARACTERIZATION OF FAULT CROSSING

The Calaveras fault near Sunol is an active feature that is expected to produce substantial ground rupture during a large earthquake. The main objectives of our effort in characterizing the Calaveras fault crossing for the Line B seismic upgrade were to (1) determine the location and width of active fault trace at the pipeline crossing, (2) evaluate the pipeline-fault crossing angle, (3) develop geotechnical data on subsurface soil conditions, (4) estimate the amount of expected coseismic surface fault displacement and (5) assess the distribution of fault displacement across the fault zone. Our investigation of the pipeline-fault crossing included compilation and review of aerial photography, field geological mapping, excavation and documentation of two trenches across the fault and soil sampling and testing (e.g., see Reference [1]). Our field characterization provided the following geologic and geotechnical input for the Line B project:

1. Line B crosses the Calaveras fault near Sunol, California. The fault at this location consists of a single active strand less than about 10 feet (3 m) wide.
2. The pipeline-fault crossing angle (β) is estimated to be 73°. The fault motion is right-lateral strike slip, which in addition to bending the pipe near the fault, subjects the pipe to a net compression force (due to the acute pipeline-fault crossing angle: $\beta=73^o<90^o$).
3. The mean expected surface fault offset is about 43 inches (109 cm). The estimated upper bound surface fault offset is about 76 inches (193 cm). These offsets correspond to a 3000 year return period or a 1.7% probability of occurence in 50 years.
4. Figure 1 shows the postulated distribution of fault offset across the fault zone. Based on fault characteristics exposed in trench excavations and on field observations made during historical ruptures throughout the world, 85% of the total fault offset at this location is expected to occur within ±5 feet (±1.5 m) of the primary fault strand. The remaining 15% of the offset is expected to be distributed equally across 30 foot (9 m) wide zones on either side of the main fault strand.
5. The native soil changes dramatically across the Calaveras fault along the Line B alignment. The native soil east of the fault consists of relatively dense silty sand and sandy gravel with cobbles, whereas the native soil west of the fault consists of relatively loose silty sand with gravel. Soil parameters were established based on laboratory tests of representative samples taken from both sides of the fault.



BURIED PIPE DEFORMATION ANALYSIS MODELS

SSD's work began with the development of buried pipe deformation analysis models of the as-built and as-retrofit pipeline fault crossing designs using their PIPLIN program [2]. The first step in the modeling was to establish the pipeline geometry and a profile of the depth of cover for pipeline alignment in the vicinity of the fault. These items were provided by a detailed field survey undertaken by the PG&E land department. The depth of cover profile was idealized as several regions with "blocks" of uniform soil cover depth. In general, the idealized profile was selected to provide an upper bound of the cover depth within each uniform depth "block" region. For the retrofit sections of the pipeline, a uniform soil cover depth of 3 feet (0.91 m) was assumed.

The next step in the modeling was to develop pipe-soil springs for the buried pipe. For the model of the as-built pipeline, the pipe-soil springs were computed based on the best estimate in-situ soil properties. The native soil on the east side of the fault had a bulk density of 120.3 lb/ft^3 (1.93 gm/cm^3), a cohesion of 1054 lb/ft^2 (50 kPa), and a friction angle of 32.2°. This soil is referred to as the "strong/east side soil". The native soil on the west side of the fault had a bulk density of 120 lb/ft^3 (1.92 gm/cm^3), a cohesion of 100 lb/ft^2 (4.8 kPa), and a friction angle of 24.5°. This soil is referred herein as the "weak/west side soil". For the retrofit sections of the pipeline, a select sand backfill and bedding material with the same properties as the "weak/west side soil" was assumed. Bilinear (elastic-perfectly plastic) pipe-soil springs were developed for all of the required soil and cover depth combinations using well established procedures described in Reference [3].

Another component of the deformation analysis model is the inelastic pipe steel stress-strain relationship. Based on SSD's previous experience with similar pipe materials and on engineering judgment, stress-strain curves were developed to represent the pipe steels to be considered in this investigation using API 5L specified minimum strengths. The existing Grade B pipe steel was assumed to have a yield stress (at a strain of 0.5%) of 35 ksi (241 MPa). The new pipe to be used for the retrofit sections is an X-60 steel with and assumed yield stress of 60 ksi (414 MPa). at a strain of 0.5%. Both of these steels were assumed to have an elastic modulus of 30,000 ksi (207,000 MPa) and strain hardening (fully plastic) modulus of 350 ksi (2,414 MPa).

