



NUMERICAL INVESTIGATION OF PIPELINE RESPONSE TO LONGITUDINAL GROUND MOVEMENT

G. Banushi⁽¹⁾, B. Wham⁽²⁾, C. Davis⁽³⁾, I. Weidlich⁽⁴⁾

⁽¹⁾ Postdoctoral Research Associate, HafenCity University Hamburg, gersena.banushi@hcu-hamburg.de

⁽²⁾ Assistant Research Professor, Center for Infrastructure, Energy, and Space Testing, University of Colorado Boulder, brad.wham@colorado.edu

⁽³⁾ C. A. Davis Engineering, cadavisengr@yahoo.com

⁽⁴⁾ University Professor, HafenCity University Hamburg, ingo.weidlich@hcu-hamburg.de

Abstract

Current efforts are underway to address buried pipeline susceptibility to damage from ground movements triggered by earthquakes, such as liquefaction-induced lateral spreading, landslides, and fault rupture. The linear nature of water and wastewater pipelines promotes failure due to ground displacement at locations of weakness, which for segmented pipelines is typical at joints or fittings linking adjoining sections of pipe. Pipe connections can be characterized as unrestrained (bell-and-spigot joints), fully restrained (continuous systems with bolted or welded/fused connections), or hybrid segmented joints, which provide the ability to displace axially in response to ground movement before locking up and behaving as a continuous system. The joint type and geometry contribute significantly to the expected performance of a given pipe system subjected to axial ground movements. Furthermore, the connection force capacity of the joints is an important limit state for predicting failure of pipe systems for which the joint has less strength than the pipe barrel.

To support the development of an American Society of Civil Engineer's Manual of Practice on Seismic Design of Water and Wastewater Pipelines, this paper presents a numerical model, simulating the response of two different hybrid-segmented pipelines subjected to block ground movement oriented parallel to the pipeline axis: (1) hazard-resilient ductile (DI) iron pipe and (2) oriented polyvinylchloride (PVCO) pipe with joint restraints capable of axial deformation. The imposed ground displacement is representative of measured lateral spreads observed during post-earthquake reconnaissance. Full-scale experimental results were used for fundamental analysis inputs, including joint axial force-displacement, pipe barrel frictional resistance, and soil-structure interaction associated with the enlarged joint connection displacing relative to surrounding soil. The finite element analysis demonstrates that the maximum elongation capacity of the considered DI pipe system is about 2.8 times greater than that of the PVCO pipeline. Comparison of the numerical results with a closed-form analytical solution, proposed to quantify axial connection force capacity of various pipeline systems, showed excellent agreement between the two approaches, highlighting the importance of assigning appropriate axial friction parameters for these systems. Validation of the proposed analytical solution, through the combination of experimental and numerical analysis, provides a robust first-order measure for characterizing pipeline systems, of any material or jointing characteristics, against seismically-induced longitudinal ground deformation.

Keywords: hybrid-segmented pipeline, soil-structure interaction; longitudinal ground movement; seismic performance.



1. Introduction

Traditional segmented pipelines are more vulnerable than continuous systems to the effects of permanent ground deformation (PGD), resulting from seismic-induced landslides, lateral spreading due to soil liquefaction, and fault rupture, because of the lower strength of the joints, relative to the main pipe barrels. To improve the seismic performance of water distribution systems, innovative hybrid-segmented pipeline systems are being used more frequently in practice. These systems employ joints equipped with anti-pull-out joint restraints, providing the ability to displace axially in response to ground movement before locking up and behaving as a continuous pipeline. Examples of hybrid-segmented pipeline joint connections emerging in the industry are earthquake-resistant DI pipe (ERDIP) [1] and molecularly oriented polyvinylchloride (PVC0) pipe fitted with extendable joint restraints [2], as shown in Figure 1.

The joint type and geometry, including its connection force capacity (CFC), significantly influence the seismic performance of a pipe system subjected to ground displacement. Moreover, the enlarged joint restraining mechanisms of hybrid-segmented pipelines and some continuous pipelines behave like vertical anchors, increasing the soil reaction to the relative soil-pipeline movement. This effect is not considered in current seismic design guidelines of buried pipelines, requiring implementation of analytical solutions, validated based on advanced numerical and experimental analysis, to accurately evaluate the system performance.

Specifically, longitudinal PGDs typically induce larger damage rates in non-seismically designed buried pipes than transverse PGD [3, 4] due to lower flexibility in the axial direction. The performance of the buried pipeline subjected to longitudinal PGD depends on the block length L_b , displacement magnitude δ , and pattern of the ground deformation. Herein, the soil block pattern, where all the soil within the PGD zone undergoes the same ground movement δ , has been widely used in engineering research and design to assess the pipeline performance under longitudinal PGD [4–7].

Expanding on the work of M. J. O'Rourke & Nordberg [6], on the longitudinal PGD effects on buried continuous pipelines, Wham & Davis [7] developed a simplified analytical approach for evaluating the pipe strain due to various magnitudes of ground movement, for pipelines of any material stiffness and mechanical joint characteristics. This approach uses soil-pipeline axial resistance per unit length of pipe, f_r , and other pipe system characteristics to approximate the axial force demand on a pipeline for given soil block movement with length L_b and magnitude δ . Two conditions are established for which the pipeline force demand is evaluated, depending on whether the soil block length L_b is short (Condition II) or long (Condition I) enough to allow full mobilization of the reaction along the soil-pipeline interface, due to the imposed ground displacement δ . The proposed analytical model permits calculating the CFC required to accommodate a specific quantity of ground movement δ , providing a fundamental basis for engineering design selection of continuous and segmented pipelines in hazard-prone regions.

While the Wham & Davis analytical approach has demonstrated ability to predict hybrid-pipeline response for well-documented case studies in Japan [8], more advanced numerical analysis, calibrated with experimental data, are needed to confirm its capacity to accurately evaluate the effect of complex system nonlinearities, including the response of the enlarged joint restraints, for various burial conditions and pipeline system characteristics. Moreover, this analytical model requires investigation of the soil-pipeline axial friction resistance, f_r , appropriate for estimating axial demand on the pipeline system, necessitating a numerical study that captures nonlinearities measured during full-scale experimentation.

Three main finite element modelling approaches are commonly used to assess the response of soil-pipeline system subjected to seismic induced PGD, including the simplistic beam on Winkler foundation, the shell-spring, and the more complex continuum model [9, 10]. Although the latter has addressed many of the deficiencies of the Winkler foundation models, permitting realistic simulation of pipe-soil behavior for large deformations, it presents disadvantages in terms of elevated computational demands and the required expertise of the engineer to analyze the models for use in routine engineering applications [11, 12].



