Safeguarding the Integrity of Large-Diameter Steel Pipelines Subjected to Differential Ground Settlements

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ABSTRACT

The paper describes the application of a novel and promising concept, aimed at absorbing ground-induced displacements due to soil subsidence in buried steel pipelines entering or exiting concrete or rigid structures. In particular, the use of a patent pending concept of small projections is proposed, appropriately located along the pipeline, at the critical zone of soil subsidence, where deformation of the pipeline is expected. Using this solution, the pipeline is able to deform in a controlled manner such that there is no loss of pressure containment and the pipeline will continue to perform long term. Advanced finite element simulations have been employed to model the projection and characterize its structural behavior. The present concept is applied on an 84-in. diameter buried steel pipeline, and the results indicated that the use of projections at appropriate locations improves structural performance, decreasing both strain in the pipeline wall and the reaction forces and moments at the concrete wall.

INTRODUCTION

Pipelines are often subjected to ground settlement in areas of poor soil conditions or at pumping station/pipeline interfaces, and may cause damage to buried pipelines, threatening its structural integrity. Ground settlement is associated with permanent ground displacements (PGD), which introduces significant deformation in the pipeline because of bending and axial elongation, possibly leading to loss of containment. In several cases, soil compaction can reduce the amount of settlement, however this may not always be a solution; small amount of differential settlement (1”- 6”) in stiff soil may introduce significant amount of deformation in the pipeline.

When subjected to ground settlement conditions, the steel pipeline should be capable of accommodating the imposed ground displacement, and maintain its integrity, fulfilling its water transmission function. More specifically, to absorb this ground-induced action, the pipeline should be able to deform in an appropriate manner, compatible with the imposed action.

The present study refers to the case of pipelines entering or exiting concrete or other rigid structures, a case encountered quite often in water or wastewater facilities. The interaction between the stiff concrete wall of the building and the pipeline constitutes a critical design issue because of the possible relative vertical displacement between the building wall and the surrounding soil. Depending on soil conditions, either the building may settle with respect to the soil or the soil may settle with respect to the building. In both cases, the pipeline deforms and accommodates itself within this imposed displacement pattern, and significant strain may develop in the pipeline wall. Furthermore, the reaction forces and bending moments at the building concrete wall may also be important. Under those conditions, damage may occur either at the pipeline or at the concrete wall.

Pipelines entering or exiting a structure are, in some cases, designed with flexible joints that are used to accommodate movement from the differential settlement between the soil outside the structure and the structure itself. The common method of providing this flexible connection is utilizing flexible gasketed joints with couplings, as described in both AWWA C219, and AWWA M11. The couplings need to be either self-restrained (containing the restraining mechanism within the coupling/pipe end itself) or have external restraints provided over the couplings so the joints will not pull apart. Nevertheless, special care must be taken in pipeline settlement design using flexible joints, as most couplings will allow for either axial extension/compression movement or angular deflection (rotation) movement, but typically not both. Moreover, these type of "settlement" joints should not be utilized if there is any shear or moment across them. Therefore, this type of settlement design depends on the soil continuing to support the entire length of pipe that settles, for minimizing shear and moment; however, this may not be a realistic design assumption. Another caveat of using this type of devices is that the pipe ends must stay round (non-ovalized) due to the loads above and any movement from settlement of the flexile steel pipe; again, practical experience has shown that, in several cases, this design assumption may not be realistic.

The present paper describes the application of a novel and promising concept, aimed at absorbing ground displacement: (a) preventing water leakages in buried steel pipelines, so that water containment is maintained and (b) protecting the building concrete wall, even if significant ground settlement occurs. The use of projections of optimum size is proposed, appropriately located along the pipeline, at the critical zone of soil subsidence. Those projections define a location for the pipe to deform at specific selected locations in a controlled and safe manner, while influencing the strength of the pipe cross-section only by a negligible amount. Furthermore, the projections are fabricated at the pipe manufacturers shop, introducing a relatively small amount of plastic deformation.

