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Characterization of soil-structure interaction for seismic design of hazard-resistant pipeline systems with enlarged joints

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ABSTRACT: New segmented pipeline systems, with improved materials and jointing mechanisms, are being employed to address water distribution network vulnerability to seismically-triggered permanent ground movement such as liquefaction-induced lateral spreading and landsliding. Opposing their improved displacement capacity and overall performance, these systems typically include connections that are larger in cross-section than standard jointing mechanisms, and therefore develop elevated levels of interaction with surrounding medium in response to the relative soil-pipeline movement needed to accommodate earthquake-induced ground displacements. This assessment builds on existing design equations and full-scale experiments to assess the non-linear resistance force that develops at enlarged pipe bells and joint restraints in response to axial soil-pipeline interaction. Several methods of calculating design values for seismic evaluation are provided and compared against test data normalized to account for pipeline depth and annulus size. Results provide needed inputs for the analysis and design of hazard-resilient pipeline systems.

1 INTRODUCTION

Earthquake-induced ground deformation damages vulnerable underground infrastructure systems, leading to interruption of vital services needed for immediate emergency response and longer-term economic and societal recovery. Improved seismic resilience of vulnerable, buried infrastructure networks requires replacement or rehabilitation with hazard-resistant systems. For water distribution, new segmented pipe products have been developed that accommodate ground movement through improved materials, which allow elevated levels of axial and bending strains along the pipe barrel, and jointing mechanisms that provide improved expansion, contraction and deflection capacity. The introduction of new seismic products has catalyzed the need for new design and analysis methods.

Recognizing the need for water and wastewater pipeline seismic design guidelines, the American Society of Civil Engineers (ASCE), under the Pipeline Division of the Utility Engineering and Surveying Institute (UESI) and in collaboration with ASCE's Infrastructure Resilience Division (IRD), is developing a new manual of practice (MOP) intended to provide the basis for a future standard for the seismic design of buried pipelines. In support of this effort, Davis & Wham (2019) proposed an analytical approach for characterizing the response of various continuous and segmented pipeline systems to earthquake-induced permanent ground movement. Their approach, and the focus of this paper, concerns large permanent ground movement oriented parallel to a pipeline, patterns characteristic of shallow landslides and liquefaction-induced lateral spreads. The model provides a means of estimating the strain demand on pipelines while considering their inherent capacities to accommodate movement. The need for the new model stems from the introduction of various hazard-resilient pipeline systems into the market and supplementary efforts to define performance categories with respect to levels of potential permanent ground deformation. For example, Wham et al. (2019) employs the closed-form solution to assess the axial Connection Force Capacity required for a specific pipe system to be considered for one of the four seismic performance classifications.

The Wham & Davis (2019) approach is predicated on identifying a representative longitudinal frictional resistance force per unit length, f_r, of the pipe system. The value defined for a particular pipeline significantly impacts the system's expected performance and is dependent on both burial conditions and pipe geometry. This study focuses on appropriately defining f_r for large earthquake-induced relative soil-pipeline longitudinal displacements by considering the additional axial force from enlarged bells, joint harness restraints, and other anchor-like components that develops progressively and includes contributions from friction, passive bearing pressure, and soil yielding/flow.

2 CONTINUOUS PIPE FRICTIONAL RESISTANCE

Under large ground movements, such as those associated with landslides and earthquake fault rupture, researchers have taken various approaches to quantify axial response for different pipe materials. For example, experimental work has been undertaken to address axial response of polyethylene (Weerasekara & Wijewickreme 2008; Wijewickreme & Weerasekara 2015), steel (Wijewickreme et al. 2009) and coated pipes for gas distribution (Scarpelli et al. 2003). Various numerical works (i.e. Meidani et al. 2017) have employed beam on elastic foundation, 1-D beam element spring slider, and 3D continuum approached to characterize friction along continuous pipelines. While these and other studies provide important contributions to the problem, a traditional approach is commonly adopted in practice.

