DESIGN OF A NATURAL GAS PIPELINE SUBJECT TO PERMANENT GROUND DEFORMATION AT NORMAL FAULTS: A PARAMETRIC STUDY ON NUMERICAL VS. SEMI-ANALYTICAL PROCEDURES

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ABSTRACT

A parametric study of a pressurized natural gas pipeline crossing normal faults with steep nominal dip angles and an expected normal slip of up to 65 cm will be presented. We used the method of Kennedy et al. as well as the nonlinear Finite Element method to compute strain levels. It turns out that for the given normal faults the appraisal of the method of Kennedy et al. as providing a conservative estimate of peak axial strain does not hold anymore. Additionally, the results of our investigations concerning the impact of elbows and T-connections in the pipeline layout near the fault crossing on the peak strain levels will be presented.

Keywords: natural gas pipeline, normal fault motion, permanent ground deformation, axial strain

INTRODUCTION

Permanent ground deformations (PGD) generally are critical when working with high-pressure pipelines, for which there is concern related to system supply and safety. During earthquakes PGD can be caused by surface faulting, seismic settlement, lateral spreading due to soil liquefaction, landslides, and the consolidation of relatively cohesion-less fills and loose natural deposits. All these sources of permanent deformation involve some distribution of the ground movement, and the differential ground movement results in bending and tension or compression depending on the relative orientation of the motion and the pipeline layout.

The extreme case is an abrupt or knife-edge displacement in which all relative movement is concentrated along a single plane. Such a situation was encountered during the engineering design phase of a medium pressure natural gas pipeline on Evia island in central Greece. The pipeline layout demanded to cross three active faults on Evia island, each of them normal faults with steep dip angles. Due to restrictions on ground accessibility one of those faults had three crossings with the pipeline route, which raised the question to which extent the elbows in the vicinity of the faults will have an impact on the pipe performance.

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FAULT CHARACTERISTICS

The designations of the pipeline-fault intersections, the fault parameters as well as the nominal normal-slip displacements are summarized in Table 1.

Table 1. Summary of pipeline-fault crossing parameters

<table>
<thead>
<tr>
<th>Fault Name</th>
<th>Normal slip displacements $\Delta n$</th>
<th>Dip angle $\psi$</th>
<th>Crossing point ID</th>
<th>Fault crossing angle $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-EV/4</td>
<td>50 cm</td>
<td>80°</td>
<td>A.1</td>
<td>60°</td>
</tr>
<tr>
<td>F-EV/5</td>
<td>65 cm</td>
<td>80°</td>
<td>A.2.1</td>
<td>60°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>A.2.2</td>
<td>65°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>A.2.3</td>
<td>70°</td>
</tr>
<tr>
<td>F-EV/12</td>
<td>40 cm</td>
<td>70°</td>
<td>A.3</td>
<td>75°</td>
</tr>
</tbody>
</table>

The relative motions on a normal-slip fault are shown in Fig. 1.

Figure 1. Relative motions on a normal-slip fault after ASCE TC-LEE (ASCE, 1984)

PIPELINE CHARACTERISTICS

Mechanical properties
The pipes are manufactured from welded Grade B carbon steel according to the API Spec. 5L (1995). The pipeline material is characterized by:
The above strength and deformability parameters may be fitted either by:

- a Ramberg-Osgood stress-strain relation:

\[
\varepsilon = \frac{\sigma}{E_i} \left[ 1 + \frac{n}{r+1} \left( \frac{\sigma}{\sigma_e} \right)^r \right]
\]

with \( E_i = 210\,000\) MPa, \( \sigma_e = 320\) MPa, \( n = 17.896 \) and \( r = 9.3 \),

- or a tri-linear relation:

\[
\sigma = \begin{cases} 
E_i \varepsilon & \text{if } \varepsilon \leq \varepsilon_1 \\
\sigma_0 + E_2 \varepsilon & \text{if } \varepsilon_1 \leq \varepsilon \leq \varepsilon_2 \\
\sigma_2 & \text{if } \varepsilon_2 \leq \varepsilon
\end{cases}
\]

with \( E_i = E_1 = 210\,000\) MPa, \( E_2 = 2443\) MPa, \( \sigma_0 = 316.3\) MPa, \( \sigma_1 = 320\) MPa at \( \varepsilon_1 = 0.152\% \), and \( \sigma_2 = 414\) MPa at \( \varepsilon_2 = 4\% \)

These relations are shown graphically in Fig. 2.
• Effective weight $\gamma$: 18 kN/m³
• Friction angle $\phi$: 36°
• Skin friction angle $\delta$: 24°
• Coefficient of earth pressure at rest $k_0$: 0.5

METHODOLOGY

Regulatory provisions
Several European standards deal with gas pipeline design. EN 1594, covering on-shore gas supply networks for operating pressure above 16 bar, provides functional requirements for design, construction, and operation, but for the determination of the pipeline’s response to PGD it makes reference to the literature only. EN 1998-4 (Eurocode 8) provides in its section 6 design principles, limit states, as well as limit values for axial strain due to PGD. It also gives suggestions for mitigation measures at fault crossings, but it lacks provisions about specific methods on how to compute actual strain and stress levels.