The concept under consideration has been presented in its initial form by the authors in a series of papers in recent ASCE Pipeline conferences (2018-2020). It has been referred to as the "seismic joint" or "seismic projection" and has been validated through a series of physical experiments and extensive numerical simulations (Figure 1). Those experiments and simulations demonstrated that lap-welded buried steel pipelines subjected to ground-induced actions, the "seismic joint" allows for pipeline deformation at specific locations in a controlled manner, reducing the strain developed in the pipeline. Herein, a variation of the concept is employed, for the purposes of mitigating the effects of soil subsidence on pipeline structural behavior.

DESIGN FRAMEWORK

Pipeline design approaches are briefly presented and discussed below, to clarify some important issues related to pipeline structural behavior under severe ground-induced actions.

Allowable stress design. This approach refers to pipeline design under internal pressure containment. Hoop stress is the major design parameter in this approach; it is required that the hoop stress remains below the allowable stress of steel material, which is equal to a percent of yield stress. Furthermore, longitudinal stress due to Poisson effects or thermal conditions is also considered. In this approach the maximum allowable stress is always below the yielding limit of the material, and the pipeline response is assumed elastic. Finally, the case of compressive longitudinal stress should be limited, so that local buckling is prevented.

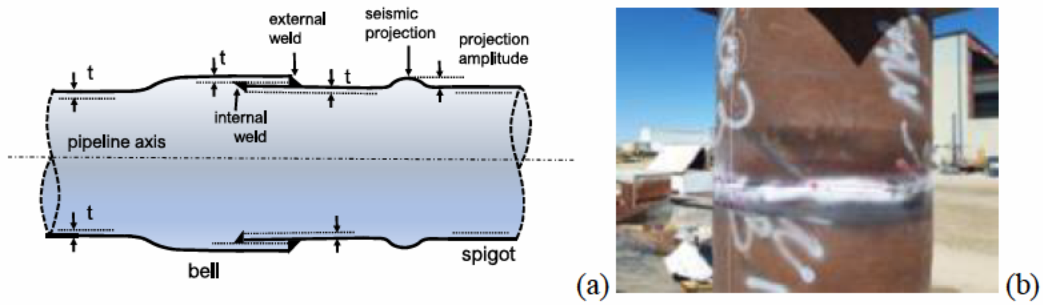

Figure 1. Seismic projection; (a) schematic and (b) specimen with projection before testing (Keil *et al.* 2020).

Strain-based design. The above elastic approach may not be appropriate for designing steel pipelines under ground-induced actions. Assuming that the pipe material remains elastic, a stress-based design severely penalizes the capabilities of the steel material, leading to uneconomical design with heavy wall thickness or over dependence on gasketed couplings. On the other hand, exceeding the yield limit of the material can be acceptable provided that the strain is below an allowable value, which depends on the joint type (butt-welded or lap-welded) and the type of loading. For extreme conditions, such as severe seismic events, a 2% tensile strain is often used as a limit, whereas in standard settlement conditions, a smaller value can be used.

GROUND-INDUCED ACTION OF SETTLEMENT

Problem description. The physical problem considered in the present paper is depicted in Figure 2. A straight steel pipeline is buried at constant depth, it passes through a stiff concrete wall at its left end and extends to "infinity" in its right. The concrete wall imposes a rotational and translational restraint at the left end and can be represented by a fixed support at the pipeline end. Two cases are considered: (a) the ground settles with respect to the building and (b) the building settles with respect to the ground. In both cases, the pipeline follows the settlement at its left part, and obtains an S-shape configuration, associated with bending and stretching.

Soil conditions. A major parameter in the present investigation refers to the soil conditions, mainly in terms of soil-pipeline interaction effects on pipeline mechanical behavior under ground-imposed deformations or settlement. The investigation considers for the first time the issue of soil stiffness effects on pipeline mechanical performance. Stiff soil conditions result in more localized, shear like movement, resulting in higher deformations and strains in the pipe than soft soil conditions, for the same amount of settlement.

