A Novel System for Assuring the Performance of Steel Water Pipelines in Ground Settlement Areas

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ABSTRACT

The paper presents the application of a new system, called "InfraShield," which increases the performance level of steel water pipelines, which are connected to rigid structures and subjected to differential ground settlement. The application of the InfraShield system in the present problem consists of a pair of pipe wall projections located at appropriate locations along the pipeline that enable the pipeline to accommodate itself within the settled soil pattern in an optimum manner, minimizing its strain and deformation without the use of couplings or more complex systems. The problem is solved numerically using advanced finite elements, which simulate the steel pipe, the soil, and the soil-pipe interface in a rigorous manner. Extensive numerical results are obtained that verify the effectiveness of this system. It is also shown that pipeline response may not be very sensitive to the location of the projections, and this is a positive result on the applicability of the InfraShield system in pipeline design practice. Furthermore, the influence of pipe wall thickness and soil stiffness on settlement response are also examined.

INTRODUCTION

Differential settlements due to soil conditions may introduce significant deformation in a pipeline due to bending and axial elongation. This movement may lead to pipeline deformations and or loss of containment in gasketed or other systems. Furthermore, in extreme cases (e.g. earthquakes) pipe wall rupture may occur, especially in areas prone to soil liquefaction.

Soil settlements in connections of buried pipelines to rigid structures are of particular interest. The stiff boundary condition imposed by the rigid structure, introduces stresses and strains in the pipe, which may be well into the inelastic range of the material and may cause local buckling of pipeline wall, associated with large strains. Under settlement conditions, the steel pipeline should be capable of accommodating the imposed ground displacement, while maintaining its integrity, and fulfilling its water transmission function without leaks. As with all differential pipe settlement options, the bending moment and axial force applied on the rigid structure due to settlement should be analyzed to assure structural integrity of the rigid structure.

The present paper describes the application of a novel concept in settlement areas. The concept has been developed into an engineered patent pending steel pipe system known as InfraShield®. The InfraShield® system is aimed at absorbing ground-induced deformations, preventing water leakages and safeguarding overall pipeline integrity. With this system, water containment is maintained, even if unexpected significant ground settlement occurs. The InfraShield® system has been presented in its initial form recently in ASCE Pipeline conference and in other publications (Keil *et al*. 2020b, 2022), and is validated with full-scale physical experiments and extensive numerical simulations. It consists of imposing pipe wall projections at specific locations and is based primarily on the capability of the welded steel material to sustain significant amounts of local plastic deformation in a controlled manner without rupture or leaking.

To absorb ground-induced action, the buried pipeline should be able to deform in a way that is compatible with the imposed action. Towards this purpose, the use of InfraShield® projections is applied to buried steel water pipelines subjected to differential settlements when connected to stiff structural systems (e.g. buildings, vaults or concrete blocks). The projections have an optimized size and are placed in appropriate locations along the pipeline, so that pipe movement occurs at specific locations in a predictable and controlled manner, which allows the pipe to accommodate itself within the soil movement, absorbing the deformation while not imposing a threat on pipeline structural integrity. In addition, the presence of those projections reduces the risk during seismic or other geohazard events.

In the 2021 ASCE Pipeline conference, Fappas *et al*. (2021) presented preliminary results from settlement analyses on buried steel pipelines connected to rigid structures, using beam-type finite element models. The present paper is a continuation of the 2021 paper and employs more advanced finite element models for simulating pipeline response to settlements (shell elements for the steel pipe, solid elements for the soil and special contact interface for soil-pipe interaction). The purpose of the present work is to demonstrate in a rigorous manner the improvement of structural response subjected to differential settlement when InfraShield® is used. It is shown that, when using InfraShield®, the pipeline deforms in a controlled manner, accommodating the ground-induced action without leaks and without pipe wall rupture, thereby safeguarding pipeline integrity in an efficient, economical, and reliable manner. Furthermore, the reaction bending moment at the end section of the pipe (at the edge of the building) is decreased with respect to the reaction moment developed by the settlement of a plain pipe without projections.

SHORT DESCRIPTION OF INFRASHIELD®

The main purpose of InfraShield® is to provide extra safety to buried welded-steel pipelines subjected to ground-induced actions and replace current settlement joint options, including those utilizing couplings or gasketed joints. The experimental results reported by Keil *et al*. (2018, 2020a), and by Sarvanis *et al*. (2020) on standard lap-welded pipeline joints, supported by finite element simulations, indicated very good structural performance of those joints in terms of axial loading and bending strength. Apart from their strength, the tested joints have been able to undergo substantial deformation (axial or bending) well beyond the maximum load, without any loss of water pressure containment (Figure 1a). In those experiments, despite the excellent performance of the lap-welded joints reported in those experiments, several specimens exhibited local buckling at the bell and through the field-applied fillet weld. On the other hand, if the buckle were forced to occur in the pipe spigot, away from the bell away from the weld, pipeline safety would be simply and reliably increased.