Therefore, to evaluate the seismic response of hazard-resistant pipeline systems under longitudinal PGD, this study develops a numerical model, considering the nonlinear properties of the system components, calibrated from large-scale test data [13, 14].

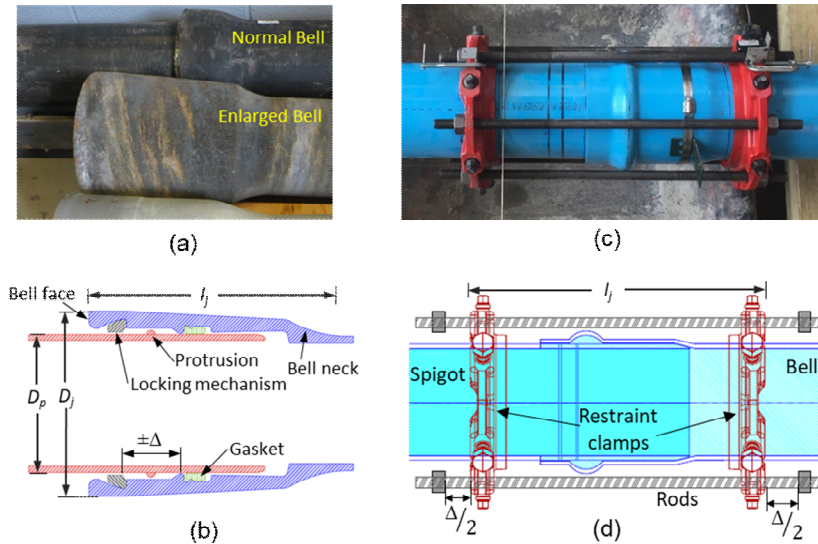


Fig. 1 – Examples of pipeline joints including: (a) photograph of normal DI push-on (top) and enlarged hybrid-segmented joint (bottom); (b) drawing of typical hybrid-segmented expansion joint; (c) photo of PVC joint with restraint harness capable of expansion; and (d) drawing of plastic pipe with restraint harness.

This paper presents first the methodology adopted to evaluate the response of the buried segmented pipelines subjected to longitudinal PGD. Second, it discusses the analysis results, examining initially the numerical simulations for evaluating the pipeline response within one region of the system behaving like a pull-out test, followed by assessment of the jointed pipelines subjected to long soil block movement. Then, the obtained numerical results are discussed and compared with the closed-form analytical solution proposed by Wham & Davis, demonstrating its capacity to capture the pipeline response. Finally, the conclusion section highlights the contributions of the present paper to the state-of-the-art practice and research of the seismic design of hybrid-segmented pipelines.

2. Methodology

This section describes the methodology for evaluating the mechanical response of an oriented polyvinyl chloride (PVC) pipeline and ductile iron (DI) pipeline subjected to seismic induced longitudinal permanent ground deformation (PGD). First, the system performance has been analyzed numerically within beam on Winkler foundation theory, using the finite element software ABAQUS/Standard [15]. Then, the obtained analysis results are compared with the closed-form analytical solution proposed by Wham & Davis [7], demonstrating its capacity to capture the pipeline response.

Both analyzed pipelines have an outer diameter, D_p , of 0.175 m and are assumed to be buried in medium-dense sand under the same cover depth of 0.76 m. The wall thickness of the PVC and DI pipeline is 6.22 mm and 10.2 mm, respectively. As schematically illustrated in Figure 2, the lay length h of each pipe segment is equal to 5.5 m, while the representative length of the enlarged joints, l_j , is 0.45 m and 0.20 m for the PVC and DI pipe, respectively.

Within the numerical approach, the pipeline is modeled using the PIPE31 beam element type, allowing the possibility to specify external or internal pressure. The soil-pipeline interaction is modeled with the



spring-like pipe-soil interaction elements PSI34, representing the soil reaction to the soil movement in the axial, lateral, and vertical direction. One edge of the element shares nodes with the underlying pipe element, while the nodes on the other edge are assigned the far-field ground motion through the boundary conditions. The adopted mesh size for the beam pipe and the underlying soil elements is 0.05 m, assuring solution convergence.