THE "SEISMIC PROJECTION" CONCEPT AND ITS USE IN SETTLEMENT AREAS

"Seismic projection" concept. The seismic projection concept has been presented extensively in the 2020 ASCE Pipelines conference, as a continuation of the work reported by Keil *et al.* (2018, 2020), and the relevant numerical calculations (Chatzopoulou *et al.*, 2018; Sarvanis *et al.*, 2019) on the structural performance of lap welded joints. The latter papers presented experimental and numerical results that indicated an excellent structural performance of the welded lap joints. However, despite the excellent performance of the lap welded joints, several specimens exhibited buckling at the bell and through the field applied fillet weld, which may cause some concerns on the capability of the joints to sustain the deformation imposed by severe ground-induced action. In response to those concerns, a small initial geometric change at the spigot, near the weld, in order to enforce the buckle to occur in the spigot and prevent the buckle to occur at the bell and avoid including the field weld in the buckle.

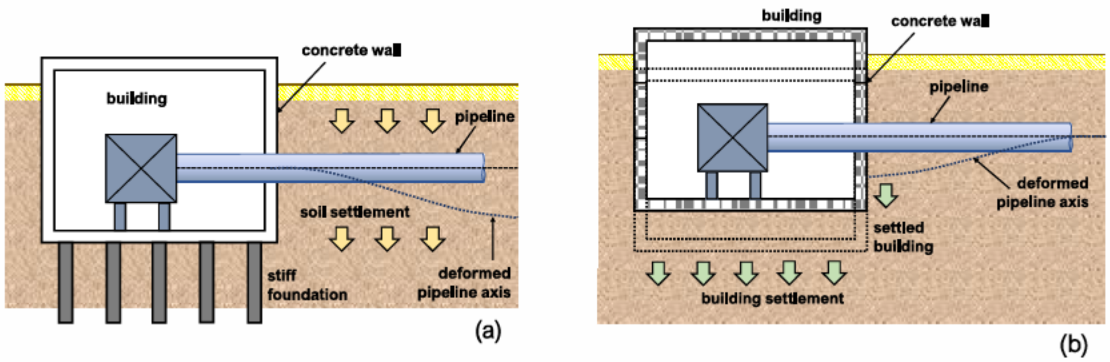

Figure 2. Ground-induced deformation of a pipeline connected to a building; (a) the ground outside the building settles; (b) the building settles with respect to the ground.

This patent pending system that includes the above geometric projection, referred to as "seismic projection", satisfies two main – opposing – requirements: (a) it should be large enough to ensure that buckling occurs at the projection in the spigot location and not in the bell, and simultaneously, (b) it should be small enough, so that the overall joint strength and stiffness are not significantly affected. Employing advanced finite element simulation tools, an optimum size of the projection under consideration has been determined. From the pipe manufacturing point-of-view, this projection is introduced within the normal fabrication process of the pipe. Finally, it should be underlined that this concept relies on the innate capability of the steel material to sustain significant amount of inelastic deformation without rupture, and this feature allows for the pipeline to undergo significant deformation at the projection area, without exhibiting any severe damage that would threaten its structural integrity and loss of containment.

"Seismic projections" in settlement areas. Motivated by the above concept, the present study provides the use of a variation of this concept as mitigation measure in settlement areas. More specifically, the use of a few projections of an optimized size, appropriately located along the pipeline at the critical zone of pipeline deformation are proposed. The projections allow the pipe to deform by a substantial amount at those specific locations in a controlled and safe manner, while influencing the strength of the pipe cross-section only by a negligible amount. Towards this purpose, the projection is optimized for the purpose of providing more flexibility at this location. In the following, the resulting projection will be referred to as "projection II", and it is shown in Figure 3a. It should be noted that, in a few instances, one may use two projections, one close to the other, with their locations optimized by structural performance. This system is referred to as "double projection" (Figure 3b), as opposed to the "single projection" shown in Figure 3a. The flexibility and strength of those projections is calculated using advanced finite element tools, described below.

