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An analytical method for strength verification of buried steel pipelines at normal fault crossings

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ABSTRACT

The complex problem of strength verification of a buried steel pipeline crossing the trace of a normal active fault is treated analytically, and a refined methodology for the calculation of the axial and bending pipeline strains is presented. In essence, the proposed methodology extends the analytical methodology originally proposed by Karamitros et al. [1] for the simpler case of strike-slip fault crossings. The modifications introduced to the original methodology are first identified, following a thorough examination of typical results from advanced 3D nonlinear numerical analyses, and consequently expressed via an easy to apply solution algorithm. A set of similar numerical analyses, performed for a wide variety of fault plane inclinations and intersection angles between the pipeline axis and the fault trace, is used to check the accuracy of the analytical predictions. Fairly good agreement is testified for pipeline strains up to 1.50–2.00%. It is further shown that, although the methodology proposed herein applies strictly to the case of right intersection angles, it may be readily extended to oblique intersections, when properly combined with existing analytical solutions for strike-slip fault crossings (e.g. [1]).

1. Introduction

Buried pipelines are vulnerable to a variety of earthquake-induced hazards, such as permanent ground displacements due to fault rupture or sloping ground failure, or transient ground displacements caused by the passage of seismic waves. Although less frequent, permanent ground displacements pose a higher threat to pipelines, as they may impose large axial and bending strains and they may lead to rupture, either due to tension or due to buckling [2]. This is especially true for step-like deformations resulting from surface faulting, as indicated by a number of case studies of damage to pipeline systems during strong earthquakes (e.g. [3–6]). Taking further into account the critical role of lifeline systems to human life support and energy distribution, as well as the irrecoverable ecological disaster that may result from the leakage of environmentally hazardous materials (e.g. natural gas, fuel or liquid waste), it becomes obvious that the seismic strength verification of buried steel pipelines at active fault crossings is among the top design priorities.

A rigorous solution of the problem should involve an advanced numerical analysis which can account consistently for the non-linear stress–strain response of the pipeline steel, the longitudinal and transverse soil resistance, typically idealized as a series of elastic–perfectly-plastic distributed (Winkler) springs, as well as second order effects induced by large displacements [7]. Such analyses are definitely possible with currently available commercial computer codes. However, they are rather demanding with regard to computational effort and expertise, so that their use in practice is justified only for the final design of large diameter, thin-walled pipes and large ground displacements. For more common applications, as well as for preliminary pipeline strength verification purposes, it is desirable to use simplified analytical methodologies which will allow reasonably accurate predictions of pipeline stresses and strains, at a fraction of the computational effort required for a rigorous numerical analysis.

Aiming at such a simplified methodology, the mechanisms governing the pipeline response at normal fault crossings are first explored with the aid of results from 3D elastoplastic finite element analyses, for the case of a pipeline with axis perpendicular to the fault trace. We consider this experience of first priority for two reasons. The first reason is to compare with the assumptions of existing analytical methods (e.g. [1,8–10]) and evaluate their capacity to provide a rational solution to this problem. The second, and probably most important reason is to identify the basic features of the pipeline response and focus upon them in order to get the required accuracy while avoiding unnecessary complexities which would make an analytical solution impossible or unfriendly to non-specialists.

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