Experimental results and finite element calculations (Keil *et al*. 2018, 2020a; Chatzopoulou *et al*. 2018; Sarvanis *et al*. 2020) indicated that the buckle location is sensitive to the presence of very small, inevitable, usually undetectable, deviations from the theoretical perfect geometry, which may occur during pipe fabrication or field construction. Therefore, a small initial geometric perturbation is imposed at the spigot in the form of a projection near the weld and enforce the buckle to occur at this specific location. The buckle is thus prevented from occurring at the bell or the weld region, and this area is protected from excessive deformation in a simple and efficient manner (Figure 1b).

The geometric projection is imposed in lap welded pipeline joints and increases structural safety in welded steel pipelines constructed in geohazard areas. The amplitude of this projection (Figure 1c) has been determined and is verified through extensive finite element results and experimental testing (Keil *et al.* 2020b, 2022). The present paper extends the application of the InfraShield® system in settlement areas, for the purpose of providing a simple and efficient solution for safeguarding pipeline integrity.

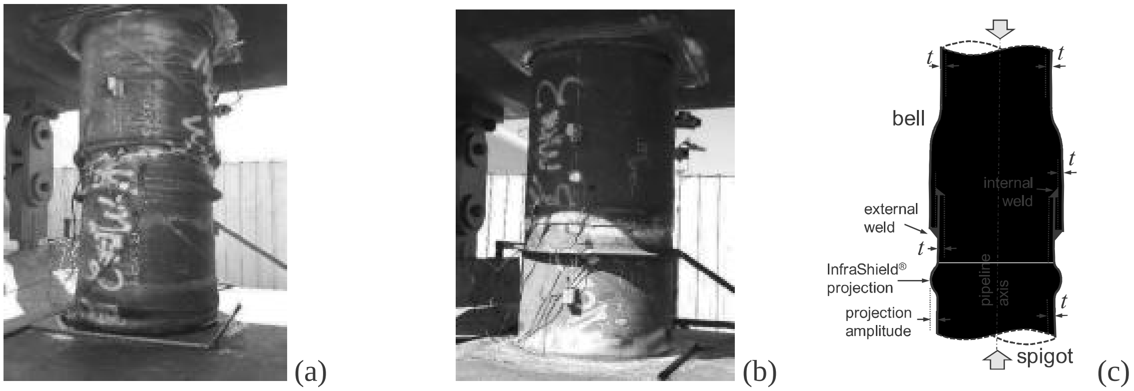

Figure 1. (a) Buckling experiment on a pressurized lap-welded joint under axial compression without projections. (b) Buckled shape with InfraShield® projections. (c) Schematic representation of InfraShield® system.

PROBLEM STATEMENT

Figure 2 shows schematically the physical problem of differential pipeline settlement. Two cases are examined: (a) the soil settles causing pipeline deformation whereas the nearby structural system has negligible settlement, and (b) the structural system settles while the soil next to it exhibits negligible settlement. In both cases, the pipeline is subjected to significant deformation, and stresses and strains develop in the pipe wall.

Considering a plain pipe (no projections) subjected to the above settlement pattern, (a) or (b) the deformed configuration of the pipe has an S-shape with double curvature, as shown schematically in Figure 3. Due to bending deformation, A and B are the most strained locations of the pipe, and in those locations local buckling of the pipe wall is expected to occur. A buckle first occurs at A, which is quite close to the fixed end conditions imposed by the building wall. Subsequently a buckle occurs at B, on the opposite side of the pipe. In our discussion, we will refer to these locations of local buckling in the plain pipe as the “original locations” of the buckles.

The use of InfraShield® projections at those critical areas is aimed at concentrating pipe deformation in the projection, controlling the shape of the deformed pipe. Clearly, if a projection is located exactly at the corresponding “original location”, then pipe deformation will localize at the projection. However, in a practical engineering application, the exact location of the buckle in a plain pipe (the “original location”) may not be a trivial task to determine or predict. Therefore, the following question arises: "if the imposed projection is not located exactly at the "original location", is it still capable of absorbing the bending deformation necessary to accommodate the pipe within the settlement pattern?". In addition: "how far from this "original location" can the projection be so that pipe deformation localizes at the projection, without the development of local buckling at the "original location"?". Those two questions constitute an essential part of the present numerical study below.

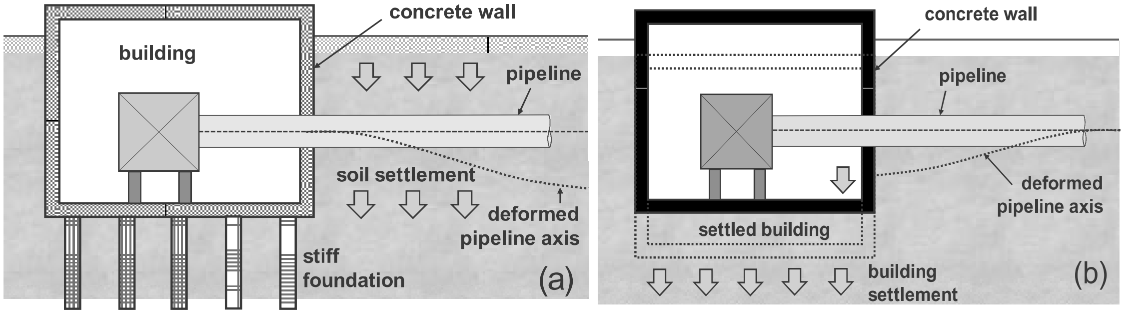

Figure 2. Settlement problem: (a) the ground settles with respect to the building; (b) the building settles with respect to the ground.