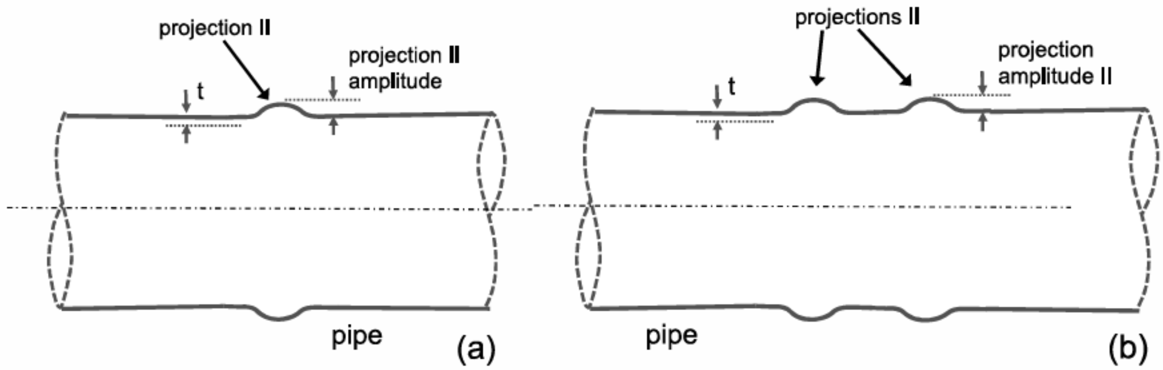

Figure 3. Schematic representation of "projection II'; (a) single projection and (b) double projection.

Simulation of projection structural performance. The projections for an 84-inch diameter pipe are simulated with finite elements, in order to determine their structural behavior. The pipeline thickness is equal to 0.625 in (15.875 mm), and the steel material is ASTM A1018 SS GR36 steel, with actual yield stress equal to 44 ksi (303 MPa), and ultimate strength 63.5 ksi (438 MPa). A 33.5 ft (10.2 m) pipeline segment is considered, with the projection in the middle cross-section, and it is subjected to bending and axial tension. Two sizes of projection are used: (a) the original "seismic projection"; (b) "Projection II".

The pipe segment is simulated with four-node reduced integration shell elements (Figure 4a) capable of representing large deformations and possible formation of local buckling. Internal pressure is also imposed, equal to 90 psi (0.62 MPa). Finally, the projection fabrication process is also included in the finite element model, in the first part of the analysis, before pressure or structural loading is imposed.

The results of this finite element simulation for "Projection II" are presented in Figure 5 for axial tension and are compared with corresponding results from lap-welded joint analysis, as well as from pipe segments containing the original "seismic projection". The axial force is normalized by the yield force which is defined as $F_p = \sigma_y A_c$, where A_c is the cross-sectional area of the pipe cross-section and is equal to 7,364 kips (32,757 kN). Also, the normalized axial deformation is equal to $\varepsilon/\varepsilon_1$, where ε is the global axial strain equal to the applied displacement over the total length of the examined pipe ($\varepsilon = \Delta L/L$) and the value ε_1 is equal to t/D. The deformed shape of the segment with the projection is shown in Figure 4b. The numerical results show that

1. the flexibility of "Projection II" pipe is greater than the flexibility of all other cases.
2. pipe deformation localizes at the projection location; because of this localization, this cross-section behaves like a plastic hinge, undergoing defined local deformation, whereas the strain outside this area is rather small.

Calculation of projection stiffness. The above finite element results allow for estimating the local flexibility induced by Projection II in the pipeline, using a simple argument from structural mechanics; this is shown in detail in Figure 6 for the case of axial tension, but can be readily extended to the case of bending.