PIPE DEFORMATION LIMITS

Compressive Strain Limit for Damage

The limit state for compressive axial and bending loads is governed by the maximum axial compressive strain in the pipe wall. For this study, the well recognized formula developed by Gresnigt [4] to estimate the pipe strain at the maximum moment (i.e., at incipient wrinkling) was used as the basis for computing the compression strain limit. The beneficial effect of 480 psi (3310 kPa) of internal pressure has been considered for this study. For the new 24-inch by 0.5 inch (610 mm by 13 mm) X-60 pipe, the compressive strain limit is 0.79% (assuming 1.5% ovality). For the existing 22-inch by 0.313 inch (559 mm by 8 mm) Grade B pipe, the corresponding compressive strain limit is 0.52%.

Reference Compressive Strain Limit for Bend Closing

Since several of the design alternates included pipe joints containing cold bends, a brief discussion of the compression strain limit for cold bends is warranted. Cold bent sections of pipe have been field bent to a specified "after-spring back" radius of curvature. The cold bending process induces significant levels of yielding and residual stress patterns in the pipe (e.g., a cold bend specification of 1.5 degrees per diameter corresponds to an extreme fiber strain of approximately 1.3%). During the cold bending process, the pipe cross-section is restrained from ovalling and wrinkling by the bending machine. When the cold bent piece of pipe is tied-in and subjected to seismic deformation demands, theoretical and experimental considerations indicate that the moment-curvature relationships for bend-opening action and bend-closing action can be significantly different than the moment-curvature relationship for straight pipe [5]. PIPLIN has an option to prestrain sections of pipe by cold bending. The Mroz kinematic hardening plasticity model [6] utilized by PIPLIN allows the yield surfaces for each longitudinal fiber around the pipe circumference to be shifted based on the cold bending operation. Once a section of pipe is prestrained by cold bending, its moment-curvature for subsequent loading will be altered based on the yield surface shifts. The approach used to investigate how cold bending may influence the compressive strain capacity was to establish the tangent bending stiffness from the straight pipe moment-curvature relationship corresponding to the selected straight pipe compressive strain limit (0.79%). This value was then used to determine the compressive strain limits corresponding to this same tangent stiffness from the bend opening and bend closing moment-curvature relationships. Based on analysis of cold-bent pipe stubs, it was estimated that the strain capacity associated with incipient wrinkling for bends subject to closing action could be as low as 0.3% while the corresponding strain capacity for bends subject to opening action could be greater than 1%. It should be noted that it is usual practice to neglect these potential strain capacity changes and assume that the capacity of cold bent pipe (subject to opening or closing) is the same as that for straight pipe. This is particularly true for deformation analyses that guard against loss of pressure integrity since the effect of residual stresses and strains tends to "wash out" with high levels of strain. For the purposes of this investigation, analyses results from models including cold bend segments were evaluated based on straight pipe compression strain capacity (i.e., 0.79%). However, for informational purposes, the results were also informally compared to a reference compressive strain capacity (0.3%) for bend-closing action.

Reference Compressive Strain Limit - Pressure Integrity

Note that the compression strain limits discussed above are associated with incipient wrinkling of the pipe wall and hence can be thought of as "damage" limit states as opposed to "failure" limit states. Full-scale experiments on pipe specimens (e.g., see [7]) indicate that there is a considerable difference (margin) between the compressive strain associated with the incipient wrinkling limit state and the compressive strain associated with the post-wrinkling loss of pressure integrity (i.e., failure) limit state. For example, Reference [3] provides the following formula for estimating the pressure integrity compression strain limit:

$$\varepsilon_P = 1.76 \cdot \frac{t}{D}$$

where ε_P = pressure integrity compressive strain limit, t = nominal pipe wall thickness, and D = pipe outside diameter. For 24-inch by 0.5 inch (610 mm by 13 mm) pipe, the pressure integrity compressive strain limit is 3.6% (roughly 4.5 times larger than the incipient wrinkling (damage) strain limit).

Tension Strain Limit

The overall tensile behavior of the pipeline is most likely to be governed by what happens at/near the pipeline girth welds. Well accepted procedures are available for estimating allowable tension strain limits at girth welds. These procedures require (a) information describing the size of the flaws likely to be present in/near the weld and (b) information describing the fracture toughness (e.g., Crack Tip Opening Displacement or Charpy Vee Notch) of the weld and HAZ regions.

As discussed in [8], fracture mechanics testing and analysis work performed for PG&E led to the development of allowable tension strains based on fracture toughness and flaw size for selected weld procedures and inspection methods. For the purposes of this study, a tension strain capacity of 0.75% was used for the new 24-inch diameter by 0.5-inch (610 mm by 13 mm) X-60 pipe. A lower bound tension strain capacity of 0.15% was assumed for existing 22-inch diameter by 0.313-inch (559 mm by 8 mm) Grade B pipe.

