ON THE RESPONSE OF BURIED PIPELINES SUBJECTED TO PERMANENT GROUND DEFORMATION

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Buried pipelines are considered among the most economical and safe methods to transport natural resources such as oil, natural gas and water. Failure of these systems can cause significant impact on the environment and can pose safety threats if flammable contents ignite in populated areas. Failure causes can be related to material deterioration, excavation damage or incorrect operation, however, natural hazardous such as earthquakes and landslides are also major contributing factors. Soil movements associated with natural events can induce high strains and stresses within the pipe and can result in sudden failure. This study aims at investigating the earth loads imposed on buried pipes due to permanent ground deformation. A coupled finite-discrete element model has been developed and used to investigate the response of rigid and flexible pipe systems under axial and lateral ground movements, respectively. In the proposed modeling approach, the buried pipe is modeled using finite elements while the surrounding soil is modeled using discrete particles. Interface elements are used to transfer forces between these two domains. The model is validated by comparing the calculated results with experimental data. The results allowed for better understanding of the axial and lateral forces developing along the affected structures due to the relative movement. Closed-form solutions used in practice to estimate earth loads on pipes are evaluated.

Keywords: Buried pipes; permanent ground deformation; numerical modeling

1 Introduction

One of the major risks to buried pipelines arises from permanent ground deformation (PGD) where soil movement can induce unacceptable strains and stresses in the pipe structure. This condition may result from creeping ground, landslides, slope instability, and earthquakes. Although it is recommended to avoid extending pipelines in areas with potential permanent ground movement, it is sometimes unavoidable that major pipelines be routed through these sloping areas.

The response of pipes to slope movement depends on the orientation of the pipeline with respect to the moving slope. Figure 1 shows an example of two conditions where soil and pipe interact. In the first condition, when the pipe axis is parallel to the direction of the sliding soil, the pipe is subjected to longitudinal (axial) strains and the different sections of the pipe will experience either tensile or compressive stresses. The second condition occurs when the axis of the pipe is normal to the soil movements, the soil, in this case, applies lateral loads to the pipe resulting in bending moment and shear loads on different sections of the pipe. It should be noted that a pipe subjected to slope movement may experience one or more of the above conditions.

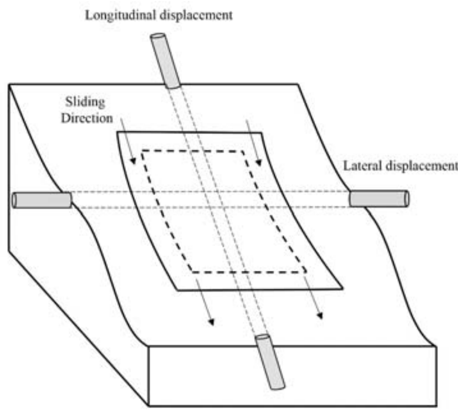

Figure 1. Soil load on pipeline passing throw an area subject to landslides

Since the early 1960s, researchers have studied soil-pipe interaction using experimental, theoretical, and numerical methods (e.g. Trautmann and O'Rourke, 1983; Honegger and Nyman, 2002; Wijewickreme et al., 2009; Daiyan et al., 2011; Ono et al., 2018). Closed-form solutions are usually used to calculate soil resistance for pipes buried in granular soil subjected to axial or lateral ground movement, including ASCE (1984) or ALA (2001). These equations are developed based on simplified assumptions related to the pipe and the surrounding soil or backfill material. Using these equations for all types of pipe and soil materials may lead to uncertainty in the calculated response. Karimian (2006) and Weerasekara (2007) showed that axial forces acting on pipes buried in dense sand are much higher than the calculated values using the commonly used guidelines equations.

The objective of this study is to present a summary of the results of Meidani et al. (2017, 2018) and illustrate the advantage of using three-dimensional (3D) discrete element method in understanding the interaction of soil and buried pipelines under different permanent ground deformations.

2 Pipes Subjected to Axial Ground Movement

ASCE (1984) recommended the following closed-form solution to determine the axial loads on buried pipes in cohesionless soils:

$$F_A = \gamma' \times H \times (\pi\ D\ L) \times \left(\frac{1+K_0}{2}\right) \times \tan(\delta) \quad (1)$$