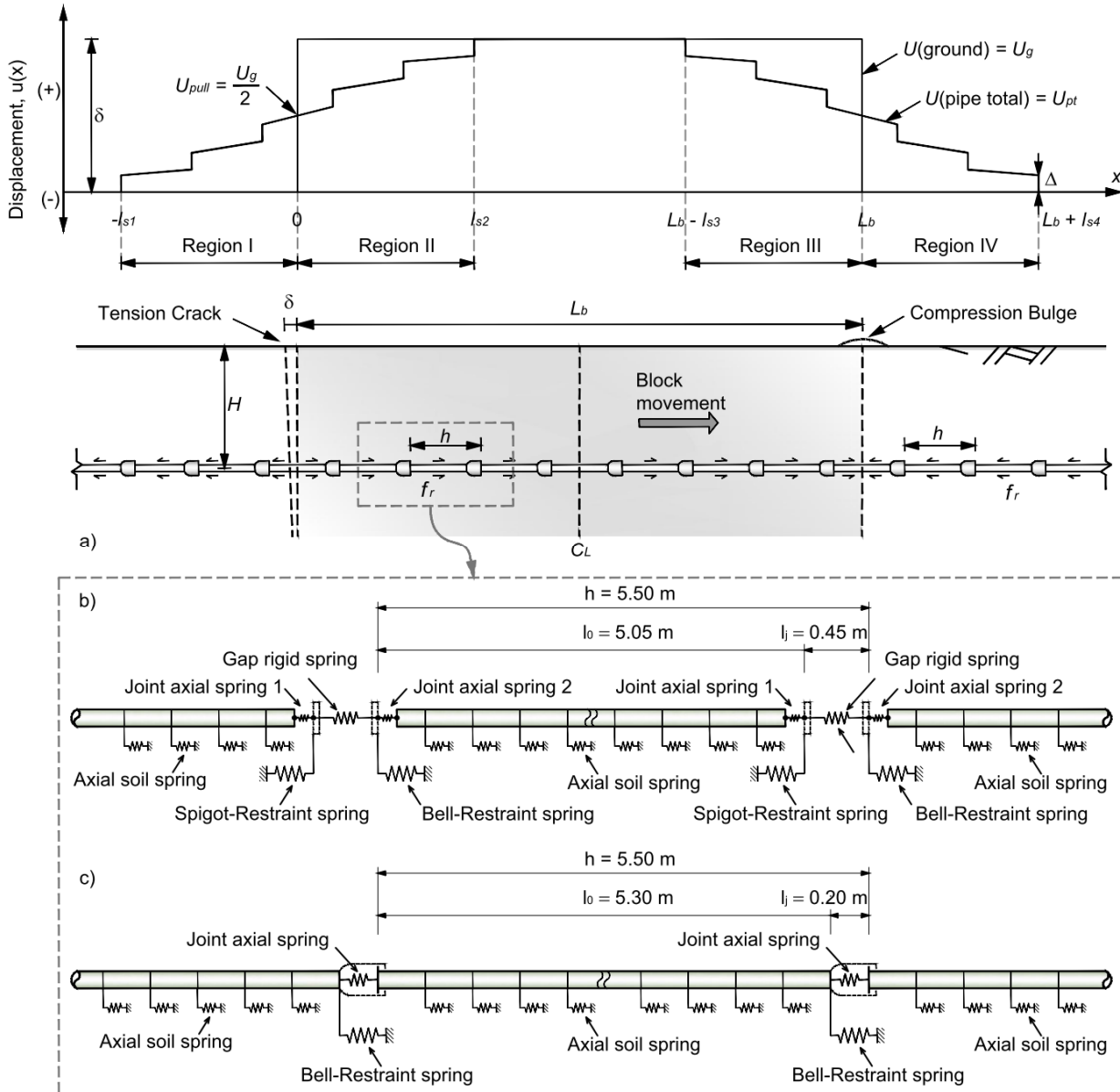


Fig. 2 – Schematic representation of the a) buried segmented pipeline subjected to the longitudinal soil block movement, including the finite element model of the b) PVC and c) DI pipeline-soil system.

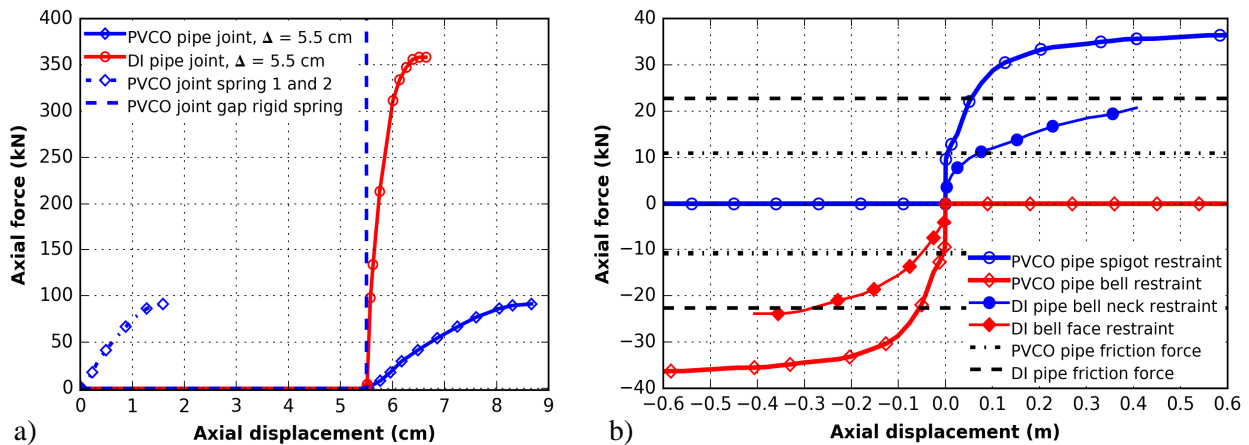
The PVC and DI material model are defined within the von Mises plasticity theory with nonlinear hardening. The implemented engineering stress-strain curve for the PVC and DI material, are obtained from uniaxial tensile tests reported by [16] and [17], respectively. Table 1 shows the material properties in the elastic range for the PVC and DI pipe material.



Table 1 – Material Properties of PVC0 and DI pipe from tensile coupon tests.

Pipe material	Elasticity	Direction	Young's modulus (GPa (ksi))	Poisson's ratio	Proportional limit (MPa(ksi))	Proportional limit strain (MPa (ksi))
PVC0	Transversely isotropic	Longitudinal	3.10 (450)	0.37	24.8 (3.6)	0.0080
		Circumferential	3.71 (538)	0.44	NA	NA
DI	Isotropic	Isotropic	157 (22,700)	0.29	248.2 (36)	0.0016

The mechanical joints are set to allow a relative displacement between two adjacent pipe barrels $\Delta = 5.5$ cm, before locking up, and restraining further movement. The PVC0 and DI joints are modeled and calibrated, considering their specific mechanical response, evaluated from the full-scale axial tension tests reported in [18] and [19], respectively. The PVC0 joint expansion, after lock up, is caused by localized deformation of the pipe wall at the connection with the joint restraints, until ultimate failure when the pipe axial force reaches the CFC (91.2 kN). Therefore, each pipe-restraint joint is modeled as a zero-length axial spring, connecting the restraint node to the correspondent pipe barrel end. The two adjacent restrained nodes, are connected by a gap-rigid axial spring, permitting relative displacement under negligible axial force until $\Delta = 5.5$ cm, while providing a rigid connection thereafter ($\Delta \geq 5.5$ cm) (Figure 2b). The combined effect of these three springs in series represents the axial tension test response, measuring the pipe axial force versus the relative displacement between the ends of two adjacent pipe barrels, at either side of the PVC0 joint (Figure 3a). On the other hand, the DI joint response is suitably modeled as axial spring connecting the end nodes of two adjacent pipe barrels (Figure 2c), using a force-displacement relationship (Figure 3a), calibrated from the full-scale axial tension tests [17]. The joint springs are modelled using the axial connector element CONN3D2, implemented in Abaqus/Standard. The numerical analysis considers, for simplicity, the same joint force-displacement relationship in compression as in tension, because elongation represents the controlling mechanism of the jointed pipeline, based on tension and compression tests [18].

Fig. 3 – Force-displacement relationship for: a) the joint springs ($\Delta = 5.5$ cm) and b) the enlarged joint restraints regarding the PVC0 and the DI pipe.