The state of practice for determining longitudinal friction along buried pipelines is typically defined as the frictional resistance per unit length of pipe, f_p, using the following equation proposed by American Society of Civil Engineers (1984):

$$f_p = \mathrm{F/L} = \left(\frac{1+\mathrm{K_o}}{2}\right)\tan(\delta)\gamma \mathrm{H}\pi D_p \tag{1}$$

where: K_o is the lateral at rest earth pressure coefficient; H is the depth to pipe springline; D_p is the pipe outer diameter; γ is the total unit weight of soil; δ is the pipe/soil interface friction angle; L is the length of pipe in contact with soil; and F is the axial force from friction.

This expression is based on assumptions of known lateral earth pressure and friction interface angle, both of which can vary, sometimes significantly, depending on backfill placement, soil properties, and many other conditions.

For typical, non-seismic, design the longitudinal soil resistance plays an important role in reducing relative soil-pipeline displacements and limiting axial pullout or force associated with internal loads induced by pipe pressurization. For example, absent the use of thrust blocks, the distance from a fitting or dead-end along which each traditional bell and spigot push-on joint must be restrained from pullout is determined based on the axial friction that develops along the pipe. Once the total frictional force, F, is greater than the axial force from pressurization, joint restraints are no longer needed to restrain joint movement due to internal pressure.

Under these traditional design assumptions, it is conservative to underestimate the frictional resistance, as this frictional component is beneficial to resisting the design load (i.e., internal pressure). Full-scale axial pull tests on pipes embedded in various soils have consistently shown that the ASCE 1984 equation under predicts the friction along a pipe (Wham et al. 2018; Wijewickreme et al. 2009). For seismic design, interface friction imposes loading onto the pipeline and should be considered a demand for which underestimation could be cause for elevated loading conditions and premature system failure.

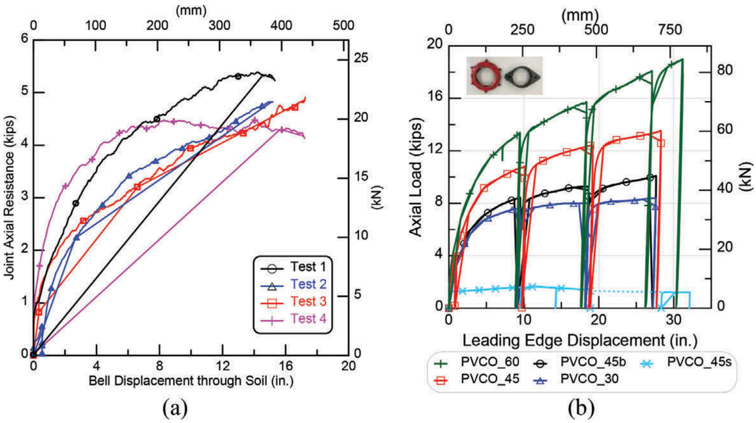

Figure 1. Full-scale axial pull tests on (a) HRDIP (Wham et al. 2017) and (b) PVCO pipe with joint restraints at various burial depths and with joint restraints of varying geometry (Wham et al. 2018).

3 JOINTED PIPE EXPERIMENTAL TESTING

While most previous studies investigate axial friction on continuous pipelines, absent joint restraints, enlarged bells, or other common protrusions of the pipe cross-section, recent full-scale experiments on pipes with jointing elements have identified the considerable influence of these

connections on the axial system response. Full-scale fault rupture simulations performed at Cornell University to seismically qualify new hazard-resilient piping systems consistently demonstrated the influence of jointing elements on the development of axial strains along segmented pipelines (Pariya-Ekkasut 2018; Wham et al. 2016). As part of an experimental testing program developed by the researchers, a series of axial pull tests on pipes buried in soil were performed on specimens with enlarged bells and joint restraint systems.