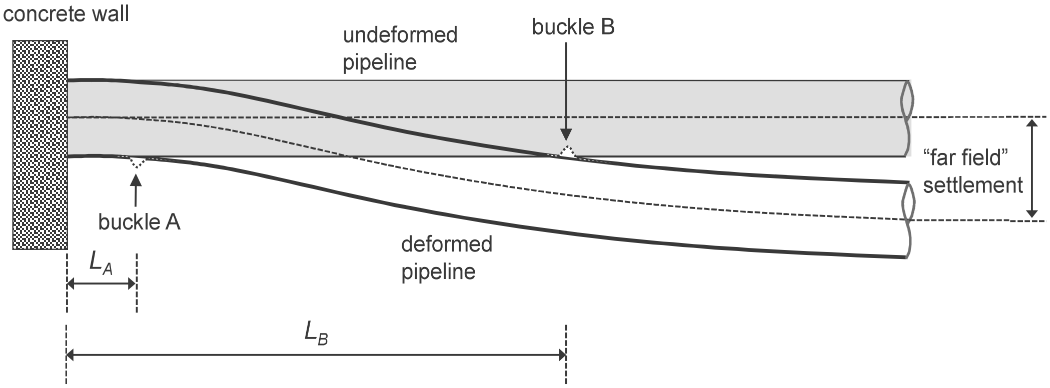

Figure 3. S-shape of deformed pipeline (schematic) with buckles at locations A and B (soil settlement with respect to the building).

In addition to the deformation induced in the pipe, bending moment and axial forces may be transmitted from the pipe to the building wall, which is penetrated by the pipeline (Figure 3). If this bending moment transmitted to the wall is large enough, then the building wall may be structurally under-designed and possibly damaged. Inclusion of projections makes the pipe more flexible and deformable, which is beneficial for the building wall; the presence of a projection reduces pipe bending resistance, thus decreasing the bending moment and the axial force transmitted to the nearby building wall.

The following parameters are examined in the present study: (a) location of projections, (b) soil stiffness, (c) pipe wall thickness, (d) type of settlement (soil settles or building settles), and the analyses are performed with advanced finite element models described briefly in the next section.

FINITE ELEMENT MODEL

A nonlinear finite element model has been developed for the purposes of this work in general-purpose finite element software ABAQUS/Standard. This model follows the modelling technique developed by the research team at the University of Thessaly for modelling soil-pipe interaction problems related to ground-induced deformations on the pipeline. Using this technique, both the pipe and the soil are modelled in a rigorous manner, allowing for the calculation of stress and strain at specific locations along the pipe and around its cross-section with a high degree of accuracy. A general view of the finite element model is shown in Figure 4.

The steel pipe is modelled with shell finite elements, capable of describing local deformations and buckling of the pipe wall. The length of the pipe in the finite element model is 131 ft (40 m), equal to 18.2 pipe diameters. This length has found to be adequate for the purposes of the present study. The pipe is fixed at its left end (inside the building) and moves with the soil at its right end. Four-node reduced-integration finite elements are used, denoted as S4R in ABAQUS, with an appropriate element size to describe pipe wall deformation. The element size is equal to 0.393 in (1 cm) in the longitudinal direction of the pipe in "critical" areas of the pipe, i.e., where projections are imposed or where local buckling is expected to occur and increases gradually to 6.299 in (16 cm) in areas where no such phenomena are expected to occur. The element size in the circumferential direction of the pipe is equal to 3.385 in (8.6 cm). The constitutive model for the pipe material is J_2 flow plasticity with isotropic hardening. A bilinear stress-strain curve is used for the pipe model with yield stress 43.9 ksi (303 MPa) and ultimate stress 74.2 kai (512 MPa), referring to a typical A1018 Grade 36 steel material.

The size of the entire soil block used in the finite element model is 127.95 ft × 32.80 ft × 26.87 ft (39 m ×10 m × 8.19 m). The soil is modelled with eight-node reduced integration "brick" finite elements, denoted as C3D8R in ABAQUS. The element size in the critical area is 19.685 in × 19.685 in × 15.748 in (500 mm × 500 mm × 400 mm) whereas away of this area, it increases to 39.37 in × 19.685 in × 15.748 in (1,000 mm × 500 mm × 400 mm). The constitutive model of the soil obeys to a Mohr-Coulomb material law, which is characterized by the cohesion c, the friction angle ϕ, the elastic modulus E, and Poisson's ratio ν. Three sets of soil parameters are considered, shown in Table 1. The first set of parameters refers to a soft-to-medium cohesive soil the second set to a rather stiff cohesive soil, and the third set to a stiff cohesiveless soil (compacted sand).

