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

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The attempt to meet the worldwide rising energy demands often leads to the construction of hydrocarbonate pipelines to very long distances. Thus, crossing seismic areas is in many cases inevitable for the pipeline route, taking also into account the fact that the design of new pipelines is undertaken within a stringent framework of regulations considering environmental protection and avoidance of populated areas. Several of these seismic areas encounter active tectonic faults and thus pipeline – fault crossing might be unavoidable. In such cases, the potential for large ground differential movement due to fault activation often becomes the premier cause of pipeline failure, compared to other seismic induced actions, such as soil liquefaction and seismic waves, as has also been demonstrated by past earthquake events.

As buried steel pipelines deform to adapt to movement of the surrounding soil, possible failure modes are tensile fracture of girth welds between adjacent pipeline parts due to tensile strains, local buckling of the pipeline wall due to compressive strains and upheaval buckling due to high compressive forces in 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 commonly not relevant for the relatively thin-walled pipelines used to transport fuel.

Mitigating the consequences of induced large ground displacements on pipeline integrity is nowadays 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 and retaining 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 ratio crossing reverse faults. This issue is investigated numerically in the present research by modeling the pipeline with beam-type finite elements and the surrounding soil with nonlinear translational springs and calibrating the numerical models by comparison to experimental tests. Numerical analyses incorporating geometrical nonlinearities as well as pipeline steel and soil nonlinearities are then 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. Obtained results indicate that during pipeline design a balance has to be achieved between the advantages of using flexible joints to reduce strains and the limitation of hazard against failure due to upheaval buckling.

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