Wham et al. (2017) report on one series of hazard-resistance ductile iron pipe (HRDIP) pull-through procedures. These four tests were performed at consistent burial depths, H_c=760 mm (30 in.) of cover to pipe crown, and soil properties, but with modifications to geometry of the test specimen, soil conditions, and pipe wrapping. Figure 1a shows the joint resistance force that develops when pulling a 3.8-m (149-in.)-long section of 150-mm (6-in.) nominal diameter pipe approximately 400 mm (16 in.) through soil.

Another series of axial pull tests were performed on PVCO pipe with bell-and-spigot joints restrained from pullout by metallic joint restraints at each connection (Wham et al. 2018). The axial force required to pull the specimens at variable depths and with different joint restraints are provide in Figure 1b. These tests were performed at representative burial depths of 760, 1140 and 1520 mm (30, 45, and 60 in.) and with two different joint restraints of varying geometry and cross-sectional areas, as shown in Figure 2a and 2b. The test results vary significantly with depth and are impacted by the size of joint restraint.

3.1 *Experimental normalization*

The joint resistance for each of the six pull tests under consideration are provided in Figure 3a. The unload/reload curves were removed from the PVCO data sets and the contribution of frictional resistance from the pipe barrel, estimated from straight pipe pull test results (PT45s shown in Figure 1b), was subtracted from the specimen axial pull force to provide an isolated measure of the axial joint resistance force, F_{jr}.

Drawing on the normalization method employed by Wijewickreme et al. (2009), the data from full-scale tests are compared in Figure 3b utilizing the expression:

$$(F_{jr})' = F_{jr} / [\gamma H \pi D_p] \tag{2}$$

Given that the soil unit weight and pipe diameter for all tests were identical, Figure 3b shows the data normalized relative to depth. The three tests performed with the same PVCO joint restraint show good correlation while the other three tests are less compatible. The results suggest a that a normalizing factor for considering joint geometry is useful.

To define joint geometry normalization the cross-sectional area of influence perpendicular to the longitudinal axis of the pipeline is required. For circular bells this projected area is simply determined from the bell outer diameter, D_b. For joint restraints and other more complicated geometry this value can be approximated from CAD drawing to estimate the connection influence area (and should eventually be provided by the manufacturer). The influence area is used to back calculate a representative outer diameter, D_j, which is equivalent to a circular annulus of equal bearing area.

Figure 4a plots the test data for a normalization considering the ratio of pipe diameter, D_p, to joint diameter, D_j, following:

$$(F_{jr,dia})' = F_{jr} / [\gamma H \pi D_p] (D_p / D_j) = F_{jr} / [\gamma H \pi D_j] \tag{3}$$

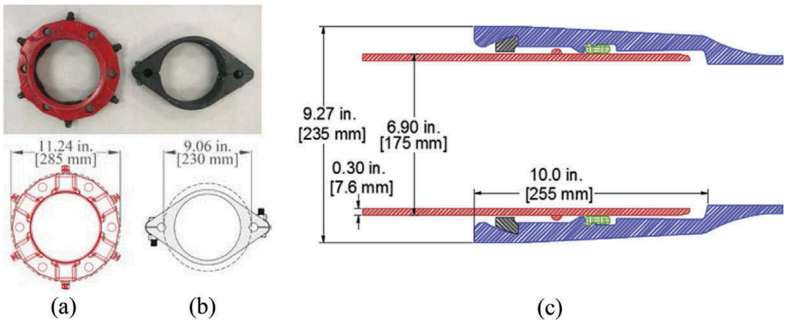

Figure 2. Drawings of joint restraints used for (a) PVCO axial pull tests 30, 45, and 60, (b) PVCO restraint used for axial pull test PVCO_45b, and (c) HRDIP bell used in the DI_30 pull tests.

