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Underground pipeline response to earthquake-induced ground deformation

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ABSTRACT

The principal causes of earthquake-induced ground deformation are identified and their interaction with underground infrastructure, primarily pipelines and conduits, is described. The coupled forces normal and parallel to underground pipelines arising from earthquake-induced ground movement are evaluated, including a review of measured stresses on pipe surfaces during large-scale testing, evaluation of frictional forces related to soil-pipe interaction, and the resolution of interaction forces along and across pipelines. Methods for characterizing soil reaction to pipe lateral and vertical movements are presented. The maximum downward pipe force is only about one-third the maximum force determined with conventional bearing capacity equations, thus requiring changes in current analytical and design practice. The analytical results for pipeline response to strike-slip and normal fault rupture are shown to compare favorably with the results of both large-scale and centrifuge tests of soil-pipeline interaction simulating these types of severe ground deformation.

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1. Introduction

Earthquake-induced ground deformation is a major concern for underground infrastructure in areas vulnerable to seismic risk. It is also representative of extreme conditions of soil-structure interaction that accompany floods, hurricanes, landslides, large soil movements caused by tunneling and deep excavations, and subsidence resulting from dewatering and/or withdrawal of minerals and fluids during mining and oil production. Hence, pipeline performance during earthquakes provides a framework for the analysis and design of underground infrastructure that is resilient to a variety of natural and construction-related hazards.

This paper focuses on methods for analyzing underground pipeline and conduit response to large permanent ground deformation caused by earthquakes. It begins with a review of the sources of earthquake-induced soil movement and shows how these movements are converted into soil-pipe reactions normal and parallel to the longitudinal axis of the pipeline. Two-dimensional (2D) finite element (FE) analytical approaches are described, and improved methods are presented for 2D modeling of the coupled forces normal and parallel to underground pipelines during large permanent ground displacements. Methods for characterizing soil reaction to pipe lateral and vertical movements are presented with reference to large-scale tests involving pipe lateral and uplift movement in dry and partially saturated sand as well as plane strain FE soil and pipe continuum models. The analytical results for vertical downward movement of pipe in soil are presented. Analytical results for pipeline response to strike-slip and normal fault rupture are shown to compare favorably with the results of both large-scale and centrifuge tests of soil-pipeline interaction simulating these types of ground deformation.

2. Earthquake-induced ground deformation

As described previously (e.g., [15,17]), earthquakes cause transient ground deformation (TGD) and permanent ground deformation (PGD), both of which affect underground infrastructure. TGD is the dynamic response of the ground, and PGD is the irrecoverable movement that persists after shaking has stopped. It may involve pulses of strong motion that locally exceed soil shear and tensile capacity, causing surficial soil cracks and offsets. PGD frequently results in large movements, such as those associated with surface fault rupture, liquefaction-induced lateral spreading, and landslides.

The principal causes and types of TGD and PGD have been summarized by Bird et al. [5] and are presented in Table 1. In aggregate, they represent the total seismic hazard affecting the performance of underground pipelines and conduits.

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Table 1
Summary of the principal causes and types of transient and permanent ground deformation associated with earthquakes [5].

Type	Cause	Description
Transient	Travelling ground waves	Near surface ground deformation caused by body waves propagating from a seismic source.
	Surface wave generation in large sedimentary basins	Surface waves generated by scattering incoming waves in large sedimentary basins typically several km wide, with depths <1 km.
	Vibration of relatively narrow soil-filled valleys	Deformation of sediment-filled valleys with respect to relatively rigid valley boundaries. Valley width and depths are typically several hundred and several tens of meters, respectively.
	Ridge shattering	Ground disturbance along steep ridges and elevated topography that may be accompanied locally by slip in fractured rock.
	Ground oscillation	Transient lateral shear strains and horizontal movement of liquefiable soil relative to adjacent and underlying competent material.
Permanent	Faulting	The principal components of fault movement include 1) strike, 2) reverse, and 3) normal slip. Reverse and normal faults promote compression and tension, depending on the angle of intersection between lifelines and the fault trace.
	Tectonic uplift and subsidence	Regional changes in dimension associated with crustal deformation. Deformation occurs over a long distance so strains imposed will be small. Subsidence adjacent to water bodies can flood sections of a lifeline and possibly lead to erosion and undermining.
	Liquefaction	Displacement caused by transformation of saturated, cohesionless soils to liquefied state or condition of substantially reduced shear strength. Liquefaction-induced lifeline deformation can be caused by 1) lateral spread, 2) flow failure, 3) local subsidence, 4) post-liquefaction consolidation, 5) buoyancy effects, and 6) loss of bearing.
	Landslides	Mass movement of the ground triggered by inertial forces from seismic shaking. Many displacement patterns are possible. Principal forms of movement include 1) rock falls, 2) relatively shallow slumping and sliding of soil, and 3) relatively deep translation and rotation of soil and rock. Landslides include lurching and soil block movement in which ground displacements are triggered by transient loading of gently sloping deposits underlain by weak soil not susceptible to liquefaction.
	Densification	Decrease in volume caused by seismic vibration of dry or partially saturated cohesionless soil.