DESIGN CASES

PG&E developed a detailed plan and profile drawing based on field survey information and available as-built information for the existing Line B at the Calaveras fault crossing. This was used as the basis for developing a best estimate, "base-case" PIPLIN buried pipe deformation analysis model representation of this fault crossing. The pipeline crosses the center of the fault zone at Station 1178+40 and crosses a nearby road between Stations 1177+90 and 1177+64. The line runs essentially in a southwest to northeast alignment across the fault zone. The fault crossing model starts at a location 1268 feet (386 m) southwest of the fault crossing and terminates at a location 1342 feet (409 m) northeast of the fault crossing. For all analysis cases, the analysis results were checked to verify that the model was long enough to include the virtual anchor points on each side of the fault.

The analysis approach was to first analyze the best estimate model of the existing pipeline at the fault crossing, then to analyze a series of design alternates and to evaluate the design performance based on both the relative deformation demands and on how much fault offset was required to reach the compression and tension strain limits. In addition to the as-built configuration, a total of 7 different fault crossing designs alternates were considered. A detailed discussion of each design alternate considered is beyond the scope of this paper. Herein, the focus is on a comparison with the as-built design to the final selected retrofit design. The model configurations considered to evaluate these cases are described briefly as follows.

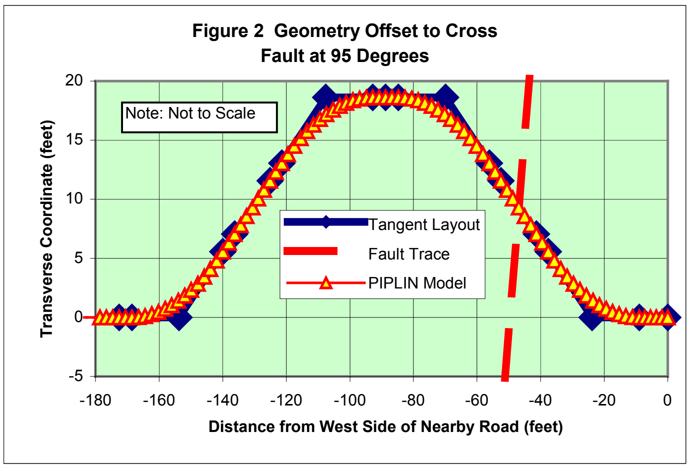
As-Built Configuration

This configuration represents the base case model of the existing 22-inch (559 mm) diameter pipeline at the Calaveras fault crossing. The pipe-soil springs are based on the "strong/east side soil" on the northeast side of the fault and the "weak/west side soil" on the southwest side of the fault. The wall thickness of the existing Line B is 0.313 inches (8 mm). The pipe material is a Grade B seamless with a specified minimum yield stress (SMYS) of 35 ksi (241 MPa). The fault crossing angle is 73°.

Final Retrofit Configuration

The final fault crossing design alternate for Line B at the Calaveras fault crossing is based on a geometry "offset" modification in the approaches to the fault such that the pipeline crosses the fault with a slightly tensile alignment (i.e., $\beta=95^o$). A plan view of the modified geometry near the fault zone is shown in Fig. 2.

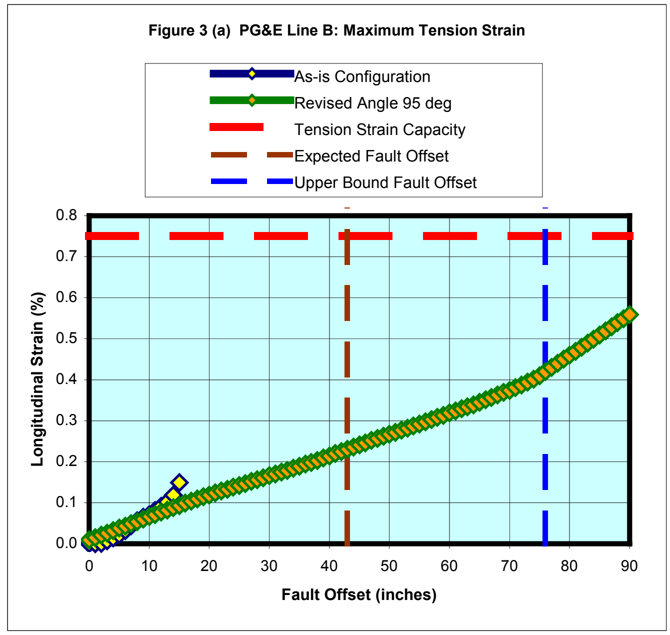
- The offset geometry change occurs between Stations 1179+63 and 1177+99.
- The replacement pipe, which is 24-inch diameter, 0.5-inch wall (610 mm by 13 mm) API 5L grade X-60, extends 130 feet (40 m) to the southwest side of the fault and 80 feet (24 m) to the northeast side of the fault.
- The four side bends in the geometry offset are cold bends with an average radius of 76.4 feet (23.3 m) corresponding to an angle change of 1.5^o per diameter with a 22^o angle change across each bend. Each end of the bends includes a 4 foot (1.22 m) long straight tangent section.
- The modified geometry provides a 12 foot (3.66 m) long straight run "pup" section centered on the fault zone.
- The easternmost 5 feet (1.5 m) of the bend closest to the nearby road extends into the toe of the road fill.