Due to the symmetric joint restraint configuration in the PVC0 pipe, the response of the spigot and bell restraint springs are mutually antisymmetric, with the former following a tension-no compression behavior, and the latter a compression-no tension behavior. Conversely, the bearing response in the neck side of the DI pipe bell restraint is slightly lower compared to the response in the face side of the bell restraint, due to the different shape of the restraint counteracting passive soil pressure during pipe movement [13]. Evidently, the restraint reaction is greater for the PVC0 than in the DI pipe (Figure 3b), because of the greater cross-sectional area of the former, counteracting passive soil pressure [14, 20]. The force-displacement relationship for the axial soil-pipe interaction along the pipe barrels is considered as elastic-perfectly plastic, defined by the sliding soil friction force per unit length of the pipeline f_p , and the relative



soil-pipe displacement at the onset of friction sliding u_0 . The latter is assumed equal to $u_0 = 1$ mm, for both cases of axial soil-pipe interaction, while the selected soil friction reaction f_p along the pipe barrel for the PVC0 and DI pipeline is 2.15 kN/m and 4.29 kN/m, respectively, as also adopted in Wham & Davis [7]. Therefore, the resultant friction force along the straight pipe barrel amounts to 10.86 kN in the case of PVC0 system and 22.74 kN in that of DI (Figure 3b).

The ground deformation is idealized as rigid-block movement, defined by a downslope movement δ over a block length L_b , resulting in a tension crack of width δ at the upslope end, and compression ridge over a distance δ on the downslope end (Figure 2a). Evidently, the region of the soil-pipeline system beyond the soil block behaves like a pull-out test in tension (Region I) and in compression (Region IV), with the end displacement applied at the pipe points underlying the tension crack and compression bulge, respectively. Hence, to evaluate the maximum elongation capacity of the jointed pipelines under longitudinal PGD, the pipeline response subjected to pull-out displacement is investigated first.

The pull-out analyses are conducted in one static step, where one end of the pipeline is displaced axially to an amount U_{pull} , while the free nodes of the pipe-soil interaction elements are fixed. The length of the PVC0 and DI pipeline-soil system in the pull-out analysis is chosen equal to 8 pipe barrels (44 m) and 20 pipe barrels (110 m), respectively, so that the pipeline response to the imposed ground displacement is representative of an infinitely long segmented pipeline, unaffected by far end boundary conditions.

Subsequently, the global analysis, simulating the soil-pipeline system subjected to long soil block condition ($L_b = 182.9$ m), are performed, taking into account the results from the pull-out analysis. The soil block is located at the center of the soil-pipe system so that its midpoint lies on the pipeline bisector, as illustrated in Figure 2a. Herein, the lengths of the PVC0 and DI pipe-soil systems are about 300 m and 400 m, respectively, so that the pipeline response to the imposed ground displacement is not affected by boundary conditions at the far ends of the modelled pipeline. The global analysis are conducted in one step, where the soil block movement is applied statically, with a maximum step increment equal to $\Delta\delta = 1$ mm. Herein, the free nodes of the pipe-soil interaction elements are assigned the ground displacement $\delta = 2$ m within the soil block length, while outside of the moving block the soil nodes remain fixed. On each step increment, the nonlinear equilibrium equations are solved iteratively by the Newton-Raphson method, allowing the assessment of system response at any level of applied ground displacement, until joint failure.

3. Analysis results and discussion

This section presents the seismic performance of the buried jointed pipelines, evaluated using the proposed methodology. First, the deformation capacity of the PVC0 and DI pipelines is analyzed numerically, examining initially the pipeline response within one region of the system behaving like a pullout test, and then the system performance subjected to a long soil block movement ($L_b = 182.9$ m). Finally, the obtained analysis results are compared with the closed-form analytical solution proposed by Wham & Davis [7], validating its capacity to capture the pipeline response.

3.1 Response of the jointed pipelines subjected to pull-out displacement

The pull-out analysis intends to evaluate the maximum elongation capacity of the jointed pipelines subjected to an axial displacement that is imposed until the maximum connection force capacity (CFC) is achieved at the joint closest to the pull-out end. The analysis focuses on the response of the jointed pipelines in tension, as elongation represents the controlling mechanism of axial pipeline performance, based on full-scale tension and compression tests [1, 18]. Figure 4 illustrates the different stages where the joints expand until locking up in a consecutive pattern, starting from the joint closest to the pipeline end subjected to pull displacement, up to failure, as well as the activated forces between the different system components. Table 2 presents the values of the forces and displacements for different pipe components at joint failure, including the maximum joint force ($F_{j,max}$) and corresponding displacement ($\Delta_{j,max}$), the maximum soil-pipe interaction resisting force at the first joint ($F_{r,max}$) and corresponding relative displacement ($\Delta_{r,max}$), the maximum pullout force ($F_{pull,max}$)



and displacement ($U_{pull,max}$), the maximum friction force (F_{fn}) applied to the pipe barrels with fully engaged joints, and the associated length of engaged pipeline (l_{sn}).