Table 1. Soil properties considered in the numerical analysis

Set of soil parameters	**Set I: soft-to-medium clay**	**Set II: stiff clay**	**Set III: sand**
Cohesion c (psi)	7.25	14.50	0
Young's modulus E, psi	1,159.5	2,318.8	2,898.5
Poisson's ratio ν	0.45	0.45	0.35
Friction angle φ, degrees	0°	0°	36°

The model also accounts for the connection to the concrete wall of the building and its interaction with the pipe, as shown in Figure 5. The wall has been modelled with C3D8R solid elements. The size of the concrete block used in the finite element model is 3.28 ft × 32.8 ft × 26.87 ft (1 m × 10 m × 8.19 m) and the corresponding finite element size is 7.874 in × 19.685 in

× 15.748 in (200 mm × 500 mm × 400 mm). The interface between the pipe and the soil is simulated with a contact algorithm, which allows separation of the pipe and surrounding soil surfaces, and accounts for interface friction, through an appropriate friction coefficient μ. A similar interface is also used between the pipe and the concrete wall.

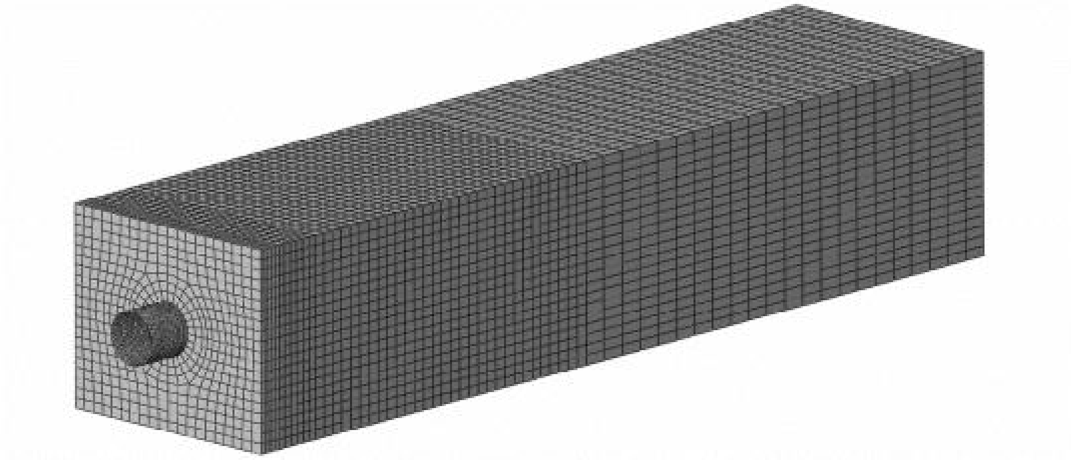

Figure 4. General view of the finite element model; soil block. pipe and concrete wall.

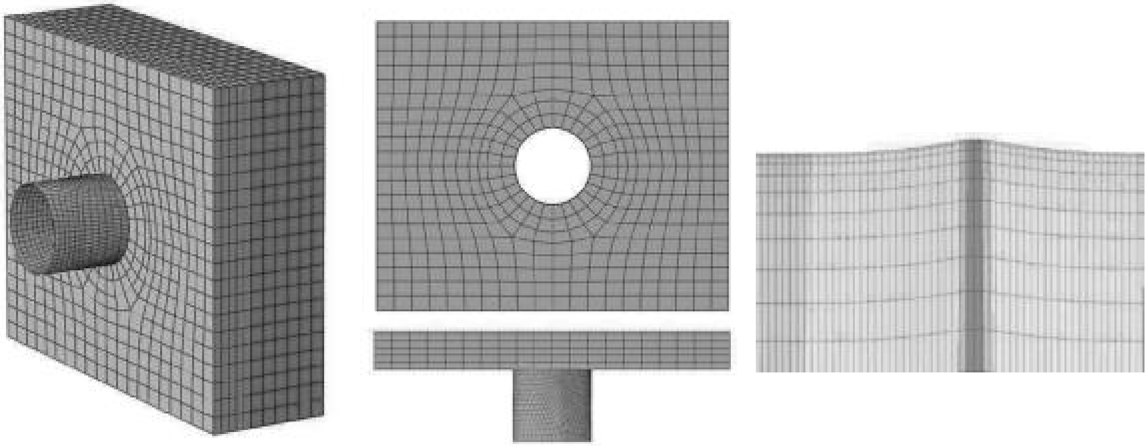

Figure 5. (A) Detailed view of the model at the building concrete wall. (B) pipe projection detail. (C) Finite element mesh at the projection area (after expansion).

The projection is introduced in the pipe model by simulating the corresponding manufacturing process, expanding the pipe at the desired amplitude in an axisymmetric manner. Rigid parts are used to simulate the expansion mandrels, and hard contact is assumed between the pipe and the mandrels.