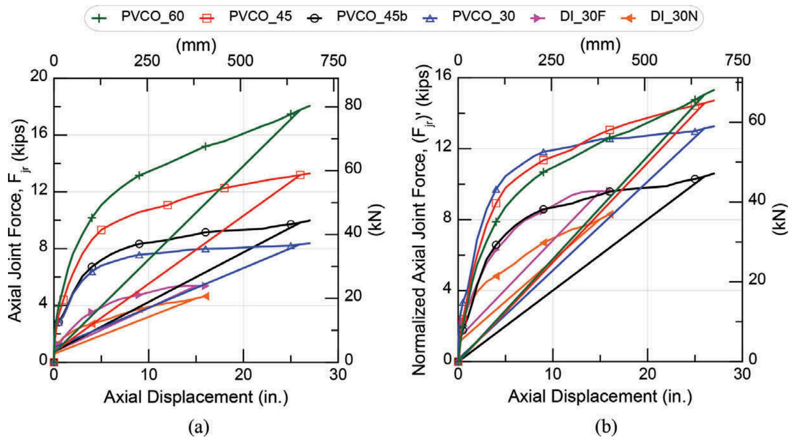

Figure 3. Full-scale axial pull test results for (a) axial joint resistance force and (b) that data normalized by depth of burial.

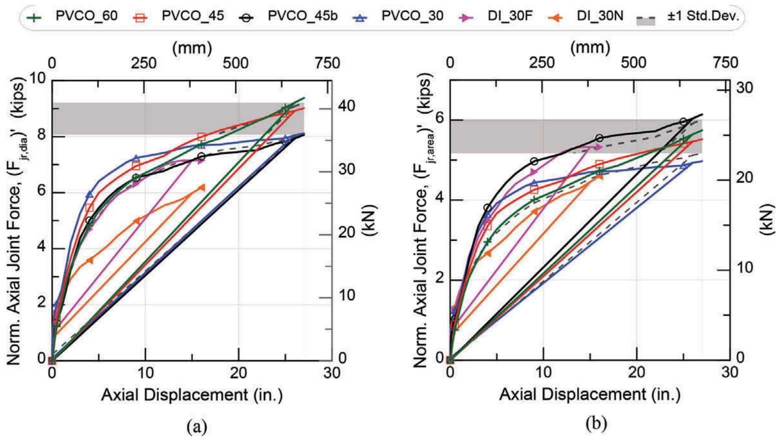

Figure 4. Full-scale axial pull tests normalized by (a) depth and joint diameter and (b) depth and joint cross-sectional area

while Figure 4b provides the same dataset plotted relative to the effective area ratio given by the expression:

$$(F_{jr,area})' = F_{jr}/[\gamma H \pi D_p](A_p/A_j) = F_{jr}/[\gamma H \pi D_p](D_p{}^2/D_j{}^2) \quad (4)$$

The shaded area in Figure 4a represents plus/minus one standard deviation from the average of the five flat faced tests (excluding DI_30N) while Figure 4b provides one standard deviation considering all six large-scale tests. The normalization plots demonstrate good correlation among full-scale results. The correlation suggests that the axial friction force vs. displacement curve from the tests may be useful in approximating the response of other jointed systems when the pipeline burial depth and joint geometry are appropriately considered.

The outlier to the comparisons in Figure 4 is test DI_30N, in which the bell neck was pulled through the soil. This test result suggests a caveat when the leading edge of the annulus is sloped relative to the pull direction and shows normalizing by projection area provides a better estimate than by diameter. Wham et al. (2017) demonstrated an approximately 15% increase in required pull force when comparing results from the flat bell face direction (DI_30f) to the sloped bell neck orientation (DI_30n). While beyond the scope of this paper, further study is necessary to better characterize the influence of annulus inclination. Until further research is available, the authors suggest the conservative approach of assuming flat face interaction based on a joint's largest cross-sectional dimensions.

4 PROPOSED FRICTIONAL RESISTANCE SOLUTIONS

Three potential solutions for providing an estimate of resistance force per length, f_r, along a segmented pipeline will be investigated relative to the ASCE (1984) solution and full-scale experimental results. Essentially, the intention is to define the resistance force per unit length of a pipe system, f_r, by considering the primary contributions of the (1) barrel frictional resistance distributed along the pipeline and (2) localized resistance force of the enlarged joints as:

$$f_r = f_p + f_j = f_p + F_{jr}/L_p \quad (5)$$

where f_p is defined as the frictional resistance along the pipe barrel, estimated from Equation 1, and f_j is the joint resistance force distributed along each pipe segment length, L_p.

