Response Analysis of Buried Pipeline Under Seismic Action: A Numerical Study

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Abstract

Buried pipes are lifeline utilities as they afford appropriate means to transport drinking water, sewage, gas, etc. During an intense seismic action, the excitation led to the moderate to fatal damage of buried pipelines, eventually disrupting basic human needs. A considerable amount of research has been conducted on analyzing the buried pipelines under fault rupture. However, the discussion on the response of buried pipelines during intense shaking is seldom found in technical writings. To address the current gap, a numerical study on buried pipelines subjected to seismic action has been carried out in order to grasp the pipeline mechanics when the earth shakes. In this research, a 3D soil-buried Ductile Iron (DI) pipe model has been developed, and the seismic excitation has been applied at the base of the soil model considering the seismic force applied to the bedrock. The elastoplastic constitutive model has been considered for soils, while shell element has been chosen to model pipe elements. Seismic analysis is carried out with the El Centro earthquake record applied in the vertical, longitudinal and transverse directions. Simulation results show that the seismic response of the pipeline resulting from the axial earthquake input motion is highest, and consequently, the axial seismic excitations have more influence on the underground pipeline than the other two-dimensional seismic excitations. The present study can be used to develop performance-based design methodologies for buried DI pipelines.

Keywords: *Buried pipe, Seismic excitation, El Centro earthquake, Time-history, Response.*

1. Introduction

A buried steel pipeline is a vital lifeline facility that typically transports water, gas, oil, and other liquids. In general, pipelines are buried underground as they often travel long distances from the source to the distribution. Apart from regular superimposed loads, a significant effect has been seen when the entire pipeline or segment of a pipeline network experiences seismic excitation. The disruption of essential services such as water, oil, gas, etc., can lead to a major catastrophe for the community. To date, a considerable number of damages have been reported due to different earthquakes such as the 1971 San Francisco (O'Rourke et al., 1984), 1994 Northridge (O'Rourke et al., 1996), 1999 Chi-Chi (EERI, 1999b), 2010 Chile (EERI, 2010) earthquakes, 1971 San Fernando earthquake (Jennings, 1971), 1995 Kobe earthquake (Nakata T, 1995), 1999 Kocaeli earthquake (EERI, 1999a), and so on. These examples demonstrate that it is necessary to study failure aspects of buried structures caused by a severe earthquake to protect lifelines from earthquake hazards. Since buried pipelines usually traverse large geographical distances, they could experience a variety of failures due to permanent ground displacement (PGD) and/or wave propagation under seismic excitations.

The seismic response analysis of buried pipelines is somewhat complex since it requires the 3D dynamic analysis of the soil-pipeline interaction under multipoint earthquake excitation (Bulent AO., 1985). Therefore, rigorous analysis is difficult. However, the advent of technology allows the use of a numerical model to investigate complicated problem domains explicitly. Though the drop-down list of numerical tools is quite long, the Finite Element Method (FEM) is considered the most effective and reliable tool for modeling complex analysis. The response of buried pipelines under earthquake faulting has been extensively analyzed and formulated, while the behavior under seismic excitation was seldom found in the literature.

In the particular case of earthquake action, the main purpose of pipeline operators is to minimize seismic risk on the pipeline, safeguarding the unhindered flow of water resources following an earthquake event. Towards this purpose, the structural damage of the pipe should be minimized, in order to maintain the structural integrity of the pipeline and prevent leakage.

Based on the aforementioned discussion, this paper aims to address two challenging objectives: The first is to provide a thorough insight into the seismic behavior of buried flexible pipes subjected to soil loads, traffic load and water pressure. The second is to investigate the displacement, Von Mises stress of the buried pipeline in dry sandy soil under static load conditions and seismic excitations in the axial, transverse vertical and transverse horizontal directions.

2. Numerical Modelling of Buried Pipeline with Soil

A 3D-Finite Element (FE) model was developed to check the response of the buried ductile iron pipeline. In the meantime, the pipeline was defined as a 3D-deformable shell because of the thin thickness of the pipeline and the soil model was defined as a 3D deformable solid body. The pipeline model was aligned with the soil model in the center of the soil model's width according to the buried depth of the pipeline from the top surface of soil to the crest of the pipeline such as 1D (D stands for the outer diameter of pipe) meters as critical depth. The soil model has been formed as a cuboid with a buried pipeline at its center. Following the length of the pipeline, the length (L) of the soil model was also maintained at 30 meters. The width (W) and height (H) of soil were taken as 10 meters both in order to ensure the affordable space in which the pipeline with soil failed when finite element analysis was executed.

