Simulating Seismic Wave Motions for Pipeline Design

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ABSTRACT

This paper presents a methodology for more accurately simulating synchronized seismic wave motions along buried pipelines compared to techniques in use today. This phenomenon, referred to as seismic wave propagation, is typically modeled using a single input motion propagated along the pipeline axis with a speed arbitrarily chosen from either shear or surface wave speed ranges. The selection of wave propagation speed is the biggest source of uncertainty in the analysis and can result in measurable differences in pipeline longitudinal strain. Results using the new method also confirmed that the potential impact of seismic wave propagation on buried modern steel oil/gas pipelines is small, well within the range implicit in stress-based design. In addition to confirming the low levels of longitudinal strain in straight sections, designers can also use this methodology to calculate strains in pipeline bends, tees, etc., where the potential exists for strain amplification.

KEY WORDS: Pipeline; earthquake; seismic; wave; surface; propagation; strain.

INTRODUCTION

Observed damage to pipelines in seismic events (O’Rourke et al 1985, O’Rourke and Liu 1999) has been generally attributed to two hazards:
- Permanent ground deformation (PGD); and
- Wave propagation hazards.

In some instances, the damage was credited to the combination of the two (Eguchi 2002). To the author’s knowledge, there have been no pipeline failures due solely to seismic wave propagation except for low-pressure segmented, not welded, water pipelines.

Permanent ground deformation can be either localized and abrupt or spatially distributed. A localized relative displacement example is fault fracture; distributed displacement examples include seismic landslides, liquefaction-induced lateral spreading and seismic settlement. Unlike PGD, wave propagation hazard is transient in nature and is manifested in ground strain and curvature due to traveling seismic waves (Eguchi 2002, Bolt et al 2004).

Ground strains induced by seismic wave propagation are generally very small. Depending on the pipe-soil coefficient of friction, the resulting pipeline strains can be equal or less than ground strains in the case of a straight pipeline segment. However, it is possible that strain localizations may be induced by geometric discontinuities caused by pipeline bends, tees and/or valves.

There are two fundamental approaches for estimating strains induced by seismic wave propagation:
- The ASCE approach (ASCE 1984, 2001), based on Newmark (Newmark 1967) with the assumption that a buried pipeline follows the ground motion. The maximum pipe axial strain can be approximated by the maximum ground strain, estimated as \( \varepsilon = \text{PGV} / C \) where PGV is the peak ground velocity and C is the apparent wave propagation velocity.
- The Japanese Gas Association (JGA) methodology (JSCE 2000), based on direct measurements of ground strain at multiple locations during the 1994 Kobe earthquake in Japan. ASCE leaves the selection of C to the analyst from a range of surface waves associated with the top layer (low-speed) to shear waves associated with the bedrock (high-speed) while JGA presents estimates that are only applicable to sites with Kobe-like conditions. In addition:
  - Use of shear wave speed to propagate an earthquake record is not a complete representation of ground strain. Should we factor up ground strain or introduce variability through slower waves? By how much? Or should we introduce variability through earthquake incoherence models?
  - Surface waves are present in every earthquake record. How can one decompose a single earthquake record into shear waves and dispersed surface waves?
  - Spatial incoherence and site response variability increase seismic ground strain. What are their relative contributions?
  - Near field surface waves are amplified by basin edge effects (San Fernando, Northridge, Chi-Chi). Is the considered pipeline located in a geological basin?

The above uncertainties lead to the search for a better method to systematically generate a more realistic set of synchronized motions along a pipeline, and hence better modeling seismic wave propagation. This would offer an improvement over ASCE practice of using a single input motion, and propagating it along the pipeline at a speed arbitrarily chosen from a range of shear to surface wave velocities.