A preliminary method for estimating a reasonable frictional resistance is to implement Equation 1 with the addition of a term that utilizes the effective joint diameter, D_j, rather than the pipe diameter, D_p. In other words, this approach simply assumes the entire pipe barrel is enlarged to account for elevated friction. The expression can be written as:

$$f_{r,dia}=\left(\frac{1+\mathrm{K_o}}{2}\right)\tan(\delta)\gamma\mathrm{H}\pi D_j \tag{6}$$

Another approach is to utilize an effective area ratio. The increase in frictional resistance is proportional to the increase in area provided by the joint over the area of the pipe barrel. The frictional resistance can be expressed as:

$$f_{r,area}=\left(\frac{1+\mathrm{K_o}}{2}\right)\tan(\delta)\gamma\mathrm{H}\pi D_p\left[1+\frac{(A_j-A_p)}{A_p}\right] \tag{7}$$

Another estimate of frictional resistance of pipe protrusions stems from a pipe ramming solution proposed by Meskele & Stuedlein (2015) based on work by Weber & Hurtz (1981). Pariya-Ekkasut (2018) demonstrates how this solution can be adapted to provide an estimate of the force that develops from relative movement of soil and an enlarge annulus. The face resistance, R_f, is define as:

$$R_f = r_f A_{eff} = r_f \frac{\pi}{4}\left[D_j{}^2 - D_p{}^2\right] \tag{8}$$

where A_{eff} is the additional effective area of the enlarged bell or joint restraint. The unit face resistance, r_f, is defined as:

$$r_f = \lambda H' \tan\phi' \tag{9}$$

where H, depth to pipe centerline, and γ', effective unit weight of soil, represent overburden stress at the pipe springline and ϕ' is the effective soil friction angle. The coefficient of face resistance, λ, for $\phi' \leq 45°$ can be estimated as (Stuedlein & Meskele 2012):

$$\lambda = \frac{3\pi}{2}e^{\pi\tan(\phi')} \tag{10}$$

Combining Equations 8 to 10 provides a single expression from which the contribution of joint frictional resistance can be approximated from the pipe ramming solution:

$$R_f = \frac{3\pi}{2}e^{\pi\tan(\phi')}H\gamma'\tan(\phi')A_{eff} \tag{11}$$

Applying the solution over a typical pipe length, L_p, the follow expression can be written for the pipe ramming solution:

$$f_{r,ram}=\left(\frac{1+\mathrm{K_o}}{2}\right)\tan(\delta)\gamma'\mathrm{H}\pi D_p+\frac{3\pi}{2L_p}e^{\pi\tan(\phi')}H\gamma'\tan(\phi')\ A_{eff} \tag{12}$$

The proposed single value approximations for system resistance force are shown relative to the six experimental procedures in Figure 5. The plots provide the frictional resistance force per unit length, f_r, of each test calculated from the measured axial pull force divided by the burial length. It is noteworthy to observe that the pipe barrel frictional resistance, calculated from Equation 1 and typically used in practice, is reached at marginal levels of specimen displacement, consistently under predicting the force required to initiate relative movement between the segmented pipe specimen and soil. This observation is consistent with continuous pipe experiments noted previously and occurs in both the PVCO and DI tests despite considerably different f_p values, owing to the difference in interface friction angle and material stiffnesses.

The three proposed methods for approximating f_r provide varying attributes. While the pipe ramming solution, $f_{r,ram}$, has the greatest value for the PVCO tests with larger restraint influence area, the experimental data exceeds this value at axial displacements ranging from 380 to 640 mm (15 to 25 in.). The DI tests exceed the pipe ramming solution after only 125 to 230 mm (5 to 9 in.). Interestingly, the area ratio method provides the largest estimates of frictional resistance per length for the DI tests. All test results exceed the pipe ramming solution at or before about 400 mm (16 in.) of displacement, except for PVCO_30 where this solution correlates well with the maximum value of that test. The pipe diameter and area solutions provide intermediate values of f_r that are appropriate for axial displacements ranging from about 6 to 75 mm (0.25 to 3 in.).