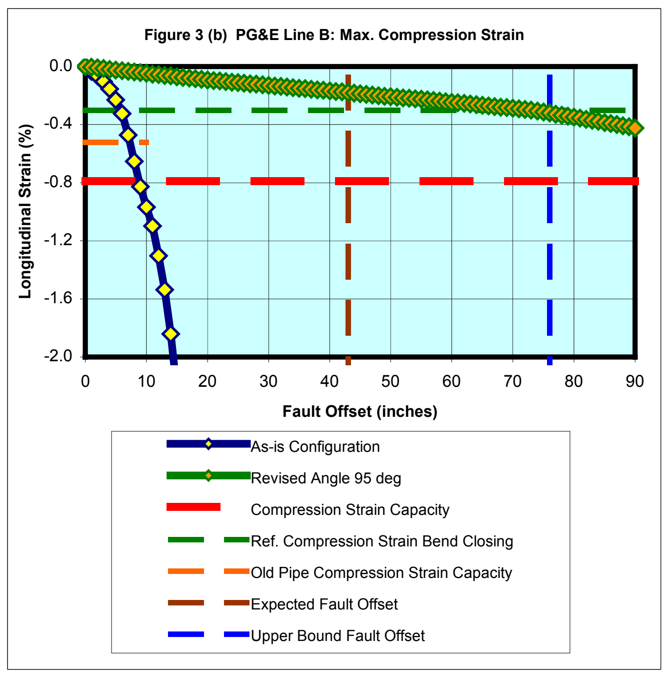


For the new pipe from Station 1179+63 to the toe of the fill on the west side of a nearby road, the design assumes 3 feet (0.91 m) of soil cover. From this point eastward, the design is based on the existing cover depth profile. For the trench length extending eastward from the fault to near toe of road fill, this design assumes the use of an imported backfill and bedding material based on the weak/west side soil properties. This was done to avoid the higher pipe-soil spring strengths associated with the native strong/east side soil properties in this vicinity. The pipe backfill within approximately ±40 feet (±12 m) of the fault is assumed to be installed with the minimum amount of compaction effort permitted by PG&E trench specifications.

ANALYSIS RESULTS

For each analysis case, the pipeline was first pressurized to 480 psi (3310 kPa) (a temperature differential of zero was assumed) and then the fault offset profile shown in Fig. 1 was imposed using PIPLIN's settlement profile option. The resulting pipe and soil deformation state was obtained as output at 1-inch increments. The pipe state includes the distribution of pipe axial force, bending moment, curvature, extreme fiber compression and tension stresses and strains as well as the forces and deformations in the pipe-soil springs. The maximum value of each of these quantities can be established at any level of fault offset. The key analysis results are the maximum compression and tension strain demands at a given level of fault offset. Sequence plots of the maximum compression and tension strain as a function of fault offset provide a useful basis for comparing the relative performance of the different design alternates considered. The fault crossing design with the best performance is the design which results in the least amount of deformation (strain) demand for a given level of fault offset. The addition of horizontal lines at the strain levels corresponding to the compression and tension strain capacities to the sequence plots provides a basis for making decisions regarding the pipeline structural integrity. Figure 3 compares the maximum pipe compression and tension strain vs. fault offset for the as-built and retrofit configurations.





The as-built configuration model was analyzed for up to 15 inches (38 cm) of imposed right lateral offset (i.e., offset imposed in 1-inch (2.54 cm) increments) at the fault location. This case was governed by the (old pipe) compression strain limit of 0.52% on the "hard" (east) side of the fault at about 7 inches (18 cm) of fault offset. The final retrofit configuration was analyzed for up to 90 inches (2.3 m) of fault offset. At this point, the maximum tension strain in the new pipe was about 0.56% (<0.75% tension strain capacity) and the maximum compression strain in the new pipe was about 0.42% (<0.79% compression strain capacity). At 76 inches (193 cm) of fault offset (the expected upper bound surface fault offset), the maximum compression strain demand in the new pipe is about 0.32% (i.e., approximately equal to the reference compression strain capacity (0.3%) associated with bend closing action). At 90 inches (2.3 m) of fault offset, the maximum tension strain demand in the old pipe is 0.03% (corresponding to a longitudinal stress of approximately 14 ksi or 97 MPa) and the maximum compression strain demand in the old pipe is 0.00% (i.e., the stain demands in the old pipe are negligible).