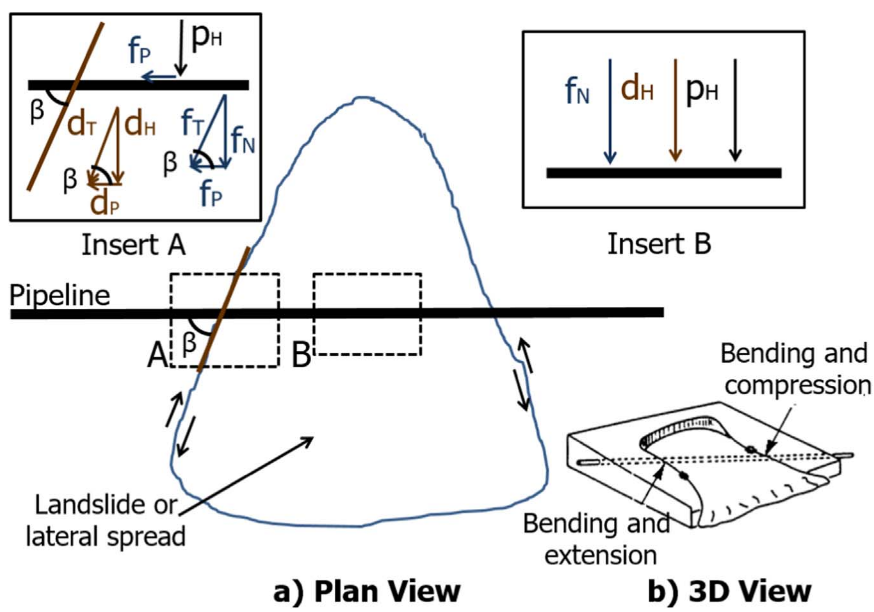

Fig. 1. Plan and 3D views of pipeline intersection with landslide or lateral spread.

To illustrate soil-pipeline interaction, Fig. 1a provides a plan view of an underground pipeline deformed by soil mass movement associated with a landslide or liquefaction-induced lateral spread. There is abrupt ground deformation at the margins of the slide/lateral spread where the pipeline is affected by movement oblique to its longitudinal axis. Insert A shows the direction of lateral soil movement, d_H, and horizontal soil reaction force/unit distance, pH, at the left-hand side of the soil mass. Insert B shows the direction of lateral soil movement and soil reaction force/unit distance, pH, at the center of the soil mass, where two-dimensional (2D) conditions control the horizontal force mobilized against the pipe. The plane strain conditions of soil-pipe interaction in Insert B are consistent with the large-scale tests and numerical simulations used to estimate the maximum horizontal soil reaction forces and force vs. displacement relationships for lateral soil-pipeline interaction (e.g., [12,19]). For 2D plane strain soil movement pH, d_H, and frictional force/unit distance, f_N, are normal to the longitudinal axis of the pipeline.

As illustrated in Insert B, pH under conditions of oblique soil movement is estimated from the large-scale test results and numerical simulations for 2D plane strain conditions in which lateral force vs. displacement relationships use the component of soil displacement, d_H, normal to the longitudinal axis of the pipeline (parallel to the normal frictional force, f_N). There is ample experimental evidence to justify this approach. Ha et al. [7] report measured maximum horizontal soil forces under oblique soil movement in centrifuge tests on pipelines subjected to strike-slip fault displacement that compare favorably with those from large-scale 2D plane strain test results. Moreover, bending strains predicted from 2D finite element simulations of pipeline response to