It is necessary to put these results in context. Figure 6 shows an illustration of a segmented pipeline response to a pattern of ground movement (Wham & Davis 2019). While the joints close to the ground cracks may experience significant levels of relative soil-structure displacements, not all joints along a pipe's length will experience equal levels of relative displacement. Moreover, the length of pipe over which friction will develop is dependent of the pipe system's characteristics. For example, consider a low-modulus continuous pipe system that does not have mechanical joints capable of axial displacement vs. a hybrid system composed of relatively stiff segments of pipe connected by large, displacement accommodating joints every 6 m (20 ft). The continuous pipeline must mobilize a significantly longer section of pipe to develop strain needed to accommodate ground movement, resulting in smaller average relative movement between pipe and soil. In contrast, the segmented pipe will accumulate significantly larger near fault displacements over a shorter pipe length resulting in greater soil-structure

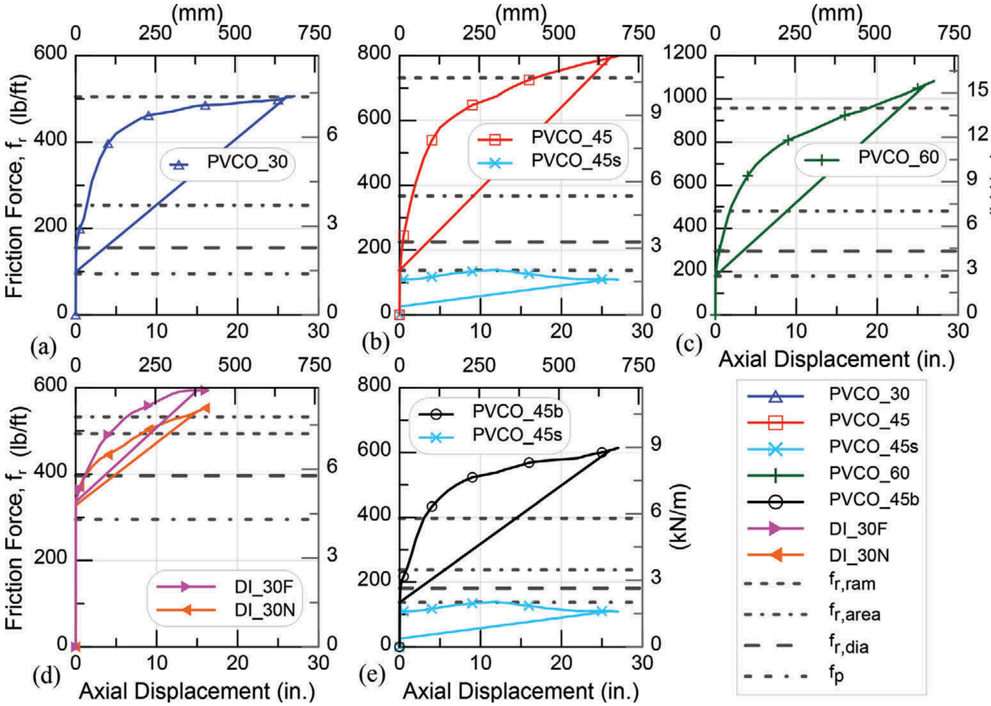

Figure 5. Comparison among full-scale axial pull test results and methods of approximating frictional resistance