The analysis procedure follows a sequence of steps. Considering that the projections are fabricated at the pipe mill, the projection(s) is(are) imposed first, with the set of expansion mandrels described above. Subsequently, gravity is applied, followed by internal pressure in the pipe. This step is omitted when a plain pipe without projections is analyzed. The final step of the analysis is the application of soil (or building) subsidence, which applied incrementally until the target value of settlement is reached. In each step, stresses and strains are recorded in the model, whereas bending moments of any pipe cross-section during the analysis can be computed by appropriate post-processing of the numerical results.

NUMERICAL RESULTS

A pipe with diameter 86.25 in (2190.75 mm) is considered, made of A1018 grade 36 steel. The pipe wall is 0.625 in (15.875 mm), the soil parameters are those of set I, and the soil settles with respect to the building. Initially, the analysis considers a plain pipe under settlement, and the deformed pipeline shape is shown in Figure 6 for three values of settlement: 2.755 in (7 cm), 5.9 in (15 cm) and 11.8 in (30 cm), refering to “free field” settlement (Figure 3). The latter is a large value of settlement and should be considered as an extreme condition, associated with subsidence under seismic event, rather than normal operating conditions. As expected, the pipeline exhibits local buckling at two cross-sections, located at a distance of 0.52 ft in (0.16m) (A: bottom side of the pipe) and 35.79 ft (10.91 m) (B: top side of the pipe) from the building wall; these two locations are the “original locations” (see Table 2). The buckle in A is very close to the building wall and occurs at settlement 3.54 in (9 cm). The second buckle in B occurs at settlement 11.65 in (29.6 cm). Upon buckling, pipe deformation localizes at A and B, and exhibits significant local rotation.

Table 2. Cases without projections, analyzed with the finite element models.

	case analyzed without projections	**distance of buckle A from concrete wall (ft)**	**settlement when buckle A occurs (in)**	**distance of buckle B from concrete wall (ft)**	**settlement when buckle B occurs (in)**
1	Reference case (soil set I, 0.625-inch-thick)	0.52	3.54	35.79	11.65
2	Stiffer soil (soil set II, 0.625-inch-thick)	0.52	3.07	27.95	9.21
3	Thicker pipe (0.75-inch-thick, soil set I)	0.59	4.41	-	-
4	Thinner pipe (0.50-inch-thick, soil set I)	0.46	3.19	30.12	9.06
5	Thicker pipe (0.75-inch-thick, sand soil set III)	0.52	3.54	-	-
6	Thinner pipe (0.50-inch-thick, sand soil set III)	0.49	2.95	34.20	10.83
7	Building settlement (soil set I, 0.625-inch-thick)	0.52	3.94	27.94	8.52

The above case is considered as the “reference” case for our study. Subsequently, the pipe under consideration with the same soil conditions (set I) is subjected to differential settlement (the soil settles with respect to the building), assuming the presence of projections at different locations. Three different locations are considered for the first projection, denoted as projection A, from

1.31ft (0.4m) to 6.23ft (1.9m). Four locations are also considered for the second projection (projection B), namely 29.98 ft (9.14 m), 33ft (10.06 m), 38.97ft (11.88 m) and 42.25ft (12.88 m) from the building wall. Those results demonstrate that – for the range of locations considered – the localized deformation and rotation of the pipe under settlement conditions occurs at the InfraShield® projections and not at the "original locations". This is attributed to the fact that the projection makes the corresponding pipe cross-section to behave as a "plastic hinge" and enables the deformation to concentrate at this location. From the practical point-of-view, this constitutes a very good result for the applicability of the InfraShield® system, demonstrating that the structural response of the pipe may not be very sensitive to the location of the projections, and that strain localization occurs at the projection. In other words, the two projections act as "plastic hinges" absorbing pipeline deformation imposed by the differential settlement.