A water supply pipeline, designated as DN 1000 (Nominal Diameter of 1000 mm), was selected to execute the study for the largest diameter DI pipeline. The chosen thickness of wall (t) was 15 mm and outer diameter (OD) was 1048 mm, also selected by the following design criterion of DN 1000 (ISO 2531/BS EN 545 and 598). Table-1 shows the mechanical property of DI pipe and material properties of dry sandy soil. A schematic representation of the 3D-FE model of pipeline and soil can be delineated as in Figure 1.

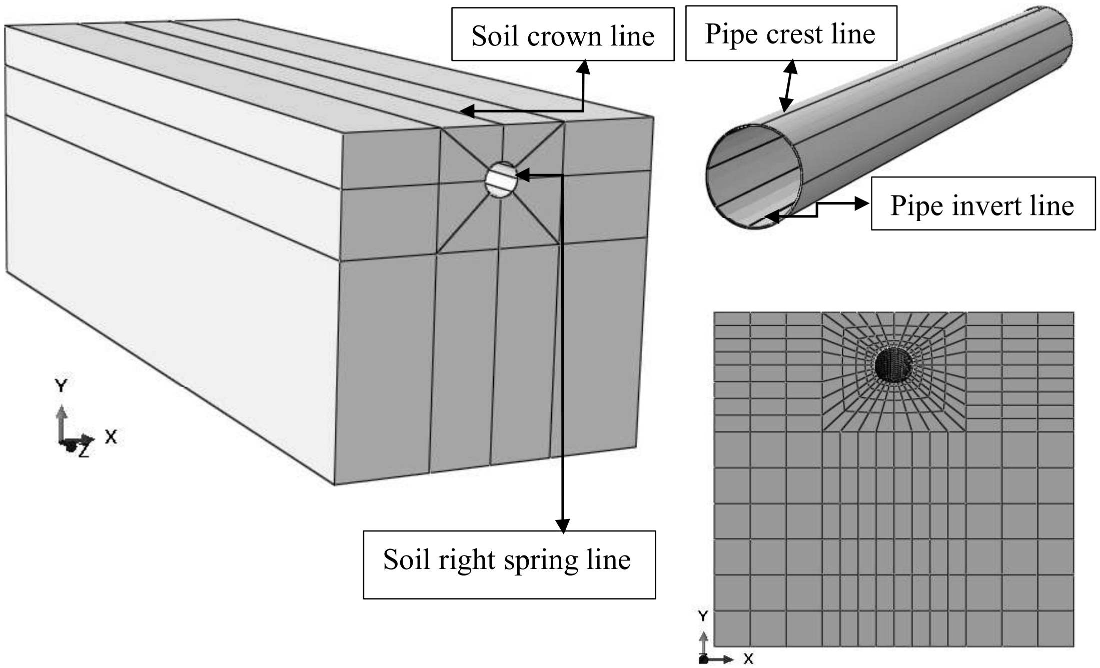

Figure 1: 3D FEM Model of Soil and Pipeline with meshing pattern (XY plane) in CAE Environment

Table 1: Mechanical properties of Kubota Ductile Iron pipe (ISO 2531/BS EN 545 and 598) and Material properties of Sandy soil (Liu et al., 2010)

		Pipe	Soil
Mechanical/ Material property	Parameter	Value	
Elastic property	Mass density (kg/m^3)	7050	1700
	Young's modulus (MPa)	170,000	19
	Poisson's ratio	0.27	0.2
Plastic property	Yield strength (MPa)	300 (minimum)	---
	Tensile strength (MPa)	420 (minimum)	---
	Minimum elongation after fracture (%)	10 (DN 80-DN 1000)	---
	Cohesion (c - Pa)	---	200
	Friction angle (φ - deg)	---	30
	Dilation angle (ψ - deg)	---	2

Table 2: Static and dynamic loads (BSI., 2010, and https://strongmotioncenter.org)

Static Loads	Gravity (N)			9.81
	Traffic load onto ground (kPa)			1100
	Internal water pressure in pipeline (Psi)			100
Seismic Load		X (S00E-Longitudinal Component)	Y (Vertical. Component)	Z (S00E- Lateral Component)
	(PGA) (g)	0.35 at 2.12 sec.	0.21 at 0.98 sec.	0.35 at 2.12 sec.
	History Time (sec)	91.26	91.54	91.26