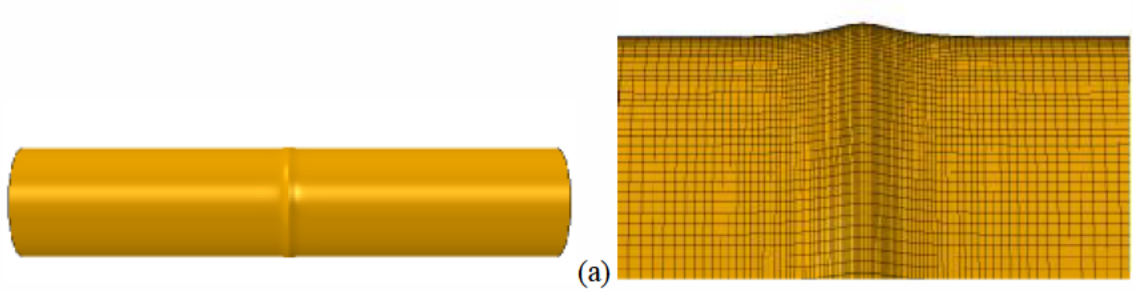

Figure 4. Finite element model of Projection II; (a) initial (undeformed) configuration and (b) final deformed configuration.

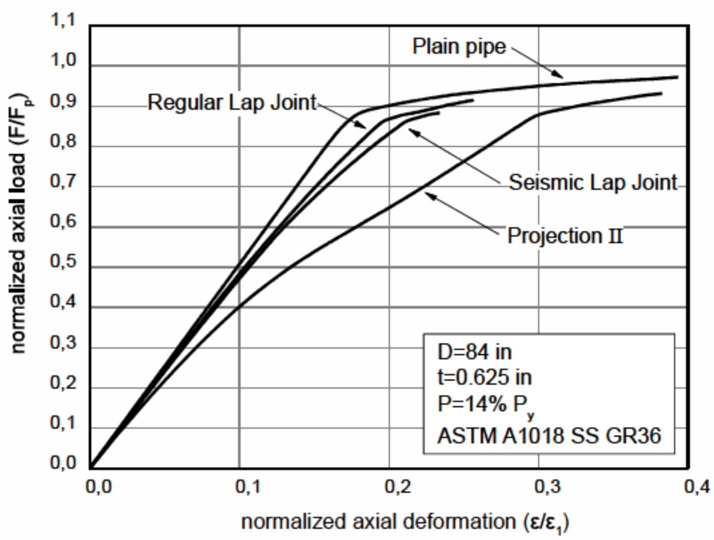

Figure 5. Comparison of load-displacement diagrams for a five-diameter-long pipe segment subjected to axial tension: (a) plain pipe, without projection; (b) pipe with lap-welded joint without projection; (c) pipe with "seismic projection"; (d) pipe with "Projection II" (D=84 in, t=5/8 in, yield stress 44 ksi).

- For a pipe segment without projection subjected to axial load F, the elongation of the pipe segment is equal to ΔL_0, and its stiffness is equal to

$$K_0 = F/\Delta L_0 \tag{1}$$

- For a pipe segment with projection subjected to axial load F, the elongation of the pipe segment is equal to ΔL_T, and its stiffness is equal to

$$K_T = F/\Delta L_T < K_0 \tag{2}$$

Clearly, the total elongation ΔL_T is larger than ΔL_0 because of the extra flexibility of the projection. Therefore, denoting with ΔL_P the extra elongation due to the presence of the projection, one may write:

$$\Delta L_T = \Delta L_0 + \Delta L_P \tag{3}$$

This leads to the following expression for K_P, which is the stiffness of the projection itself.