Where, F_A is the axial soil resistance, γ' is the soil effective unit weight, H is the depth from ground surface to the pipe springline, D is the pipe outer diameter, L is the pipe length, K_0 is the coefficient of lateral earth pressure at rest and δ is the friction angle between the soil and the pipe. Over the past few decades, researchers have studied soil-pipe interaction using experimental, theoretical, and numerical methods (e.g. Newmark and Hall, 1975; Trautmann and O'Rourke, 1983; O'Rourke and Nordberg, 1992; Honegger and Nyman, 2002; Wijewickreme et al., 2009; Daiyan et al., 2011; Dang and Meguid, 2013; Liu et al., 2015; Almahakeri et al., 2016; Zhang et al., 2016). Most of the numerical analyses were performed using the finite element (FE) method. The discrete element method (DEM), on the other hand, has proven to be suitable for modeling granular material subjected to large deformation. The method was first proposed by Cundall and Strack (1979) and has been used to analyze various geotechnical engineering problems. Laboratory tests have been successfully modeled by researchers using DEM to investigate the microscopic behavior of soil samples. Cui and O'Sullivan (2006) used discrete elements to study the macroscopic and microscopic behavior of granular soil under direct shear test conditions. Tran et al. (2013; 2014) proposed a finite-discrete element framework for the 3D modeling of soil structure interaction under various loading condition. The analysis allowed for the soil arching and radial pressure on a cylindrical wall to be visualized. Furthermore, Ahmed et al. (2015) conducted laboratory experiments and finite-discrete element analysis to study the role of geogrid reinforcement in reducing earth pressure on buried pipes. It has been shown in these studies that discrete element or coupled finite-discrete element approaches are effective in capturing the response of structural elements such as buried pipe and investigating their interaction with the surrounding soils.

2.1 *Numerical model*

The experimental results used to validate the numerical model are based on those reported by Wijewickreme et al. (2009). The response of a buried steel pipe subjected to axial soil movement was investigated in a test chamber measuring 3.8 m in length, 2.5 m in width and 1.82 m in height. Graded Fraser River sand with in-situ density of 16 kN/m^3 was used as a backfill soil. The mechanical characteristics of the sand are reported based on triaxial and direct shear tests conducted under confining pressures that range from 15 to 50 kPa. The steel pipe used in the experiments has an outside diameter of 46 mm and a wall thickness of 13 mm. The interface friction angle (δ) between the backfill material and the steel pipe was reported to be 36^o. The pipe is placed over 0.7 m of bedding layer up to the springlines and covered with 1.15 m of the backfill material. This corresponds to a height-to-diameter ratio (H/D) of 2.5.

A numerical model has been developed using the open source code YADE (Kozicki and Donzé, 2008) such that it replicates the geometry and test procedure used in the experiments. Various packing algorithms can be used to generate DEM samples for both standard soil tests and large scale pullout simulations. Techniques such as the compression method (Cundall and Strack, 1979), gravitational method (Ladd, 1978), triangulation-based approach (Labra and Onate, 2009) and radius expansion method (Itasca, 2004) are widely used for this purpose. Details regarding the calibration of the DE model using direct shear and triaxial tests are given elsewhere (Meidani, 2018). Particle upscaling with two different scale factors has been used in this study to gradually reduce the number of particles and maintain the time step at a reasonable value. In this process, a balance between the computational costs and the scaling effects on the global response needs to be considered. The pipe is modelled using triangular facet elements (flat discrete elements) with material modulus comparable to that of the pipe. The interface friction angle between the facet elements and the soil particles is known to play an important role in the analysis and needs to be properly chosen. The pipe wall is modeled using a total of 1216 facet elements arranged in a Hexadecagonal shape. The length of the pipe is chosen such that it extends slightly outside the back of the chamber to ensure continuous contact with the soil during the pullout process. A close view of the pipe and the nearby particles is shown in Figure 2.

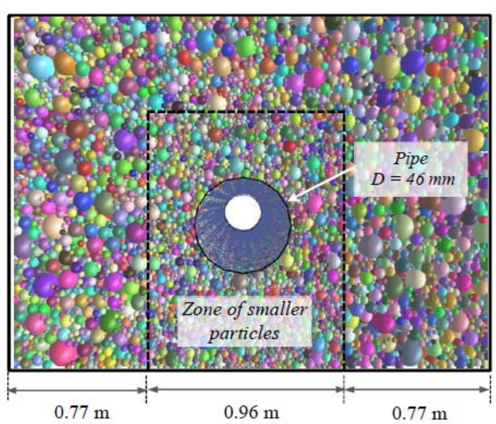

Figure 2. Particle distribution in the close vicinity of the pipe

2.1.1 *Pipe response to axial loading*

The relationship between the pullout force and the corresponding pipe displacement is shown in Figure 3. To facilitate comparison between the numerical and experimental results, the axial resistance F_A is normalized with respect to soil density, pipe length (L), depth (H) and diameter (D) as represented by Eq. 2.

$$F'_A = F_A / (\gamma' \times H \times \pi \times D \times L) \tag{2}$$

The calculated pullout response (Figure 3) shows a peak normalized axial force of about 1.0 at pipe displacement of approximately 9 to 12 mm with post peak value of 0.89 after reaching axial displacement of about 115 mm. The overall response of the soil-pipe system is found to be reasonably captured by the model and the calculated peak value of the pullout force is similar to the measured value with 20% overestimation in post peak resistance. As the maximum axial soil resistance (pullout force) is of prime importance in this case, and giving the simplified nature of the DEM model, the calculated response is considered to be acceptable.

