On the efficiency of flexible joints in mitigating the consequences of seismic fault activation on buried pipelines

Attempts to meet rising worldwide energy demands, often leads to the construction of hydrocarbonate pipelines over very long distances. Crossing seismic areas is often inevitable for such pipeline routes even though the design of new pipelines takes place within a stringent framework of regulations to protect the environment and avoid populated areas. In such cases, the potential for large ground differential movement due to fault activation often becomes the primary cause of pipeline failure.

Buried steel pipelines deform to adapt to movement of the surrounding soil, so possible failure modes are tensile fracture of girth welds between adjacent pipeline parts, local buckling of the pipeline wall due to compressive strains, and upheaval buckling due to high compressive forces in the case of reverse-type faults. The latter is the dominant failure mode for relatively shallowly buried pipelines with low diameter-to-thickness ratio, but is not usually relevant for the relatively thin-walled pipelines used to transport fuel.

Minimizing the consequences of induced large ground displacements on pipeline integrity is both an industrial and academic research topic of high priority. Among conventional mitigating measures, such as constructing a wider trench and backfilling with loose granular soil to reduce soil-pipeline friction, research is directed towards integrating flexible joints between adjacent steel parts in buried pipelines crossing areas prone to large ground displacements. This approach aims at concentrating strains at the joints, leaving the steel pipe virtually undeformed. Thus, the failure modes caused by high strain concentrations, i.e. tensile fracture of the welds and local shell buckling, are avoided.

However, the introduction of flexible joints - acting as internal hinges and transforming the continuous pipeline to a segmented one - tends to decrease pipeline global stiffness and render them more susceptible to upheaval buckling, to the extent that it may become the dominant failure mode, even for deeply-buried pressurized pipelines with relatively high diameter-to-thickness ratios crossing reverse faults. This issue is investigated numerically by modeling the pipeline with beam-type finite elements, and the surrounding soil with nonlinear translational springs. The numerical models are calibrated by comparison to experimental tests. Numerical analyses incorporating geometrical nonlinearities as well as pipeline steel and soil nonlinearities are carried out in order to investigate upheaval buckling and post-buckling global behavior of pipelines with flexible joints at reverse fault crossings, and compare it to the aforementioned local - compressive or tensile - failure modes. Results indicate that during pipeline design a balance has to be struck between the advantages of using flexible joints to reduce strains and the limitation of hazard against failure due to upheaval buckling.

Abstract

Attempts to meet rising worldwide energy demands, often leads to the construction of hydrocarbonate pipelines over very long distances. Crossing seismic areas is often inevitable for such pipeline routes even though the design of new pipelines takes place within a stringent framework of regulations to protect the environment and avoid populated areas. In such cases, the potential for large ground differential movement due to fault activation often becomes the primary cause of pipeline failure.

Buried steel pipelines deform to adapt to movement of the surrounding soil, so possible failure modes are tensile fracture of girth welds between adjacent pipeline parts, local buckling of the pipeline wall due to compressive strains, and upheaval buckling due to high compressive forces in the case of reverse-type faults. The latter is the dominant failure mode for relatively shallowly buried pipelines with low diameter-to-thickness ratio, but is not usually relevant for the relatively thin-walled pipelines used to transport fuel.

Minimizing the consequences of induced large ground displacements on pipeline integrity is both an industrial and academic research topic of high priority. Among conventional mitigating measures, such as constructing a wider trench and backfilling with loose granular soil to reduce soil-pipeline friction, research is directed towards integrating flexible joints between adjacent steel parts in buried pipelines crossing areas prone to large ground displacements. This approach aims at concentrating strains at the joints, leaving the steel pipe virtually undeformed. Thus, the failure modes caused by high strain concentrations, i.e. tensile fracture of the welds and local shell buckling, are avoided.

However, the introduction of flexible joints - acting as internal hinges and transforming the continuous pipeline to a segmented one - tends to decrease pipeline global stiffness and render them more susceptible to upheaval buckling, to the extent that it may become the dominant failure mode, even for deeply-buried pressurized pipelines with relatively high diameter-to-thickness ratios crossing reverse faults. This issue is investigated numerically by modeling the pipeline with beam-type finite elements, and the surrounding soil with nonlinear translational springs. The numerical models are calibrated by comparison to experimental tests. Numerical analyses incorporating geometrical nonlinearities as well as pipeline steel and soil nonlinearities are carried out in order to investigate upheaval buckling and post-buckling global behavior of pipelines with flexible joints at reverse fault crossings, and compare it to the aforementioned local - compressive or tensile - failure modes. Results indicate that during pipeline design a balance has to be struck between the advantages of using flexible joints to reduce strains and the limitation of hazard against failure due to upheaval buckling.