$$\frac{1}{K_T} = \frac{1}{K_0} + \frac{1}{K_P} \tag{4}$$

or

$$K_P = \frac{K_0 K_T}{K_0 - K_T} \tag{5}$$

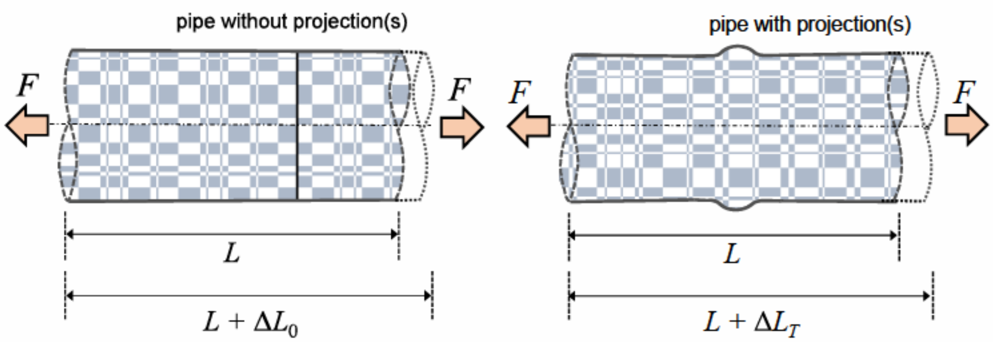

Figure 6. Stiffness of plain pipe and stiffness of pipe with projection.

Extension to the case of bending is straightforward, replacing the axial force F with the bending moment M, and elongation ΔL with relative rotation of the two ends of the pipe segment $\Delta\phi$. The above information on projection stiffness can be introduced in a beam-type finite element model to account for the effects of projections in a pipeline analysis procedure under ground-induced actions, as described in the next section.

DESIGN EXAMPLE

A design example is presented, where the above concept is applied. The solution of the problem is based on a finite element model, developed for the purposes of the present case.

Description of the generic case. An 84-inch nominal diameter steel pipeline is considered buried, assuming two different soil conditions, the properties of which are given in Table 1. Subsequently, the soil stiffnesses are calculated through the ALA guidelines (2005). The pipeline thickness is equal to 0.625 in (15.875 mm), and the steel material is ASTM A1018 SS GR36 steel, with yield stress equal to 44 ksi (303 MPa), ultimate strength 63.5 ksi (438 MPa) and uniform elongation more than 40%. The pipeline has a horizontal configuration, with constant burial depth. The soil conditions may be considered as medium density sand (soil case A) at soil cover 7.87 ft (2.4 m) and dense sand or gravel (soil case B) at soil cover 21.65 ft (6.6 m). Two loading cases are considered: (1) the soil settles with respect to the building and (2) the building settles with respect to the surrounding soil.

Table 1: Soil properties of two soil conditions examined.

Soil parameter	Loose soil (Condition A)	Dense soil (Condition B)
friction angle (φ)	30°	40°
elastic modulus (E)	8 MPa (1.16 ksi)	25 MPa (3.63 ksi)
Poisson ration (ν)	0.3	0.3
soil effective unit weight (γ)	15 kN/m^3 (95.5 pcf)	21 kN/m^3 (133.7 pcf)
coefficient of lateral soil pressure at rest (K_0)	0.47	0.29

Numerical model. The finite element solution is based on a "global" finite element model, which has been used extensively for the analysis of buried pipelines under ground-induced actions. The model is developed in software ABAQUS/Standard, which is capable of simulating pipeline response accounting for inelastic deformation of the pipe and for soil-pipe interaction. The pipeline is modelled with "elbow" elements, which are basically beam-type elements, but are capable of considering the effects of internal pressure and cross-sectional ovalization. The soil is modelled with PSI (pipe-soil interaction) elements, which account for soil-pipe interaction in an accurate and efficient manner (Figure 7a). The loading pattern consists of a vertical displacement pattern at the top of the PSI elements, as shown in Figure 7b; the triangular displacement pattern at the left part of the pipeline is equal to about two pipe diameters and has been necessary for avoiding the abrupt differential displacement between the concrete building and the adjacent soil, which is rather unrealistic and causes numerical problems to the solution. Finally, single projections are assumed along the pipeline, located at two locations: (A) at a distance equal to half pipe diameter from the wall and (B) at a distance equal to two diameters from the first projection. The projections are simulated with the use of special-purpose connector elements at the specific locations, which allow for axial displacement and rotation, with the stiffness calculated from equation (5).

Numerical results. Three cases are examined in the present paper:

- Case A-1 (soil conditions A and ground settlement with respect to the building)
- Case B-1 (soil conditions B and ground settlement with respect to the building)
- Case A-2 (soil conditions A and building settlement with respect to the ground)

The results refer to (a) the deflection of the pipeline; (b) the strain in the pipeline at the top and bottom generators and (c) the reaction forces at the fixed point, i.e. at the concrete wall.