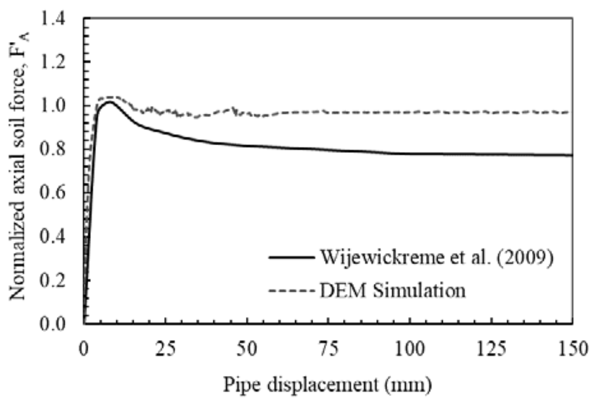

Figure 3. Comparison between calculated and measured pullout response of the pipe

The normalized pullout load is compared with the maximum axial load recommended by ASCE (1984). Eq. 1 is used to determine the peak pullout load, where K_0 value ($K_0 = 1 - \sin\phi'$) is calculated using ϕ' of 44° and the interface friction angle (δ) is assumed to be 36°. This corresponds to the reported peak friction angle of Fraser River sand. Figure 4 shows the normalized axial pullout load obtained using DEM and peak axial soil resistance calculated based on the ASCE recommendation.

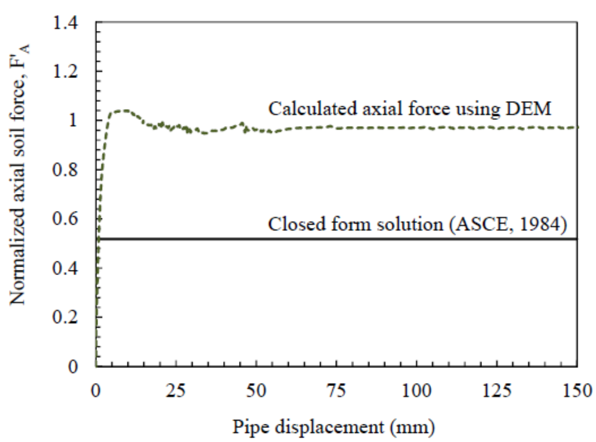

Figure 4. Normalized soil load in the axial direction versus pipe displacement

The closed-form solution was found to give a significantly lower peak pullout load as compared to that calculated using DEM. Among the parameters in Equation 1, the use of K_0 value under these loading conditions seems to be unrealistic. The discrepancy between the analytical and numerical solutions arises mainly from the underestimated normal stresses. To investigate the role of normal stresses on the pullout load, Meidani et al. (2018) compared the measured resistance with those calculated numerically using different earth pressure coefficients. For the given soil density (dense sand) and pipe depth (H = 1.12 m) the average normal stress on the pipe at the end of the pullout procedure is found to be about 23 kN and the corresponding K value is found to be about 1.6. Caution needs to be exercised when analyzing rigid pipes under axial loading condition using the available closed-form solutions.

3 Pipes Subjected to Lateral Ground Movement

The commonly used approach to calculate the ultimate lateral soil resistance on a buried pipe is generally expressed as follows (ALA, 2002):

$$P_u = \gamma \times H \times N_q \times D \tag{3}$$

where P_u is the peak soil lateral resistance; H is pipe burial depth; D is diameter of pipe and N_q is a dimensionless force factor. It is noted that N_q is a function of H/D ratio and soil friction angle and there are different charts to obtain this value. The American Lifeline Alliance (ALA, 2001) recommended the use of Hansen (1961) to estimate N_q value.

In this section, the coupled FE-DE approach is used to evaluate the response of medium density polyethylene (MDPE) pipe buried in dense sand and subjected to lateral ground movement. The numerical model was created based on the experimental work reported by Weerasekara (2007). A polyethylene pipe 1.5 m in length was buried under 0.6 m of Fraser river sand and pulled laterally while recording pipe deformations and pulling forces. The Fraser River sand used in the experiment, with relative density of 75%, is modeled using spherical particles following the same particle size distribution of the actual soil. Given the size of the 3D model in this study, particle upscaling was used where a scale factor of 30 was assigned to the particle size distribution. To simulate the loading process, lateral load was applied symmetrically to the pipe ends as illustrated in Figure 5. Model calibration and other numerical details and are given elsewhere (Meidani, 2018). The model is first validated using experimental data and then used to investigate the response of the MDPE pipe to lateral soil movement. The available design expression of ALA (2001), that is conventionally used to calculate lateral loads on buried pipes, is evaluated.