Based on these results, it is clear that the retrofit design based on the offset modification provides a significant performance upgrade for this fault crossing. The fault offset capacity has been improved through the use of increased wall thickness, increased steel grade, improved backfill conditions and a more favorable local fault crossing angle. For this configuration, right lateral fault motion results in (a) a "closing" action within the two cold bends located on either side of the fault and (b) a net tension force in the pipe (due to the obtuse β value) centered on the tangent section of the offsetting leg containing the fault crossing. The net tension force in the offsetting leg results in an "opening" action within the two adjacent cold bends on either side of the fault. By adjusting the local fault crossing angle β, the "bend opening" action that results from pipe extension across the fault can be made to nearly offset the "bend closing" action induced by the transverse component of the fault offset. The use of a select sand backfill in the retrofit section allows the bends to engage the soil with relatively low transverse and longitudinal resistance thereby enhancing the overall flexibility/compliance of the fault crossing design. Implementation of this unique design concept at the Calaveras fault crossing increased the amount of fault offset required to damage the pipeline from about 7 inches (18 cm) for the "as-built" design to well over 90 inches (2.3 m) for the retrofit design.

EXTENSION OF "OFFSET" DESIGN CONCEPT

The offset geometry design developed for the Line B Calaveras fault crossing is a unique concept that is applicable to highly focused fault zones. The offset geometry allows the pipe to cross the narrow fault zone at a local tensile crossing angle. As noted above, when subject to right lateral fault offset, the transverse component of the fault motion subjects the horizontal cold bends on either side of the fault to a closing action (i.e., the intrados of the bend tends to go into compression). At the same time, the longitudinal (tensile) component of the fault motion acts to pull the pipe across the fault which tends to impose an opening action on the cold bends adjacent to the fault (i.e., the bends on either side are being pulled open like the coils of a large spring). The closing action caused by transverse fault motion is nearly offset by the opening action caused by the large tension force across the fault. The net result is a more flexible and compliant fault crossing design that provides very low levels of strain for a given level of fault offset.

Although design alternates with offset geometries similar to the final offset configuration that provided smaller local fault crossing angles were considered, a full sensitivity study on the crossing angle was not pursued as part of the original design study. The main reason for this was that because the Line B fault crossing was so close to a nearby road, the design was geometrically constrained for this application.

In order to more fully investigate the potential of this offset geometry design configuration, an "unconstrained" design sensitivity study has been pursued herein. In this study, the entire length of the pipeline model is assumed to be a 24-inch diameter, 0.5-inch thick (610 mm by 13 mm) X-60 pipe with the same original alignment as Line B. The fault location and width are unchanged. A uniform 3-foot (0.91 m) select sand cover depth is assumed for the entire model In addition to the a "straight pipe" design across the fault zone, the sensitivity study considers offset geometries with the same bend radius and general configuration as the final Line B design. Offset geometries that provide local fault crossing angles of 90°, 95°, 100°, 105° and 110° were evaluated A plan view of these offset geometries is shown in Fig. 4. For each case, the geometry is laid out such that the center of the fault zone crosses the pipe in the middle of the 12 foot (3.66 m) long pup section between the cold bends adjacent to the fault.

Figure 4 Plan Layouts of Unconstrained Offset Geometries for 90-110 deg Crossing Angles