A settlement value equal to 5.9 in is considered for case A-1. The deflected shape of the pipeline for this displacement value is shown in Figure 8a. For a pipeline without any projections, this settlement corresponds to a maximum strain of 2.6%. The numerical results show that the introduction of two single or double projections significantly reduces the strain in the pipeline to about 1%. The difference in strain values between single and double projections in this case may be negligible.

The settlement value considered for case B-1 is equal to 3.15 in, and the corresponding deflected shown in Figure 8b. For a pipeline without any projections this corresponds to a maximum strain of 2.78%. The numerical results show that the introduction of two single or double Projection II's significantly reduces the strain in the pipeline, to approximately 0.73%.

The deflected shape of the pipeline for case A-2 and for settlement value equal to 5.9 in is shown in Figure 8c. Without projections the maximum strain is equal to 3.57 %. The introduction of two single or double projections results in a substantially smaller strain in the pipeline, whereas the introduction of two double Projection II's decreases further the maximum strain to 1.2%.

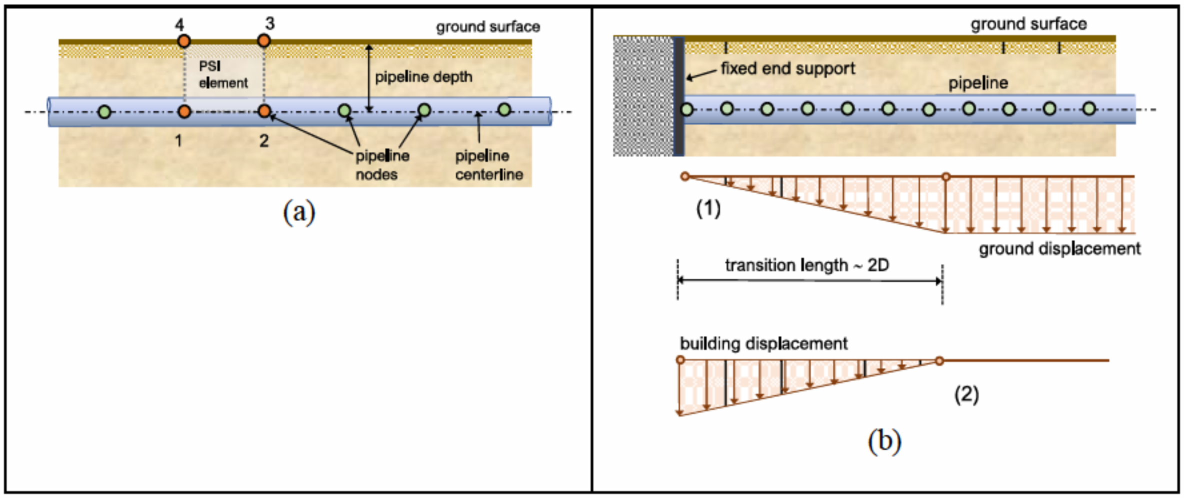

Figure 7. (a) PSI elements and (b) imposed settlement pattern.

Finally, the numerical results indicate that the reaction forces and moments at the pipeline wall are reduced by a substantial amount when projections are employed. More specifically, for Case A-1, the projections result in a 25.1%, 26.4% and 67.6% reduction of the axial force, vertical force and bending moment respectively. Similar reduction of the reactions has also been observed for Cases B-1 and A-2.