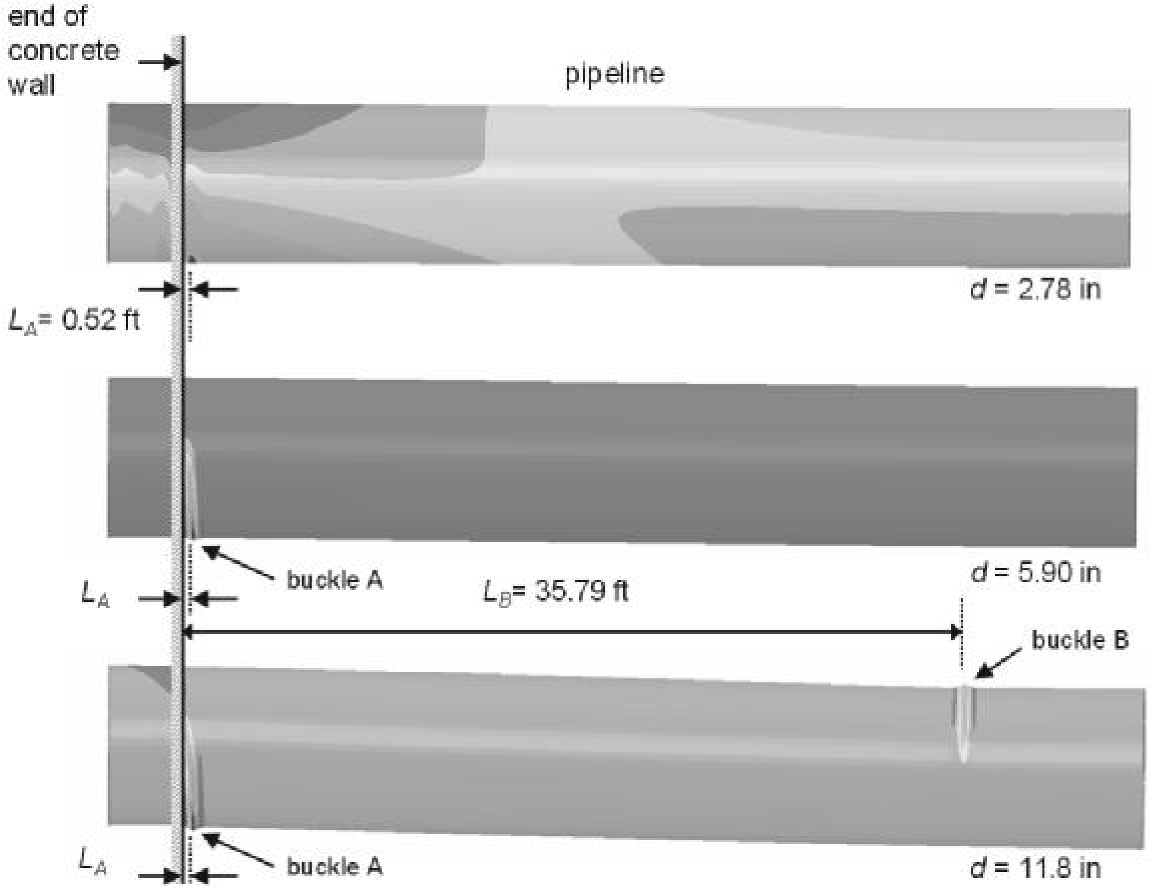

Figure 6. Deformed shapes of the pipeline (D/t=137.6) at three levels of settlement amplitude (2.75 in, 5.9 in and 11.8 in) for the reference case (without projections) and the "original locations" of the buckles at points A and B.

The finite element model is also capable of computing the stress resultants (bending moment, axial force, shear force) at any cross-section along the pipeline. The bending moment at the cross-section located at the edge of the building wall is of particular interest for the integrity of the building wall (see Table 2). Figure 7 shows the evolution of bending moment at this cross-section with respect to the size of ground settlement for two cases: (a) pipe without projections and (b) pipe with projections at 1.31 ft (0.4 m) and 32.79 ft (10.0 m) from the building wall. The comparison shows the beneficial effect of projections, which reduce the reaction bending moment by approximately 35%.

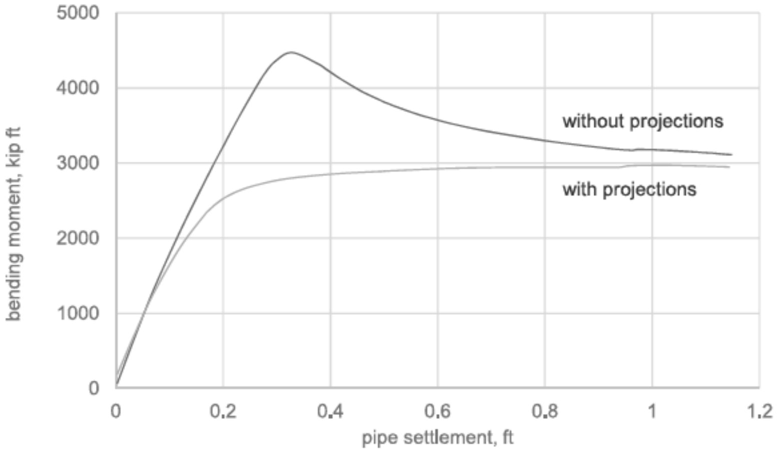

Figure 7. Evolution of bending moment at the pipe cross-section located at the edge of the building wall; comparison of plain pipe with InfraShield® System

Pipes with different pipe wall have also been considered. Analysis of a thicker pipe with 0.75in pipe wall thickness ($D/t = 114.6$) indicates that the first buckle (location A) occurs at a settlement size equal to 4.4 in (11.2 cm) and at a distance of 0.59 (0.18m) from the building wall. Due to its relatively large thickness, this pipe does not exhibit a second buckle at location B up to a settlement value equal to 13.77 in (35 cm). On the other hand, the analysis of a thinner pipe (0.5-inch-thick) shows that the first buckle occurs at 3.15 in (8cm) settlement, at a distance 0.59 in (0.18m) from the concrete wall, and the second buckle (location B) occurs at 8.85 in (22.5 cm) settlement and at a distance of 30.12 ft (9.18m) from the building wall. The two buckle locations 0.59 ft (0.18 m) and 30.12 ft (9.18m) from the pipe wall are the "original locations" for this case. The deflected and buckled shape of the pipe at a settlement equal to 13.779 in (35 cm) is shown in Figure 8, showing the two buckle locations. Subsequently, the thinner pipe case has been re-analyzed assuming two projections at 6.23 ft (1.9 m) and 33 ft (10.06 m) from the building wall respectively. Application of settlement resulted in localized deformation at the projections, whereas the strains outside the two projections remained at a very low level.