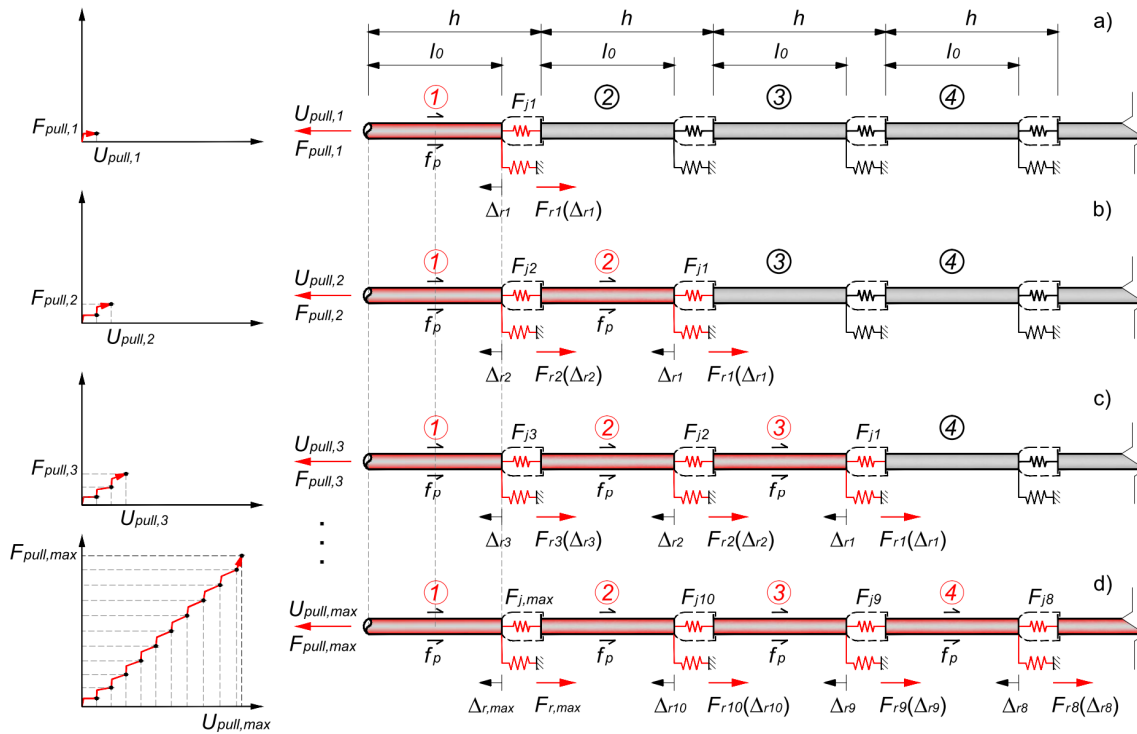


Fig. 4 – Representation of the activated forces during the consecutive locking up of the joints, as the DI pipeline is subjected to pull-out displacement in the direction of the neck face: a) first joint expansion until lock-up; b) second joint expansion until lock-up; c) third joint expansion until lock-up, and so on, up to d) failure of the joint closest to the pull-out end, as the 11th joint starts displacing.

Table 2 – Values of the forces and displacements in the pipeline components at joint failure for the PVC0 pipeline, and DI pipelines subjected to pullout displacement in the direction of the bell face and bell neck.

	First joint (critical)			First restraint		Pipe pullout end		Total soil friction	
	n	$F_{j,max} = CFC$ (kN)	$\Delta_{j,max}$ (cm)	$F_{r,max}$ (kN)	$\Delta_{r,max}$ (cm)	$F_{pull,max}$ (kN)	$U_{pull,max}$ (cm)	$F_{fn} = (n+1) \cdot l_0 f_p$ (kN)	$l_{sn} = (n+1) \cdot h$ (m)
PVCO	2	91.2	7.9	32.09	17.2	102.2	23.8	32.76	16.5
DI face	9	358.1	6.6	23.93	46.5	380.8	53.3	215.2	55.0
DI neck	10	358.1	6.6	20.68	58.85	401.5	59.1	228.5	60.5

Overall, the DI pipeline with expansion joints accommodated approximately 2.3 times greater pull displacement than the PVC0 equipped with displacement accommodating restraints, average DI $U_{pull,max} = 56.2$ cm vs. PVC0 $U_{pull,max} = 23.8$ cm (Table 2). Although the CFC of the DI pipeline (358.1 kN) is about four times larger than that of the PVC0 pipeline (91.2 kN), the latter is more deformable, accommodating a greater amount of the imposed ground displacement through axial elongation of the pipe barrels. The resulting maximum total elongation of the joints at failure ($\sum \Delta_{ji}$) in the PVC0 pipeline amounts to 15.2 cm (64% $U_{pull,max}$), while in the DI pipeline is equal to 52.2 cm and 57.8 cm (98% $U_{pull,max}$), in the situation of bell face and bell neck resisting soil reaction, respectively. The maximum number of fully engaged joints (n) in the PVC0 pipeline is two, while in the DI pipeline is nine and ten, for the case of pipe displaced in the direction of the bell face and bell neck counteracting passive soil pressure, respectively. Therefore, the maximum length of the system having friction applied due to relative soil-pipeline movement ($l_{sn} = (n+1) \cdot h$)



is 16.5 m for the PVC0 pipeline, while reaching 55.0 m and 60.5 m for the DI pipeline in the case of bell face and bell neck resisting soil reaction, respectively (Table 2).

The PVC0 and the DI pipeline subjected to pull-out displacement in the direction of the bell face, fail both at the joint connection in the first pipe barrel, as the maximum pull-out force reaches 102.2 kN and 380.8 kN respectively. Conversely, the deformation capacity is greater for the DI pipeline subjected to pull-out displacement in the direction of the bell neck, resisting a greater maximum pull-out force equal to 401.5 kN, due to the reaction of the bell restraint ($F_{r,max} = 20.68$ kN) in the first pipe barrel undergoing pull-out displacement (Figure 4).

3.2 Response of the jointed pipelines subjected to longitudinal PGD

This study focuses on the response of the jointed pipelines in Region 1 ($x < 0$) and Region 2 ($x < l_{s2}$), undergoing tension (Figure 2a). In each region, the pipeline behaves like a pull-out test, displaced in tension at the point of application of the soil block movement ($x = 0$). This point represents the location of the maximum tensile axial force and associated axial strain in the critical pipe barrel underlying the tension crack, decreasing linearly thereupon. Clearly, the elongation of the pipeline in tension is equal to the total elongation in Region 1 and Region 2. These latter values may differ from one another, depending on the pipe axial flexibility, the restraint reaction in each longitudinal direction, as well as the relative position of the head of the soil block ($x = 0$) with respect to the critical pipe barrel underlying the tension crack.

Table 3 presents the analysis results for the PVC0 and DI pipelines subjected to long soil block movement ($L_b = 182.9$ m), in terms of maximum ground displacement at joint failure, as well as the resulting strength and deformation demand. Figure 5 and Figure 6 show the variation, with the distance from the head of the soil block, of the pipe axial force, axial stress, axial displacement, axial strains, as well as the soil friction reaction, for increasing values of the applied ground movement U_g , in the PVC0 and DI pipeline, respectively.

Table 3 – Global model results for PVC0 and DI pipe systems at joint failure.

Pipe	L_b (m)	δ_{max} (cm)	F_{max} (kN)	σ_{max} (MPa)	ϵ_{max}	$l_{s,1}$ (m)	$l_{s,2}$ (m)	n_1	n_2
PVC0	182.9	39.5	92.2	28.23	0.00944	15.78	11.73	2	2
DI		111.1	378.2	71.64	0.00046	54.25	50.25	9	9

Specifically, joint failure of the PVC0 and DI pipeline subjected to long soil block movement ($L_b = 182.9$ m), occur for a ground displacement $\delta_{max} = 39.5$ cm, and $\delta_{max} = 111.1$ cm, respectively. The latter are equal the total pipeline elongation in Region 1 and Region 2, that differ slightly from each other, because of the pipe deformability, and the different relative positions of the critical pipe barrel with respect to the soil block head. In the PVC0 pipeline, the joint closest to the soil block head fails first, regardless of the region it is in, given the symmetrical response of the PVC0 restraint joints in both longitudinal directions. Conversely, in the DI pipeline, the joint closest to the soil block head, in Region 1, fails first, because of the lower pipeline deformation capacity, compared to Region 2 (see orientation of bells in Figure 2).