Current practice of pipeline design against seismic risks therefore follows the guidelines published by ASCE (ASCE, 1984) and ALA (ALA, 2001). For permanent seismic ground deformation due to normal faults both guidelines are based on the same idealized structural model of soil-pipeline interaction. Furthermore, both suggest a nonlinear finite element analysis to obtain axial strain levels induced by fault motion. Besides this, the ASCE guidelines also recommend Kennedy’s method (Kennedy et al., 1977) and claim this to lead to an upper bound estimate of strain. Allowable strain levels are provided, too.

Structural model of a buried pipeline
The fundamental concept of the analytical model of a buried pipeline which is still commonly used was introduced by Newmark and Hall (1975). The fault movement is treated as occurring on a single, well defined plane and the soil masses on either side of the fault line are considered as rigid bodies. At a certain distance from the fault trace an effective anchor point is assumed such that beyond the anchor points the pipeline and the soil mass will have no relative displacement.

The ultimate subgrade reaction (bearing capacity) of the soil mass is used throughout as a resisting force by means of a distributed line force in all dimensions (Fig. 3), i.e. the soil has no elastic strain range whatsoever. The magnitude of the ultimate subgrade reaction depends on the shear strength of the soil as well as the pipe geometry, amongst other factors. Details can be found in ASCE (1984).

![Figure 3. Idealized structural model of a buried pipeline, after ASCE (1984)](image-url)
The fault displacements must equate the accumulated mean axial strain between the anchor points. Since there is no unique solution, assumptions must be made with respect to the distribution of axial and bending strain along the pipeline axis, as well as the distribution of subgrade resistance. Because the equation is non-linear it has to be solved iteratively.

Kennedy et al. (1977) returned to the ideas of Newmark and Hall and introduced some refinements. They assumed, amongst others, the longitudinal strain in a cross section near the fault trace to exceed the yield strain such that the pipe looses its bending stiffness and assumes a constant curvature between the fault plane and a point where the deformed shape approaches tangentially the undeformed line and turns to a straight line again (Fig. 4). Wang and Yeh (1985) replaced the straight segment at the far end by a beam on elastic foundation, but applied their idea to strike-slip faults only due to the larger fault motion amplitudes compared to normal faults.

Since then there has been a vast amount of publications which further refine the fundamental concept in order to obtain more reliable results. To name a more recent one, Karamitros et al. (2007, 2008) introduced an analytical expression in the concept of Wang and Yeh to account for the interaction between axial and bending strain and to obtain an improved expression for the curvature. They applied their method to strike-slip faults as well as normal faults.

**Finite Element model**

Due to the non-linear nature of the problem, it is quite natural to apply the Finite Element method to the problem at hand. The ASCE guidelines (ASCE, 1984) suggest such an approach, besides using Kennedy’s and Newmark’s method. In a Finite Element model the pipe can be discretized using beam elements, and the soil can be attached to the beams as discrete springs with elastoplastic force-displacement curve, with different yield displacements and ultimate subgrade reactions for vertical, lateral, and longitudinal direction. Fig. 5 shows the portion near the fault trace of a typical mesh with short element length near the fault, and large element length at some distance from the fault. The quadrilaterals show the fault displacement, but are not part of the Finite Element model.
In Fig. 6 the subgrade reaction vs. displacement curves are shown for medium dense sand and NPS 14 for each coordinate direction. On the fixed portion of the fault the soil represents an obstacle for the pipeline to move downward such that the resistance is governed by the bearing capacity of the soil. On the moving side of the fault it is the other way round, i.e. the pipeline represents an obstacle for the soil cover to move downward and the force applied to the pipeline is roughly proportional to the weight of the soil prism above the pipe. The magnitudes of the subgrade reactions were computed after ASCE (1984).