Stiffer soil conditions are also examined, considering set II of soil parameters in Table 1 and the initial pipe wall thickness (0.625in, $D/t = 137.6$). If no projections exist, the first buckle (location A) occurs at 3.07 in (7.8cm) settlement, at a distance of 0.52 ft (0.16m) from the wall, and the second buckle (location B) occurs at 9.21 in (23.4cm) settlement and at a distance of 27.95 ft (8.52m) from the building wall (see Table 2). The analysis has been repeated with the inclusion of two projections located at 6.23 ft (1.9m) and 34.78 ft (10.6m) from the building wall. The numerical results show that despite the presence of the projection at location A, a local buckle develops very near to the building wall, at the original location 0.52 ft (0.16m) from the wall (denoted as A′ in Figure 9). This means that the distance between the projection and the "original location" of the buckle has been quite large. This is a very useful result for the outer limit of the location away from the wall. The result of this analysis indicates that the first projection should close enough to the wall to absorb the entire deformation of the pipeline in that area. This case has been the only case where the assumed location of the projection has not been appropriate. Repetition of this analysis with projection A located at 3.58 ft (1.09 m) from the building wall, and in that case, the local buckle at the proximity of the concrete wall disappears.

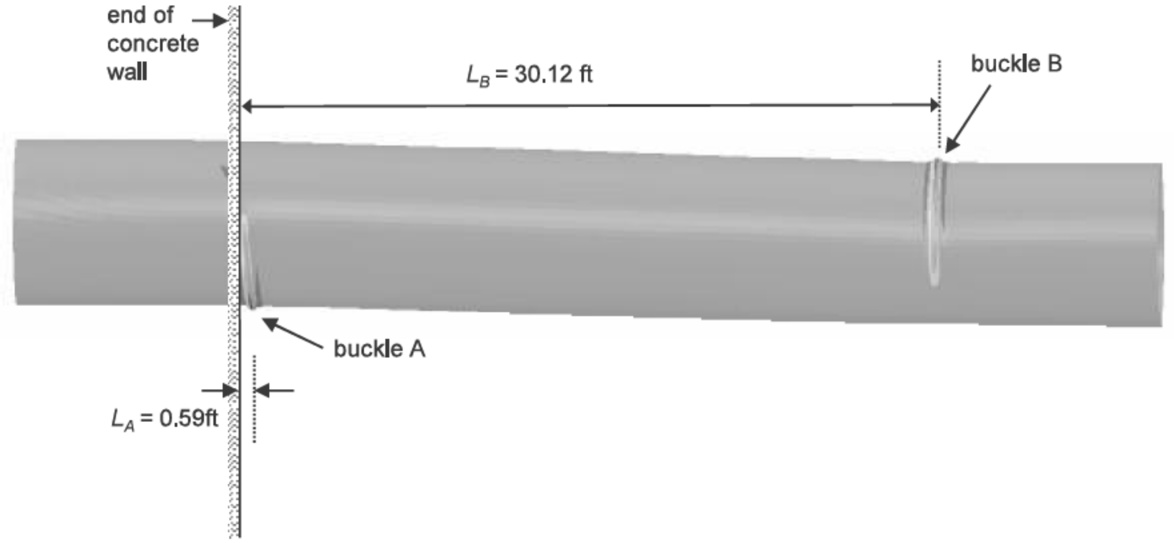

Figure 8. Shape of settled pipe without projections, for thin-walled pipe (D/t=172).

The settlement response in non-cohesive (sand) soil conditions (set III in Table 1) is also examined (soil settles with respect to the building). Considering a 0.625-inch-thick pipe, the first buckle (location A) occurs at a settlement size equal to 3.54 in (9 cm) and at a distance of 0.52 ft (0.16 m) from the building wall. However, up to a settlement value equal to 13.77 in (35 cm) a second buckle at B did not occur. Repeating the analysis with a thinner pipe (0.5 in), the first buckle (A) occurs at 2.95 in (7.5 cm) settlement, at a distance of 0.49 ft (0.15 m) from the wall, and the second buckle (location B) occurs at 10.83 in (27.5 cm) settlement and at a distance of 34.2 ft (10.43 m) from the building wall. The thinner pipe was also analyzed considering two projections at 3.44 ft (1.05 m) and 32.99 ft (10.06 m) from the building wall; the settlement resulted in localized deformation at the projections, and the strains outside the two projections remained at a very low level

Finally, numerical results have been obtained for the case of building settlement with respect to the surrounding soil. The locations of the two buckles A and B are 0.52 ft (0.16 m) and 27.94 ft (8.52 m) from the building wall respectively and are located at the opposite side of the pipe cross-section. The shape of the pipeline is shown in Figure 10. Repeating this analysis with two projections located at 3.44 ft (1.05 m) and 32.99 ft (10.06 m) from the building wall, the deformation localized at the projections, indicating a structural response consistent with the previous cases analyzed.