Clearly, the PVC0 pipeline is more deformable, accommodating a greater amount of the imposed ground displacement through axial elongation of the pipe barrels (27%), than the DI system (2%). The maximum number of fully engaged joints on either side of the soil block head (n) in the PVC0 pipeline is two, while in the DI pipeline is nine. Therefore, the maximum length of the system having friction applied due to relative soil-pipeline movement ($= (2n+1) \cdot h$) is 27.5 m and 104.5 m, for the PVC0 and DI pipeline, respectively. Moreover, the maximum pipe axial force at failure, which occurs at the head of the soil block (Figure 5a and 6a), is a function of the joint CFC, the distance of the soil block head with respect to the failed joint (x), the applied soil friction f_p , and resistance force at the joints. Hence, the maximum axial force in the PVC0 pipeline is $F_{max} = 92.2$ kN, while reaching $F_{max} = 378.2$ kN in the DI pipeline. The latter are associated with low levels of maximum axial stress (σ_{max}) and strain (ϵ_{max}) in the pipe barrels, as indicated in Table 3.

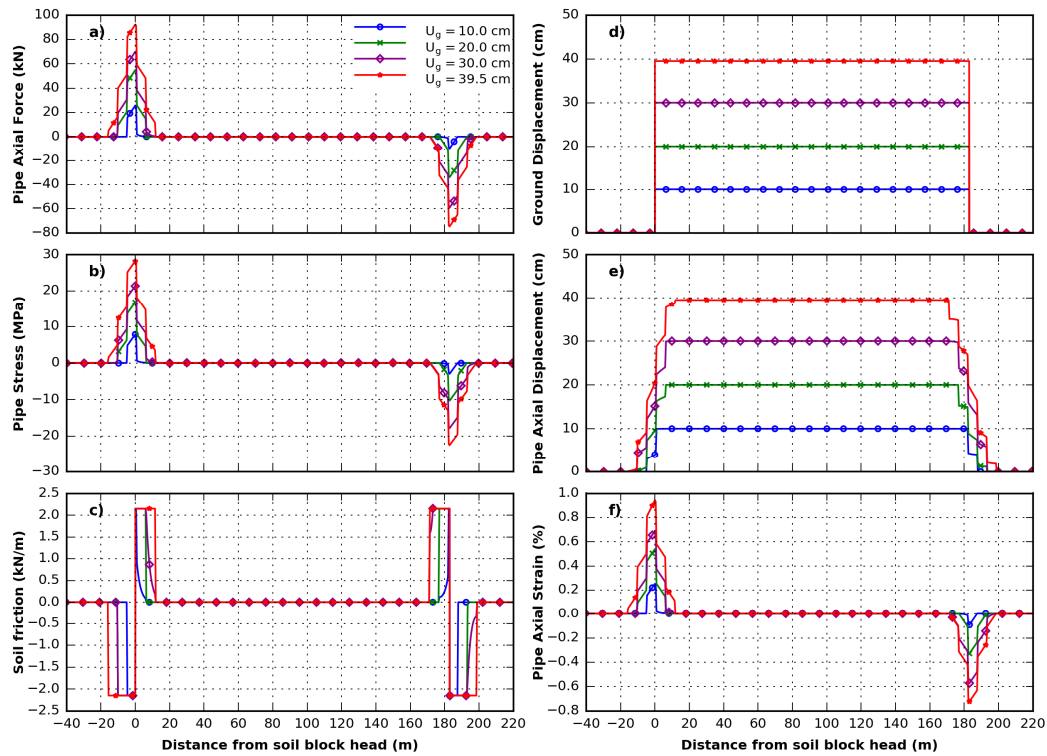


Fig. 5 – Response of the PVC pipe, subjected to long soil block movement ($L_b = 182.9$ m): a) pipe axial force; b) axial stress, c) soil friction; d) ground displacement; e) pipe axial displacement; f) pipe axial strain.

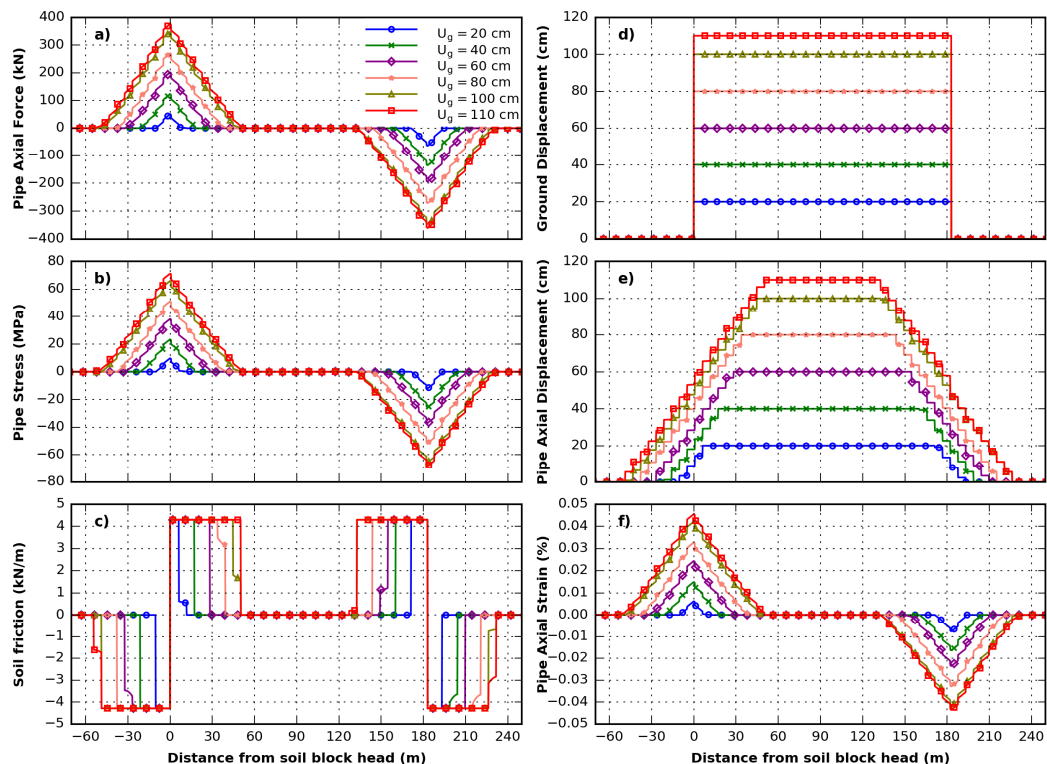


Fig. 6 – Response of the DI pipe, subjected to long soil block movement ($L_b = 182.9$ m): a) pipe axial force; b) pipe axial stress, c) soil friction; d) ground displacement; e) pipe axial displacement; f) pipe axial strain.