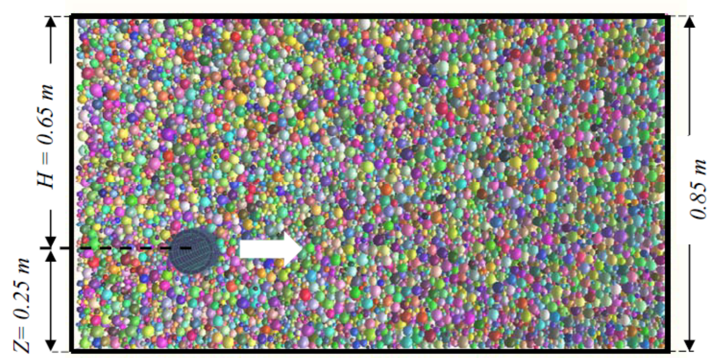

Figure 5. The coupled FE-DE model showing the loaded pipe

3.1 *Pipe response to lateral loading*

The relationship between the applied force and the lateral displacement are presented in Figure 6. It should be noted that the pulling force is for one end of the pipe. The outcome of the analysis is found to be in agreement with the experimental results and the peak lateral force is estimated at about 8 kN. Since the peak lateral force (soil lateral resistance) is of paramount importance in this study, and given the simplified nature of the analysis, the results of the coupled simulation are considered to be acceptable.

In equation 3, N_q is the capacity factor and researchers used different approaches based on empirical methods. Pipe burial depth, pipe diameter and soil friction angle are among the main parameters used to determine N_q. Less emphasis is placed on the pipe

stiffness in the equation. This implies that, two pipes of different material (e.g. steel and MDPE) of the same diameter buried at the same depth, are expected to carry the same maximum lateral soil force.
The results of the coupled analysis are compared with three different solutions to calculate the peak force for laterally loaded pipes in sand.

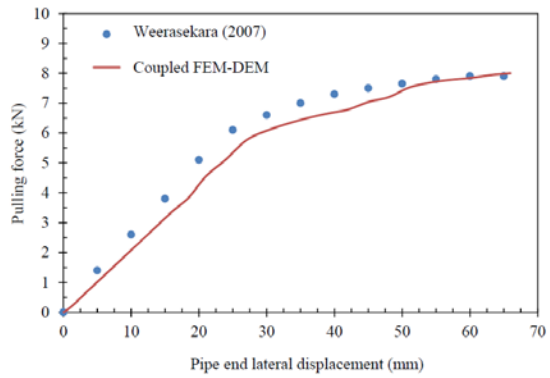

Figure 6. Comparison between the measured and calculated responses of the pipe

Table 1 compares the results of the numerical analysis with some of the common methods used to calculate the ultimate lateral resistance of pipes in sand. It should be noted that, the numerically calculated value of P_u is obtained by plotting the applied force against the lateral displacement as illustrated in Figure 6.

Table 1. Comparison between results obtained using different methods for pipes in sand

Reference	*Nq*	P_u (kN)	Comments
Current study	-	8.0	Laterally loaded MDPE pipe
Audibert and Nyman (1977)	37	66	Laterally loaded pipe
ASCE (1984) [Based on Trautmann and O'Rourke, 1985]	16	28	Laterally loaded steel pipe
ALA (2001) [Based on Hansen, 1961]	40	71	Rigid pile against transversal force

It is found that closed-form solutions generally overestimate the ultimate soil force. The commonly used ALA method produced force values that are several times higher than those calculated numerically for flexible pipes.

4 Conclusions

Three-dimensional numerical studies are conducted to investigate the behavior of pipes buried in dense sand and subjected to axial and lateral soil movements. Discrete element models are developed and used to simulate the pipe movement process under axial loading. The measured soil stresses acting on a pipe in dense sand material are significantly higher as compared to the initial radial stresses. This increase in radial stresses on the pipe under axial loading condition is explained by the dilation of the dense sand during shear deformation. Hence, soil condition surrounding the pipe is not considered at-rest and a new lateral pressure coefficient K (as opposed to K_o) needs to be determined for the calculation of peak axial resistance of the soil.

The relative soil-pipe movement for MDPE pipes subjected to lateral loading is modeled using coupled FE-DE analysis. The pipe response is found to differ from that experienced by pipes under axial loading. The numerically calculated ultimate lateral soil load on MDPE pipes is found to be significantly smaller than that obtained using the ALA (2001) recommendations. It should be noted that only symmetrical loading is considered in this study. Further analysis is needed to examine wider range of soil and pipe parameters as well as loading conditions to confirm these findings.

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