The fault slip might well exceed the diameter of the pipe, which imposes geometric second-order effects on the pipeline. Therefore the Finite Element analyses have been performed using large displacement features, i.e. the model is geometrically non-linear.
More advanced Finite-Element models, using shell elements for the pipe or solid elements for the soil, have also been proposed, e.g. Karamitros et al. (2007). However, comparing such results with results from a spring/beam model suggests that the gain in accuracy is negligible, see Fig. 7.

Validation
For the pipeline project at hand, the Finite Element method with beam and spring elements was considered as the most appropriate in terms of accuracy and computational cost. To check the results all design cases were also computed using the method after Kennedy et al., because according to the ASCE guidelines “the Kennedy et al. Procedure (…) will lead to an upper-bound estimate of strain because it overestimates bending strains by assuming that the pipeline has no bending stiffness” (ASCE 1984, p. 184). Furthermore, the Kennedy et al. method can easily be implemented in spreadsheet software such that even a large number of design cases can be computed very quickly.

Fig. 7 shows the comparison between the results of several methods to compute the maximum strain (superposition of axial strain and bending strain) in a pipeline of size NPS 42 crossing a strike-slip fault at the angle of 45°. As can be seen, all results except for the method after Kennedy et al. are equivalent for practical purposes. Kennedy et al. on the other hand yield significantly larger strain for small fault displacements, which supports the assertion of the ASCE guidelines mentioned above, and yields slightly smaller strain in case of large faults displacements.

![Graph showing the comparison between different methods for maximum strain](image)

**Figure 7. Maximum strain in a pipeline crossing a strike-slip fault obtained using different methods**

RESULTS

Straight pipeline segments
Figure 8 shows the deformed shape of the pipeline and the curvature within the curved portion, and Fig. 9 shows the corresponding strain distribution obtained by the Finite Element method. Similar results are presented in the guidelines issued by ALA (2001), experimental evidence which confirm the numerical results can be found in O’Rourke et al. (2007).
Figure 8. Deformed shape and curvature at fault trace A.2.2 after Finite Element method
Figure 9. Strain distribution in pipeline cross section at fault trace A.2.2 after Finite Element method

Figure 10 shows the maximum and minimum strain after the method of Kennedy et al. as well as the Finite Element method. It becomes obvious that contrary to the assertion of the ASCE guidelines the method after Kennedy et al. might well predict smaller tensile strain amplitudes than the Finite Element method. On the other hand, the compressive strains obtained by the method after Kennedy et al. are larger by a factor of three or more than the compressive strain predicted by the Finite Element method. Note that the two methods predict the largest strain levels at different locations.

For other sets of properties investigated for the project at hand, in particular if one considers a dense backfill, the tensile strain predicted by the Finite Element method exceeded the corresponding prediction after the method of Kennedy et al. by up to 70 %.
Figure 10. Maximum and minimum axial strain in selected straight pipeline segments

The Finite Element method predicts the largest tensile and compressive strain on the fixed portion of the soil. This is reasonable, because the soil resistance against a downward vertical displacement of the pipeline is significant larger than the resistance against an upward motion. The pipeline response is – though the actual subgrade stiffness is non-linear – similar to that of a semi-infinite beam on elastic foundation. The curvature of such a beam near a point load increases with increasing subgrade stiffness.

Another striking observation from Fig. 10 concerns the magnitude of the compressive strain. In the method after Kennedy et al. a longitudinal stretch of the pipeline along with mean axial strain will occur only if the fault motion has an axial component, which is not the case at normal faults with steep dip angles. Therefore, tensile and compressive strain have approximately equal magnitude. The Finite Element analysis, on the other hand, predicts mean axial strain at the same location and of only slightly smaller magnitude like the largest bending strain, such that the compressive strain from bending is partially canceled out by the mean axial strain (Fig. 9). This comes as a result of second order effects, which allow axial deformation even under purely lateral loads.

In Fig. 11 the displacement and the curvature after the two methods is shown in tandem. The assumed shape of Kennedy et al. has two particular features, namely a sharp bend after a straight line with no curvature whatsoever and a portion with constant curvature. This assumption is reasonable if the mean axial strain exceeds the yield strain in every cross section up to a certain distance from the fault, because then the pipe looses all its bending stiffness and a plastic hinge will develop at the sharp bend followed by a section in which the pipe acts effectively as a cable. If the mean axial strain is small, the bending stiffness will not vanish, but will decrease the curvature, and therefore the negligence of bending stiffness will overestimate the bending strain, i.e. the method is conservative.