3.3 Comparison of numerical and analytical approaches

A primary objective this study is to use the numerical model, calibrated from full-scale experiments, to assess the ability of the closed-form analytical procedure, developed by Wham and Davis [7], to capture pipeline response to longitudinal ground deformation. The axial pull and global model results confirm the general assumptions of hybrid-segmented pipeline response noted by the Wham and Davis study, including trends in the pipe strains and displacements along the pipeline due to relative soil-structure interaction.

Table 4 provides a tabulated comparison between the values obtained from the numerical analysis (“this study”) and results using the analytical approach outlined by Wham and Davis (2019) (“W&D, 2019”), considering long soil block length $L_b = 182.9$ m and ground movement at joint failure $\delta = \delta_{max}$. Three primary outputs are compared: maximum pipe axial force, maximum pipe strain, and the average value of engaged pipeline in each region, which is consistent with the total number of engaged joints in Regions 1 and 2. Indicated below each test case are the percentages that the W&D analytical approach differs from the enclosed numerical analysis.

Table 4 – Comparison of present study analysis results with Wham & Davis [7] analytical approach.

Pipe	Analysis Method	L_b (m)	δ_{max} (cm)	F_{max} (kN)	ϵ_{max}	$l_{s,avg.}$ (m)	n_{1+2}
PVC0	this study	182.9	39.5	92.2	0.00944	13.76	4
	W&D, 2019		39.5	94.3	0.00964	13.32	4.0
	% diff.			2.3%	2.1%	-3.1%	
DI	this study		111.1	378.2	0.00046	52.25	18-19*
	W&D, 2019		111.1	416.4	0.00050	54.17	19.0
	% diff.			10.1%	9.8%	3.7%	

*Depends on location of tension crack relative to the critical pipe segment

Excellent agreement between the analysis approaches is apparent. Results for the PVC0 system are consistent with the analytical approach, exhibiting differences less than 3.2% (Table 4). This comparison shows that, despite simplifications taken by the analytical procedure (e.g., elastic material model and rigid soil-pipeline interaction), the W&D approach well captures the PVC0 pipe response. For the DI system, the axial force and strain differ from the numerical results by about 10%. While this difference is notable, the length of pipeline engaged with soil ($l_{s,avg} = 54.2$ m) is consistent with the values in Table 2 ($l_{s0} = 55.0$ m), as the pipe response depends on the location of the critical pipe barrel with respect to the tension crack. Similarly, the number of engaged joints in the numerical model (18 or 19) depends on this configuration. Identifying the primary parameters responsible for the difference between the approaches and subsequently modifying the analytical approach to improve compliance with the finite element model is beyond the scope of the present study. It is, however, hypothesized that the DI model differ more than the PVC0 model because a greater length of pipe is engaged at failure, increasing the dependency of results on the non-linear joint and soil-pipeline interactions, which are simplified by the analytical approach [7].

4. Conclusions

This study investigates the capacity of buried hazard-resilient pipelines to accommodate longitudinal PGDs during earthquakes, including landsliding, liquefaction-induced lateral spreading, and other forms of ground movement. Two types of hybrid-segmented pipelines are investigated: (1) hazard-resilient ductile iron pipe and (2) PVC0 pipe with joint restraints capable of axial deformation. The developed numerical models, calibrated from full-scale tests, assess the maximum elongation capacity of the pipelines ($U_{p,max}$), subjected to longitudinal PGD. The deformation capacity is equal to the total pipeline elongation at each side of the tension crack, i.e. in Region 1 and Region 2, behaving like a pull-out test, displaced at the head of the soil block movement ($x = 0$).



The pullout numerical analysis, simulating the system response in Region 1, showed that the DI pipeline with expansion joints accommodated approximately 2.3 times greater pull displacement ($U_{pull,max} = 56.2$ cm) than the PVC0 equipped with displacement accommodating restraints ($U_{pull,max} = 23.8$ cm). While the PVC0 pipe manifests identical response in both longitudinal directions, the DI pipeline exhibits greater deformation capacity when subjected to pull-out displacement in the direction of the bell neck resisting passive soil pressure.

According to global numerical analysis, modelling the system response under longitudinal PGD, the elongation capacity of the DI pipeline ($U_{p,max} \approx 111$ cm) is about 2.8 times greater than that of the PVC0 pipeline ($U_{p,max} \approx 40$ cm). Furthermore, the percent contribution of joint expansion to overall pipe elongation is much greater for the DI pipeline (98%) than the PVC0 pipeline (73%), given the limited axial deformation capacity of the former relative to the latter. The axial pull and global model results confirm the general assumptions of hybrid-segmented pipeline response noted by Wham & Davis [7], including trends in the pipe strains and displacements along the pipeline due to relative soil-structure interaction. The numerical results also demonstrate the capacity of the Wham & Davis analytical approach to capture the expected system performance for various pipe materials and ground movement parameters, with excellent correlations between the two approaches. The results further illustrate the importance of assigning appropriate axial resistance parameters for segmented pipelines with enlarged joints and restraints.

Several limitations to the present study are important to identify. The adopted Winkler on foundation model assumes a constant friction reaction along the pipeline barrels, ignoring the effect of operational loads, and the complex soil-pipeline interaction at the edge of the ground movement zone. Circumferential expansion and contraction of the pipe cross-section due to different loading conditions, may alter the intensity of soil-pipe interaction, in the radial and axial direction, depending on the pipe deformability [11]. Furthermore, the axial friction in the pipe barrel increases in proximity of the enlarged restraint due to the greater lateral soil pressure, resisting pipe movement. Realistically simulating this behavior requires the use of more complex numerical modelling approaches, considering the nonlinear system properties, including contact interaction at the soil-pipe interface.