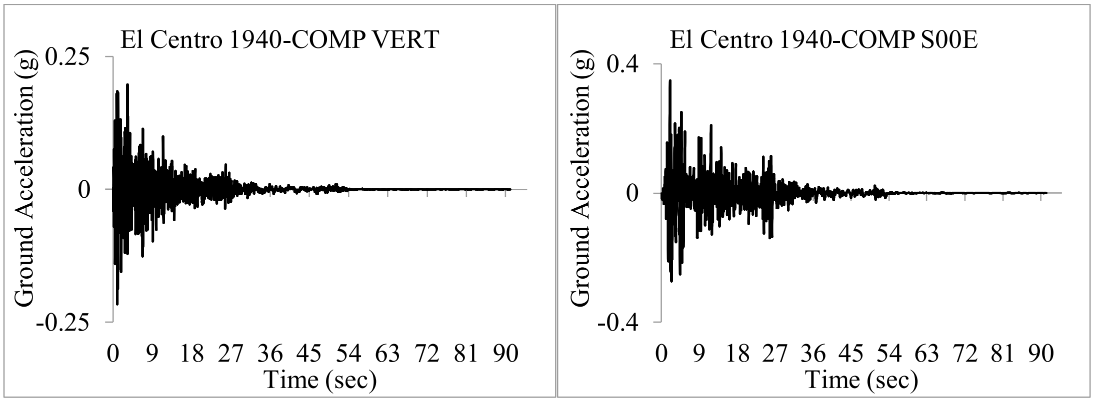

Figure 2. The accelerogram (Vertical acceleration, Transversal acceleration and Longitudinal acceleration) of the El Centro Earthquake of 18th May, 1940 (https://strongmotioncenter.org)

Four-node reduced-integration shell elements (S4R) and eight-node reduced-integration solid elements (C3D8R) were used for the pipeline and surrounding soil, respectively. Mesh encryption was carried out on the pipeline and the soil within 2m around the pipeline to calculate the stress and strain more accurately as mentioned in Figure 1.

The four boundary vertical faces of the soil continuum were constrained in the horizontal direction, i.e., perpendicular to the corresponding faces; the bottom surface was constrained in X, Y and Z directions; no constraint at the top surface was set to be a free surface. Taking into account the infinite length of a buried pipeline, the boundary condition of the pipeline ends as a roller is appropriate because the buried pipeline can be displaced comparatively easily by soil. A Penalty friction algorithm was used for soil-pipe interface interaction. Two seismic excitation components (horizontal and vertical) of the El Centro wave were considered for the present study as shown in Figure 2. The capacity of implicit modelling of pipeline behavior in dry sand was evaluated by 3-D dynamic implicit analysis.

3. Results and Discussion

The maximum pipeline displacement occurred at the crest of the pipeline than at the invert of the pipeline, causing oval shape deformation of the pipeline. Also, buckling occurred at both the crest and invert of the pipeline. Due to roller support at the pipeline end and vertically applied static loads and seismic excitation, the both end pipe sections maintained a regular circular shape, whereas at the middle section up to the pipe end, oval shape deformation generated under compression load. For this reason, the maximum pipe displacement is around 100 cm and 85 cm observed at midspan for both vertical and lateral seismic excitations as shown in Figure-6 (a). As well as from Figure-6 (a), it was also observed that the gap between the displacement distribution along the length was very low and the nature of curves was flat. But in the case of longitudinal seismic excitation, the maximum displacement was found around 180 cm and 170 cm at the left and right pipe end respectively, because of longitudinal seismic excitation with higher PGA applied in the axial direction, resulting in huge bending in the pipe. It can be demonstrated that along the Z direction the pipe experienced huge tension force because of the S00E longitudinal component of the El Centro earthquake. So, the pipe end section may be the critical section to be designed carefully for resisting longitudinal seismic excitation.

Following the oval shape deformation, the maximum stress in the pipe was found at the invert of the pipe than at the crest of the pipe. The maximum stress in the pipe was found around 305