The main conclusion from the above analyses is that the projection should be close enough to the "original location" of the buckle, but not necessarily exactly on it. Current studies are underway to determine more accurately the range of suitable location of the InfraShield® projection with respect to the original buckle location, for different pipes and soil conditions.

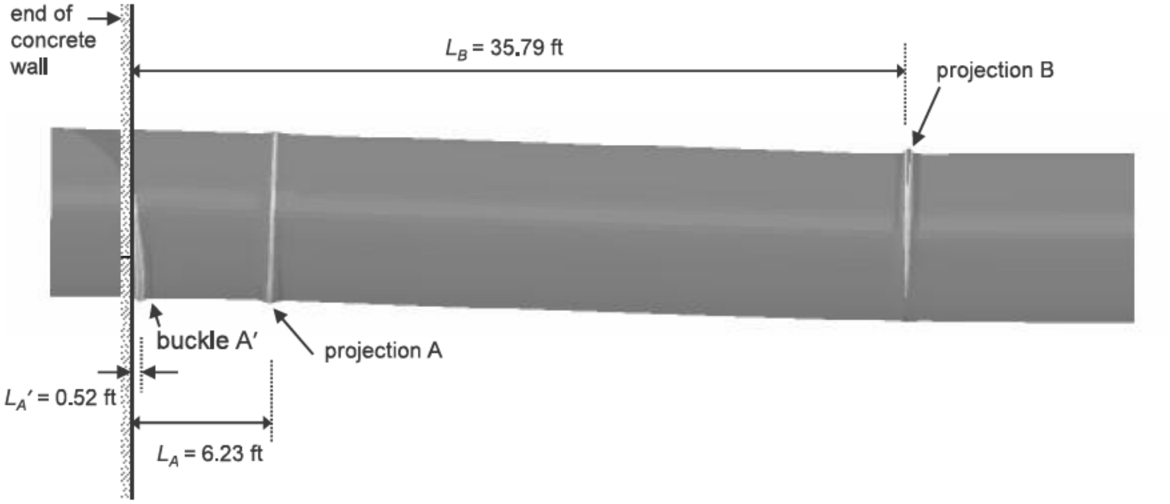

Figure 9. Deformed shape of settled pipe with InfraShield® projections at 6.23 ft and 34.78 ft from the concrete wall (D/t=137.6).

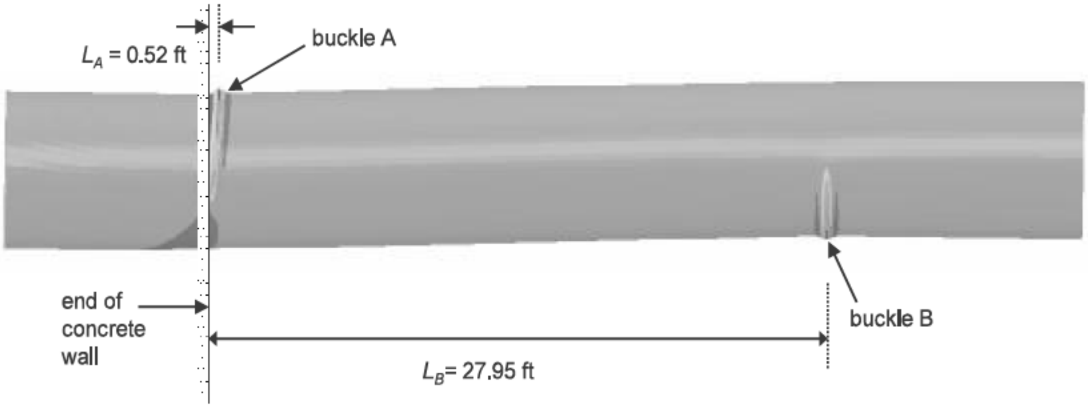

Figure 10. Deformed shape of settled pipe without projections (D/t=137.6, soil set I) for the case of building settlement.

CONCLUSIONS

Numerical results are presented on buried steel pipelines connected to rigid structures subjected to differential settlement. The study focuses on the use of the InfraShield® system for improving the structural performance of buried pipes in differential settlement areas for different soil conditions. The numerical results extend the preliminary results presented by the authors in previous conferences and employ rigorous finite element models (shell elements for the steel pipe, solid elements for the soil and special contact interface for soil-pipe interaction). It is demonstrated that the structural response under differential settlement is improved when the InfraShield® System is used. More specifically, it is shown that, when using the projections at appropriate locations, the pipeline deforms in a controlled manner, absorbing the ground-induced action, safeguarding pipeline integrity in an efficient, economical, and reliable manner. Furthermore, using the projections, the reaction bending moment of the pipe at the edge of the building is decreased by a substantial amount, reducing the strength requirements of the building wall or decreasing risk. Current research is underway to examine the effects of a wider range of pipe and soil parameters on the structural response of pipelines equipped with InfraShield® projections in settlement areas, towards developing relevant design parameters and tables.

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