Further research focused on the soil-pipeline interaction for various system configurations, including different connection geometries, is needed to expand the modelling procedure herein to other pipeline systems. Moreover, the size of the connection (joint restraint or bell) may vary depending on product specifications, including the diameter, ultimately altering the soil resistance along the system. Additionally, the joint axial capacity (CFC) was adopted from limited axial tension tests, and may differ for various connection/material types, influencing considerably the overall system performance. While many of the input parameters are product specific, this study provides a useful methodology for evaluating the performance of hybrid-segmented pipelines, subjected to longitudinal PGD, as a function of the different system parameters, highlighting the primary factors impacting system response.

5. References

- [1] Pariya-Ekkasut, C. (2018). *Experimental Evaluation of Ductile Iron Pipeline Response to Earthquake-Induced Ground Deformation* Ph.D. Thesis, Cornell University
- [2] Wham, B. P.; Berger, B. A.; O'Rourke, T. D.; Pariya-Ekkasut, C.; Stewart, H. E. (2017). *Performance Evaluation of Bionax SR PVC0 Pipeline with Extended Bell Joints under Earthquake-Induced Ground Deformation* Ithaca, NY, Cornell University
- [3] O'Rourke, M. J.; Nordberg, C. (1992). *Longitudinal Permanent Ground Deformation Effects on Buried Continuous Pipelines* National Center for Earthquake Engineering Research, NCEER-92-0014
- [4] American Lifelines Alliance (ALA). (2005). *Seismic Guidelines for Water Pipelines*, American Society of Civil Engineers, Federal Emergency Management Agency (FEMA), and the National Institute of Building Sciences (NIBS)
- [5] O'Rourke, M. J.; Liu, X.; Flores-Berrones, R. (1995). Steel Pipe Wrinkling due to Longitudinal Permanent



- Ground Deformation, *Journal of Transportation Engineering*, Vol. 121, No. 5, 443–451. doi:10.1061/(ASCE)0733-947X(1995)121:5(443)
- [6] O'Rourke, M. J.; Nordberg, C. (1992). Behavior of buried pipelines subject to permanent ground deformation, *Tenth World Conference on Earthquake Engineering* (Vol. 9), Madrid, Spain, 5411–5416
- [7] Wham, B. P.; Davis, C. A. (2019). Buried Continuous and Segmented Pipelines Subjected to Longitudinal Permanent Ground Deformation, *Journal of Pipeline Systems Engineering and Practice*, Vol. 10, No. 4, 04019036. doi:10.1061/(ASCE)PS.1949-1204.0000400
- [8] Davis, C. A.; Wham, B. P.; Toshima, T.; Hara, T. (2019). Evaluating Case Study Performances of Hybrid-Segmented Pipes to Longitudinal Permanent Ground Movements, *2nd International Conference on Natural Hazards and Infrastructure, ICONHIC2019*, National Technical University of Athens, Chania, Greece. doi:ISSN: 2623-4513
- [9] Banushi, G.; Squeglia, N. (2018). Seismic Analysis of a Buried Operating Steel Pipeline with Emphasis on the Equivalent-Boundary Conditions, *Journal of Pipeline Systems Engineering and Practice*, Vol. 9, No. 3, 04018005. doi:10.1061/(ASCE)PS.1949-1204.0000316
- [10] Xie, X.; Symans, M. D.; O'Rourke, M. J.; Abdoun, T. H.; O'Rourke, T. D.; Palmer, M. C.; Stewart, H. E. (2013). Numerical Modeling of Buried HDPE Pipelines Subjected to Normal Faulting: A Case Study, *Earthquake Spectra*, Vol. 29, No. 2, 609–632. doi:10.1193/1.4000137
- [11] Banushi, G.; Squeglia, N.; Thiele, K. (2018). Innovative analysis of a buried operating pipeline subjected to strike-slip fault movement, *Soil Dynamics and Earthquake Engineering*, Vol. 107, No. April 2018, 234–249. doi:10.1016/j.soildyn.2018.01.015
- [12] C-CORE- D.G. Honegger Consulting SSD Inc. (2009). *Guidelines for Constructing Natural Gas and Liquid Hydrocarbon Pipelines Through Areas Prone to Landslide and Subsidence Hazards, Design, Materials, and Construction Committee of Pipeline Research Council International, Inc.* Chantilly, VA
- [13] Wham, B. P.; Pariya-Ekkasut, C.; Argyrou, C.; Lederman, A.; O'Rourke, T. D.; Stewart, H. E. (2017). Experimental Characterization of Hazard-Resilient Ductile Iron Pipe Soil/Structure Interaction under Axial Displacement, *Congress on Technical Advancement*, American Society of Civil Engineers, Duluth, MN, 124–134. doi:10.1061/9780784481028.013
- [14] Wham, B. P.; Berger, B. A.; Pariya-Ekkasut, C.; O'Rourke, T. D. (2018). Hazard-resilient Pipeline Joint Soil-structure Interaction under Large Axial Displacement, *Geotechnical Earthquake Engineering and Soil Dynamics V* (Vol. 2018-June), American Society of Civil Engineers, Austin, TX, 276–285. doi:10.1061/9780784481486.029
- [15] ABAQUS. (2019). *User's guide* Providence, RI, Simulia
- [16] Wham, B. P.; Argyrou, C.; O'Rourke, T. D.; Stewart, H. E.; Bond, T. K. (2017). PVC Pipe Performance Under Large Ground Deformation, *Journal of Pressure Vessel Technology*, Vol. 139, No. 1. doi:10.1115/1.4033939
- [17] Stewart, H. E.; Pariya-Ekkasut, C.; Wham, B. P.; O'Rourke, T. D.; Bond, T. K.; Argyrou, C. (2015). *Hazard Resilience Testing of US Pipe Ductile Iron TR- XTREME™ Pipe Joints* Itahca, NY, Cornell University
- [18] Wham, B. P.; Berger, B. A.; O'Rourke, T. D. (2019). Experimental Performance Evaluation of Seismic-Resilient PVC Pipe, *Pipelines 2019*, American Society of Civil Engineers, Reston, VA, 504–514. doi:10.1061/9780784482506.053
- [19] Pariya-Ekkasut, C.; Stewart, H. E.; Wham, B. P.; O'Rourke, T. D.; Argyrou, C.; Bond, T. K. (2016). *Hazard Resilience Evaluation of US Pipe Ductile Iron TR-XTREME™ Joints : 4-16 in. (100-400 mm) Diameter Pipe*
- [20] Rajah, S.; Davis, C. A.; Wham, B. P. (2019). Soil-Pipe Interaction Characterization for Seismically-induced Longitudinal Permanent Ground Displacements, *Pipelines 2019*, American Society of Civil Engineers (ASCE). (accepted), Nashville