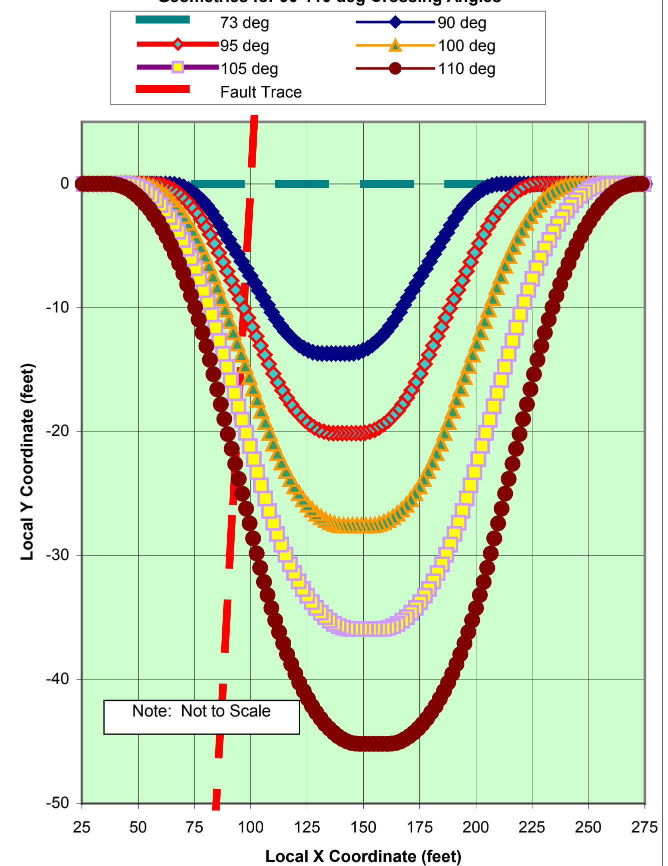


Figure 5 (a) PG&E Line B: Maximum Tension Strain

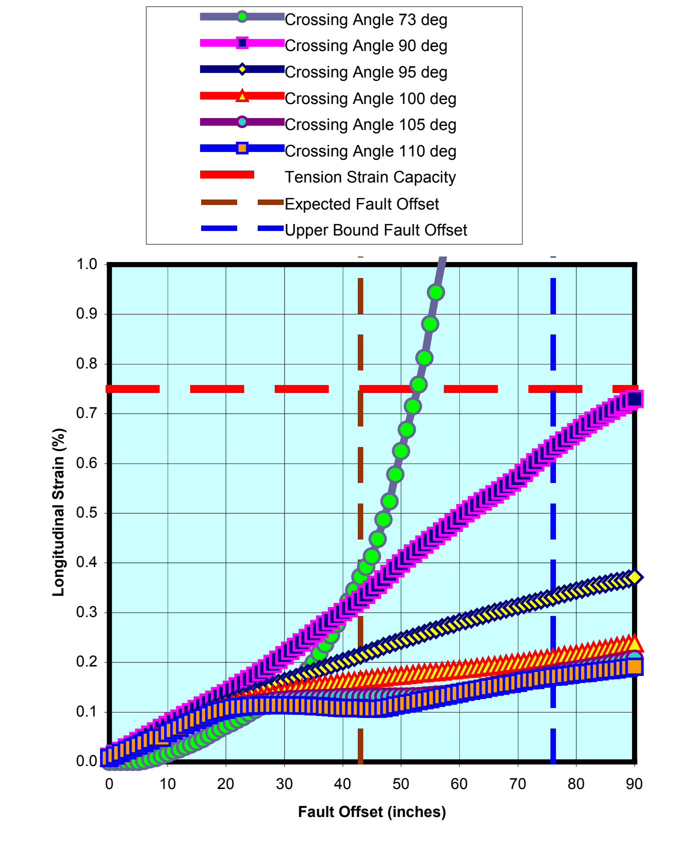
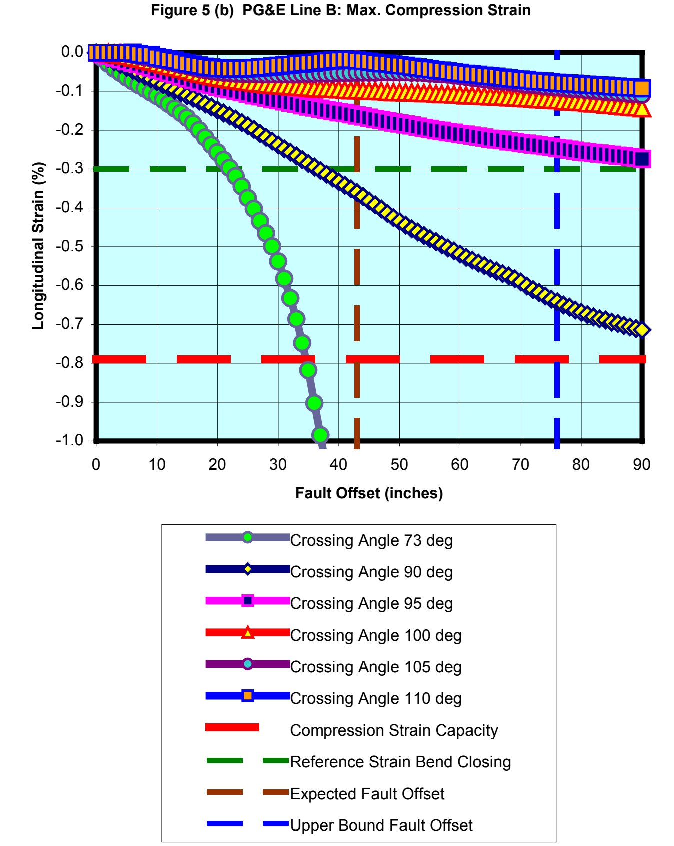