MPa at the pipe end for vertical and 308 MPa for lateral seismic excitations at mid span. But higher stress values of around 332 MPa and 329 MPa were observed at the left and right pipe end section respectively for the longitudinal seismic excitation indicated in Figure 6 (b).
Similarly, in the case of soil, the maximum soil displacement was determined at the crown line of soil due to traffic load. The maximum displacement was observed around 86 cm and 102 cm at the midspan for lateral and vertical seismic excitation; 355 cm and 390 cm at the left and right soil end respectively for longitudinal seismic excitation for the same reason. From Figure 6 (c) it was observed that the displacement distribution along the length was almost the same and flat due to the same traffic load over the entire length for both lateral and vertical earthquake excitation.
From Figure 6 (d) it is depicted that the stress in soil due to seismic excitations was very low compared to the pipe stress. Due to the oval shape deformation of the pipe, as the pipe deformed largely at the crest and invert section, the other two sections, i.e., the left and right spring line expanded outside, resulting in higher stress developing in the soil at the same side. Consequently, the maximum stress in soil was investigated at the right spring line higher than the left spring line. The maximum stress in soil was found at 1 MPa and 0.8 MPa for vertical and lateral seismic excitations respectively. Both the stress distribution curves followed the same trend and were almost flat at mid span. A higher value of stress 1.5 MPa was observed near the end of the soil model for longitudinal seismic excitation.
Finally, it can be said that longitudinal seismic excitation (along the Z direction of the model) produces greater stress and deformation in comparison to the lateral (X) and vertical (Y) directions to the buried pipeline and soil respectively.

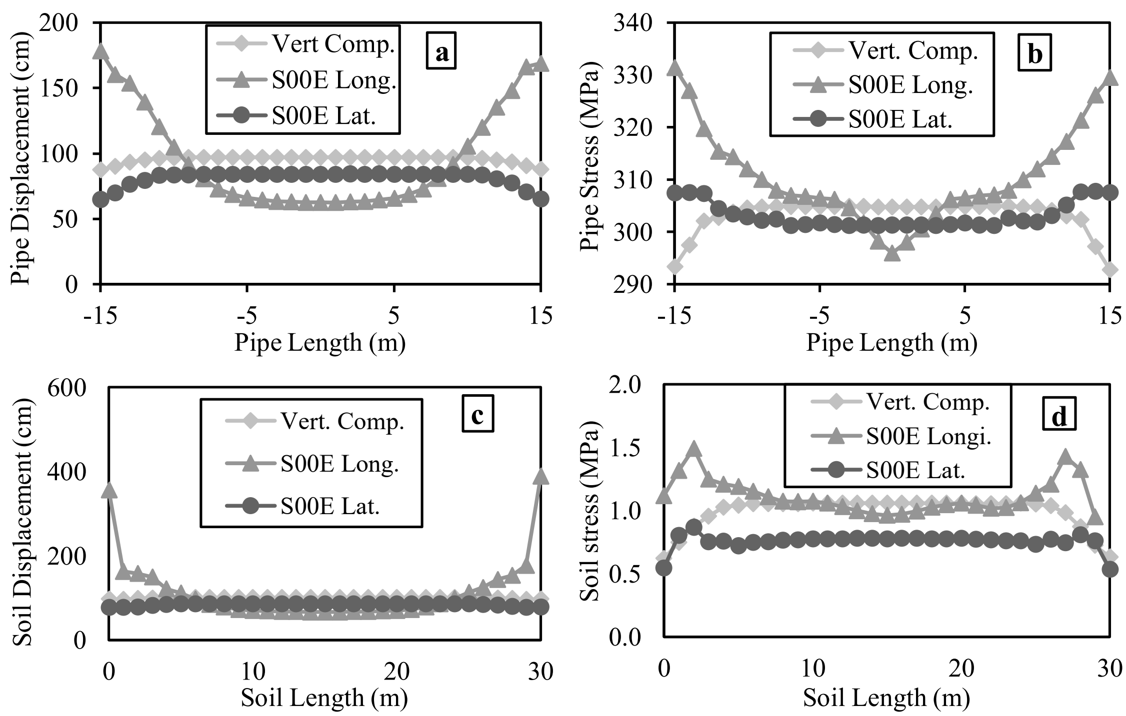

Figure 6. Seismic Response of pipe and soil (a) Max. Displacement along the pipe crest line (b) Max. Stress along the pipe invert line (c) Max. Displacement along the soil crown line (d) Max. Stress along the soil right spring line

4. Concluding Remarks

The seismic behavior of Ductile Iron flexible pipe was investigated in this study. Finite element analyses were carried out to investigate the effects of multidirectional seismic excitations on DI pipe and soil also. The following interesting observations were found:

(1) By comparing the different impacts of three-dimensional earthquakes, it was found that the Z-axes earthquake had the greatest impact on the pipeline. For segmented pipe, the joint should be designed carefully.
(2) From previous research on earthquakes, the pipeline is largely damaged by tension in Z-direction. This paper gives a clear explanation of this phenomenon.
(3) It was found that the magnitude of stress and displacement is maximum at the burial depth equal to the diameter of the pipeline. Hence, it can be concluded that avoiding the burial depth of a pipe equal to the pipe diameter can be more effective from a design point of view.

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