The curvature plot in Fig. 11 support this claim on the moving side of the fault trace but is contradicting it on the fixed side of the fault. The root of the disparity can be found in the fact that Kennedy et al. focus on the curved portion of the pipeline and neglect the bend, that is to say they hold up the assumption of the sharp bend at the fault trace, which is equivalent to a jump in the pipeline axis slope. This assumption is invalid if the bending stiffness is not negligible, because bending strain will develop at the bend, and
due to the higher subgrade reaction on the fixed side of the fault the bending strain will usually exceed the bending strain on the moving side of the fault.

**Figure 11. Displacements and curvature after Finite Element method and after Kennedy et al.**

**Pipeline segments with elbows and T-connections**

At fault trace F-EV/5 the route of the pipeline follows the existing roads with several elbows in a distance of a few hundred meters to each other. One of those elbows is as close as 70 m to the fault trace. The question arises if the elbows will increase the maximum strain the pipeline and must therefore taken into account in the pipeline design or not.

At some distance from a fault trace the pipeline is supposed to be effectively anchored, that is, beyond the anchor point no differential motion between soil and pipeline will occur. It follows that any elbow (or T-connection or bend) beyond the anchor point has no impact whatsoever on the strains. Results from the Finite Element analysis of straight pipeline segments show that the maximum unanchored length is approximately 220 m. Because the location of some elbows are within the unanchored length, for a start they must not be neglected.

With respect to the longitudinal motion of the pipeline, an elbow, if within the unanchored length, constitutes a restraint in the sense that the lateral soil resistance of the branching segment represents a longitudinal soil resistance which is the larger the longer the branching segment. In the limit, an elbow effectively constitutes an anchor point. In that case, the required elongation of the pipeline due to fault motion has to be mounted to the pipeline segment between the fault trace and the elbow location only. As a result, the axial strain will increase, and the maximum strain probably as well, with decreasing distance of the elbow from the fault.

On the other hand, the results from the Finite Element analysis of straight pipeline segments show that the curved portion of a pipeline near the fault trace has a length of less than 20 m, as shown in Fig. 5, where the displaced shape of the pipeline is shown, together with an illustration of the fixed and movable portion of the fault trace. It can be safely assumed that any elbow in a distance of more than 20 m does not constitute a restraint with respect to the lateral motion of the pipeline.
It follows that the impact of curved sections, elbows, and T-connections can be conservatively estimated by considering the beginning of such a segment as an anchor point at which the displacements are identical with the motion of the corresponding soil portion at the fault trace. By applying an anchor point to the pipeline at several distances from the fault trace it will be possible to assess the impact of an elbow on the peak strain.

A limited parametric study was performed for the pipeline at fault F-AV/5. The Finite Element model was used such that for each case displacement boundary conditions were imposed on one single node to which pipe elements are attached. If that node was on the moving side of the fault (distance > 0), the fault slip was imposed to that node, otherwise the node was fixed. The results in terms of the peak longitudinal strain in tension as well as in compression for each explicit anchor point location as well as the ratio of peak longitudinal strain in anchored and unanchored pipeline is shown in Fig. 12.

The peak longitudinal strain shows a significant change only if the explicit anchor point is within a distance of 10 m to the fault trace. Otherwise, the tensile strain is slightly increased, but less than 2% of the corresponding strain in a straight pipeline without imposed anchor point, while the compressive strain even decreases.

CONCLUSIONS

A natural gas pipeline design was analysed with respect to the axial strain imposed by permanent ground deformation at normal faults with steep dip angles. The design procedures followed the guidelines provided by ASCE TCLEE (1984), i.e. the semi-analytical method after Kennedy et al. (1977) and the Finite Element method was applied as well.

On the moving side of the fault the strain levels predicted by each of the two methods match well. On the fixed side of the fault, however, the Finite Element methods predicts significantly higher bending strain and mean axial strain than on the moving side, while the method after Kennedy assumes that no bending strain at all will be observed on the fixed side.
The method after Kennedy has two shortcomings, which is the lack to account for large displacement effect, i.e. axial stretch of the pipeline at locations subject to large lateral loads, as well as to account for the large bending strain on the fixed side of a normal fault due to assuming a plastic hinge at the fault trace, i.e. the negligence of bending stiffness at that location. It follows that contrary to the assertion of the ASCE guidelines the method after Kennedy is non-conservative in the case of normal faults with steep dip angles.

A limited parametric study was performed to assess the impact of an elbow in the vicinity of an active normal fault. It turns out that for the case at hand the elbow has negligible impact on the strain levels in the pipe if the distance between fault trace and elbow location exceeds 20 m.

REFERENCES

EN 1594:2000 Gas supply systems — Pipelines for maximum operating pressure over 16 bar — Functional requirements