Figure 5 (b) PG&E Line B: Max. Compression Strain



The key analysis results are the maximum compression and tension strain demands at a given level of fault offset. Figure 5 presents a comparison of the maximum compression and tension strain demands as a function of fault offset from these cases. Figure 6 presents the maximum compression and tension strain demands corresponding to 90 inches (2.3 m) of fault offset as a function of the fault crossing angle. Table 1 provides a summary of the geometry of these designs. Based on these results, the following observations can be made:

1. The straight pipe case (with β=73^o) was governed by the compression strain limit at a fault offset of about 34.5 inches (88 cm).
2. None of the offset geometry cases reached the compression or tension strain limits at a fault offset of 90 inches (2.3 m).
3. Increasing the local fault crossing angle in the range from 90^o to 100^o results in a significant reduction in the maximum deformation (strain) demands.
4. Increasing the local fault crossing angle in the range from 100^o to 110^o does not provide a significant additional reduction in the maximum deformation (strain) demands.
5. Increasing the local fault crossing angle using the offset geometry configuration results in increased offset "heights" and "lengths". The cost of the retrofit design will be generally proportional to the length of the offset section.
6. Based on this assessment, an offset geometry that provides a local fault crossing angle of approximately 100^o appears to provide a reasonable balance between excellent low strain performance and length (and associated cost) of new pipe required.

Table 1. Summary of Offset Geometries

(Note: 1 foot = 0.3048 m)

Crossing Angle (degrees)	90	95	100	105	110
"Height" of Offset (feet)	13.7	20.1	27.6	35.9	45.2
Length of New Pipe (feet)	162.7	189.3	216.0	242.7	269.3

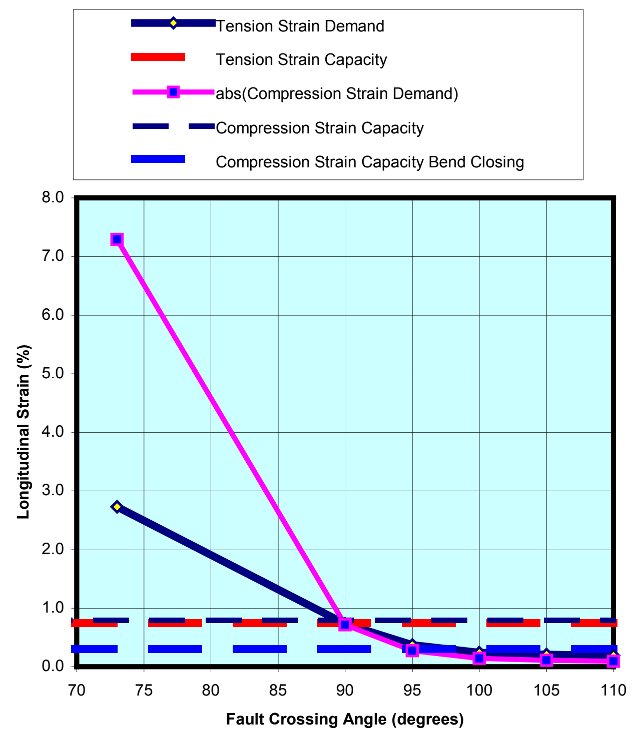


Figure 6 PG&E Line B: Maximum Strain Demands at 90-inch Fault Offset

SUMMARY

This paper describes the development and implementation of a unique pipeline fault crossing design upgrade for a 22-inch (559 mm) diameter PG&E gas transmission line where it crosses the Calaveras fault near Sunol, California. The fault offset capacity has been improved through the use of increased pipe wall thickness, increased steel grade, improved backfill conditions and a more favorable crossing angle "β" (β=73^o for the original design vs. β=95^o for the new design). The angle change is accomplished by installing an offset section of the pipeline adjacent to the fault such that the fault crosses the pipeline in the middle of a tangent section in the nearest offsetting leg. The four bends used to fabricate the offset section are cold bends with an average radius of 76.4 feet (23.3 m). The entire mitigated section of the pipeline is buried in a select sand trench. For this design configuration, right lateral fault motion results in (a) a "closing" action within the two adjacent cold bends located on either side of the fault and (b) a net tension force in the pipe (due to the obtuse β value) centered on the tangent section of the offsetting leg containing the fault crossing. The net tension force in the offsetting leg results in an "opening" action within the two cold bends on either side of the fault. The combination of the bend closing and opening actions results in a very low strain design. The offset design is much more compliant and flexible than a straight pipe design with the same crossing angle. Implementation of this unique design concept at the Calaveras fault crossing increased the amount of fault offset required to damage the pipeline from about 7 inches (18 cm) for the "as-built" design to well over 90 inches (2.3 m) for the retrofit design.