CONCLUSIONS

A new concept is introduced for minimizing the effects of settlements in buried steel water pipelines entering or exiting concrete structures, under ground-induced actions, stemming from differential settlements in pipelines connected to concrete or rigid structures. The concept is an extension of the "seismic projection" concept, introduced by the authors in recent publications, and consists of introducing a series of projections along the pipeline, so that pipeline deformation occurs at specific locations in a controlled manner, safeguarding pipeline structural integrity. Advanced finite element tools have been employed to model the projection and characterize its structural behavior. Numerical simulation of settlement actions on an 84-inch diameter buried steel pipeline have demonstrated that the use of projections at appropriate locations improves structural performance, decreasing the strain in the pipeline and the reaction forces and moments at the concrete wall. Those observations indicate that the present concept constitutes a promising tool for efficiently mitigating settlement effects in pipelines connected to concrete or rigid structures without the use of gasketed joints or couplings.

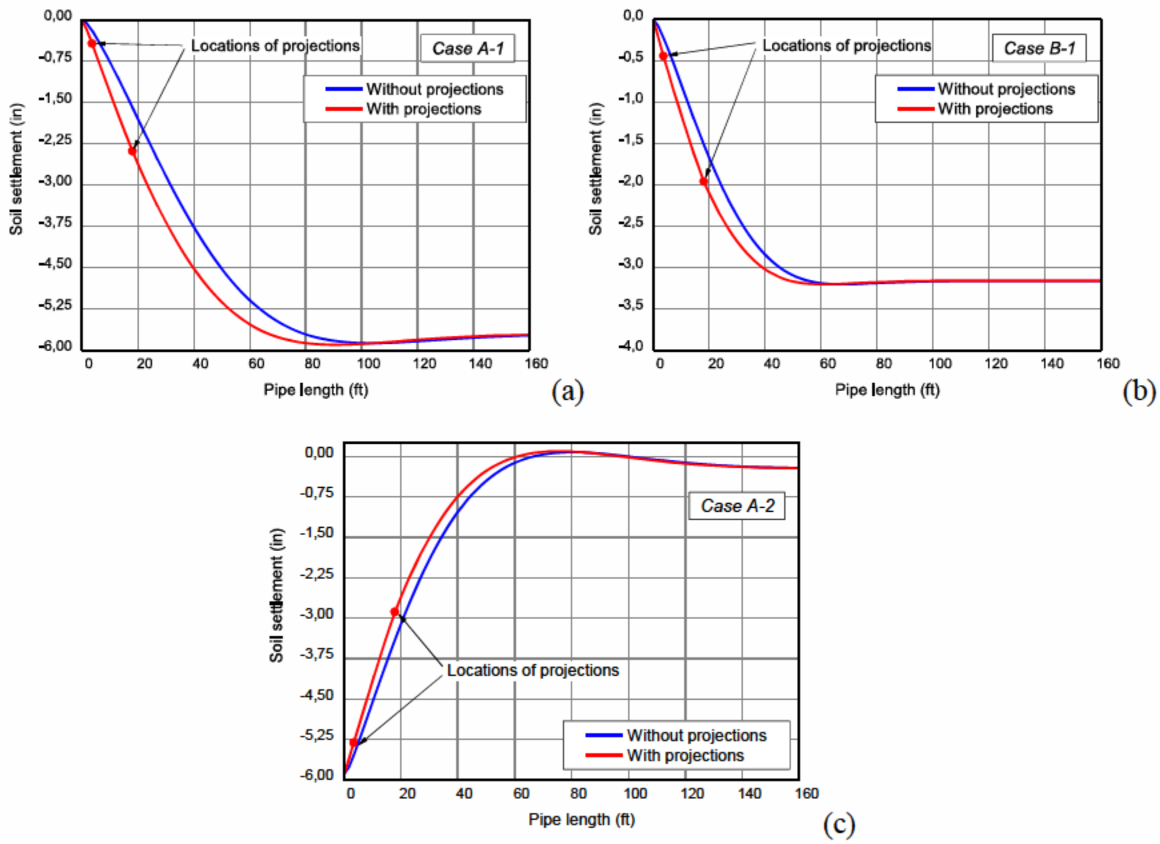

Figure 8. Deflected shape of pipeline for ground settlements and locations of the projections: (a) Case A-1 settlement equal to 5.9 in; (b) Case B-1 settlement equal to 3.15 in; (c) Case A-2 settlement equal to 5.9 in.

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