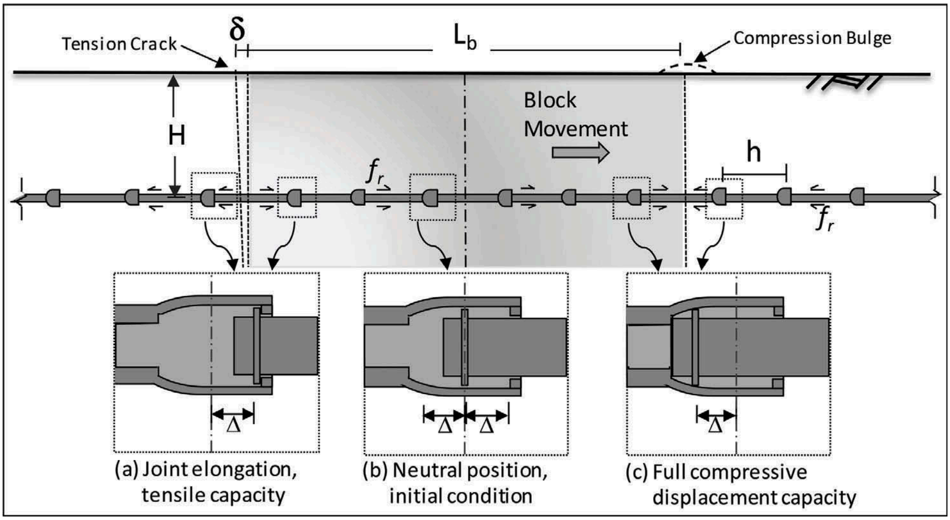

Figure 6. Comparison among full-scale axial pull test results and methods of approximating frictional resistance (Wham & Davis 2019).

interaction and, to appropriately characterize the average interaction force, selection of a more conservative method (i.e. larger f_r) for determining the force resistance parameter.

To implement a single term, f_r, to define the resistance along the entire pipe length requires averaging of the significant frictional effects close to the rupture plane with those further away. While this study presents methods that are more representative of the friction force that develops along hybrid-segmented pipelines, it is the opinion of the authors that establishment of a more robust method for characterizing frictional resistance of a system requires further investigation through development of parametric numerical simulations as well as additional experimental testing to address additional factors omitted by the present study (e.g., pipe diameter, soil type, annulus inclination).

5 CONCLUSIONS

This paper provides approaches to account for the non-linear resistance force that develops at enlarged pipeline joints in response to axial soil-pipeline interaction. The assessment builds on existing design equations used to calculate frictional resistance along buried structures and incorporates multiple full-scale experimental procedures designed to quantify the interaction between enlarged pipe bells and joint restraints typical of these new systems. Several methods of calculating design values for seismic evaluation are provided and compared against test data normalized to account for pipeline depth and anchor size. The results of this paper provide methods for estimating the frictional resistance force, f_r, along a pipe system, a necessary input for the analysis and design of hazard-resilient pipeline systems.

Several caveats should be noted. The reported experiments were performed in a soil box of finite dimensions. It is possible boundary effects may have impacted results at large levels of axial displacement. Additional assessments of boundary conditions are needed at full and/or reduced scale. Only a single pipe diameter buried in a soil of consistent properties was investigated. Further experimental efforts are needed to identify the ability of the results to scale with pipe diameter and appropriate ranges of joint geometries for various soil types.

Regarding test soil conditions, the experiments were performed shortly after the pipe was buried (typically <7 days). Granular soils may develop additional bonding over time that could contribute to elevated levels of interface friction. The present solutions currently omit contributions of soil cohesion due to the lack to experimental testing performed in such medium.

Although many design specifications require pipe installation in cohesionless backfill, further study is necessary to characterize the development of joint resistance force in other soil types.

The present study characterizes f_r for an idealized pipeline of infinite length considering only resistance contributions from the connections between lengths of straight pipe. It omits the existence of valves, tees, elbows, service connections, and other mechanisms common along everyday pipe networks. The importance of considering the frequency and capacity of mechanical system components is acknowledged, and further study is needed to establish performance metrics and incorporation for seismic design.

Despite noted opportunities for additional study, the present report provides needed information relative to the development of seismic design guidelines for water and wastewater pipelines. As such, the approaches provided herein are of immediate use to practicing engineers and researchers.

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