The location of the pipeline fault crossing close to the nearby road resulted in a spatial constraint on this design. In order to more thoroughly evaluate this design concept in an unconstrained setting, the evaluation was extended to consider a simple sensitivity study of a more general crossing application (i.e., removal of the nearby road, consideration of a uniform cover depth, holding the fault location and width unchanged). The sensitivity study considered a straight pipe case and offset geometries with the same bend radius and general configuration as the final design that provide local fault crossing angles of 90^o, 95^o, 100^o, 105^o and 110^o. This study indicated that increasing the local fault crossing angle in the range from 90^o to 100^o resulted in a significant reduction in the maximum deformation (strain) demands while increasing the local fault crossing angle in the range from 100^o to 110^o did not provide a significant additional reduction in the maximum deformation (strain) demands. For this crossing, an offset geometry that provides a local fault crossing angle of approximately 100^o appears to provide a reasonable balance between excellent low strain performance and length (and associated cost) of new pipe required.

CONCLUSIONS

The transverse geometric offset design concept described in this study provides a unique design solution that is applicable to fault crossings with well defined fault locations and highly localized fault offset profiles (e.g., for this fault, 85% of the offset is expected to occur within ±5 feet (±1.5 m) from the center of the fault trace). The retrofit design that was implemented in the field increased the amount of fault offset required to damage the pipeline from about 7 inches (18 cm) to well over 90 inches (2.3 m). The retrofit design increased the fault offset capacity through the use of increased pipe wall thickness, increased steel grade, and improved backfill conditions. However, the most dominant improvement was due to an offset geometry that provided a more favorable local crossing angle "β" through the use of cold bends adjacent to the fault. For this design configuration, right lateral fault motion results in (a) a "closing" action within the two adjacent cold bends located on either side of the fault and (b) a net tension force in the pipe (due to the obtuse β value) centered on the tangent section of the offsetting leg containing the fault crossing. The net tension force in the offsetting leg results in an "opening" action within the two adjacent cold bends on either side of the fault. The offset design is much more compliant and flexible than a straight pipe design with the same crossing angle. General consideration of this concept indicated that an offset geometry that provided β=100^o appeared to provide a reasonable balance between excellent low strain performance (maximum strains of about than 0.25% at 90 inches (2.3 m) of fault offset) and the total length of new pipe required.

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REFERENCES

[1] Kelson, K., Hitchcock, C., Baldwin, J., Hart, J. D., Gamble, J., Lee, C.H., and Dauby, F., *"Fault Rupture Assessments for High Pressure Pipelines in the Southern San Francisco Bay Area, California",* IPC04-0212, International Pipeline Conference, Calgary, Alberta, Canada, October 4-8, 2004.

[2] SSD, Inc., "PIPLIN-PC: Stress and Deformation Analysis of Pipelines", Version 4.51, User Reference and Theoretical Manual, Reno, Nevada, December, 2003.

[3] American Lifelines Alliance (ALA), *"Guidelines for the Design of Buried Steel Pipe",* ASCE American Lifelines Alliance, www.americanlifelinesalliance.org, July 2001.

[4] Gresnigt, A. M., *"Plastic Design of Buried Steel Pipelines in Settlement Areas"*, HERON, Vol. 31, no. 4, 1986.

[5] Fukuda, N., Yatabe, H., Masuda, T. and Toyoda, M., *"Effect of Changes in Tensile Properties Due to Cold Bending on Large Deformation Behavior of High Grade Cold Bend Pipe",* IPC02-27129, International Pipeline Conference, Calgary, Alberta, Canada, September 29-October 3, 2002.

[6] Mroz, Z., "On the Description of Anisotropic Work Hardening", Journal of Mechanics, Physics and Solids, 15, 163-175, 1967.

[7] Bouwkamp, J.G., and Stephen, R.M., *"Full-Scale Studies on the Structural Behavior of Large Diameter Pipe Under Combined Loading",* Report No. UC-SESM 74-1, University of California, Berkeley, Structural Engineering and Structural Mechanics, January, 1974.

[8] Stevick, G., Hart, J. D., Lee, C.H., and Dauby, F., *"Fracture Analysis For Pipeline Girth Welds In High Strain Applications",* IPC04-0146, International Pipeline Conference, Calgary, Alberta, Canada, October 4-8, 2004.