How to Accommodate Differential Settlement Using Geohazard Resistant Steel Pipe

Brent D. Keil, P.E., M.ASCE[1]; Polynikis Vazouras, Ph.D.[2];
Richard D. Mielke, P.E., M.ASCE[3]; and Spyros A. Karamanos, Ph.D., M.ASCE[4]

[1]Northwest Pipe Co., Vancouver, WA. Email: BKEIL@nwpipe.com
[2]Dept. of Mechanical Engineering, Univ. of Thessaly, Volos, Greece. Email: pvazour@uth.gr
[3]Northwest Pipe Co., Vancouver, WA. Email: RMIELKE@nwpipe.com
[4]Dept. of Mechanical Engineering, Univ. of Thessaly, Volos, Greece. Email: skara@mie.uth.gr

ABSTRACT

Quite often, buried pipelines connected to rigid structures or existing buried pipelines undergo differential settlements that, in addition to stress and strain from normal operational conditions, may impose significant stress and strain in the pipe wall. The pipeline should be capable of accommodating the imposed displacement due to settlement while maintaining its structural integrity and fulfilling its water transmission function without leaks. Currently, the use of couplings or joints that depend on gasket seating to maintain water containment after settlement is the typical solution for lesser amounts of differential settlement. The paper describes the expanded application of the engineered steel pipe solution identified as Geohazard Resistant Steel Pipe (GRSP) for use in differential settlement applications. The application of GRSP for absorption of ground displacement in a controlled and efficient manner allows for fully welded joints, eliminating the need for gaskets. GRSP has been introduced in previous ASCE Pipelines conferences and validated with a series of full-size physical tests backed with extensive rigorous finite element simulations. It was shown that GRSP can be used in seismic or ground fault areas where ground-induced actions are expected to occur. GRSP has also been applied in settlement or subsidence areas, offering a simple and economical solution for absorbing the deformation imposed by differential settlement or subsidence. This paper will provide design guidelines and design tables on the use of GRSP and, specifically the InfraShield Joint System (IJS), patent pending. The design tables and design guidelines are developed from the full-scale testing on 24-in.-diameter pipes and continued with extensive finite element (FE) simulations on 84-in.-diameter pipes under differential settlements. This paper will expand on this FE work and include 42-in. and 24-in.-diameter pipe simulations. Two primary cases are considered: (1) the soil settles, causing pipeline deformation, whereas the nearby structural system has negligible settlement, and (2) the structural system settles, while the soil next to it exhibits negligible settlement. The main parameters for the advanced FE work are: (1) soil types (stiffness); (2) diameter-to-thickness ratio (D/t); (3) level of internal pressure; (4) size of soil cover above the pipeline; and (5) amount of vertical or horizontal settlement. Using the results of these extensive studies, application tables for settlements of up to 4 in. for diameters of 24 in. through 96 in. are provided, accompanied by design and GRSP installation guidelines.

INTRODUCTION

Pipelines crossing settlement areas that experience differential soil settlements may be exposed to significant distress due to bending and axial elongation. The pipeline movement associated with settlements may lead to pipeline deformations, damage, and or loss of containment. In pipelines with gasketed joints, differential settlements may cause joint separation with immediate loss of pipeline functionality. On the other hand, in steel lap-welded pipelines, the joints may exhibit compressive and tensile action due to bending and axial elongation.

Soil settlements in connections of buried pipelines to rigid structures (e.g. pump stations, concrete tanks, valve vaults, existing buried pipe installations, or concrete block structures) are of particular interest; in those applications, settlements up to 4 inches are quite common and need to be addressed in pipeline structural design. Larger values of differential settlement may occur during geohazard events, for example, especially in areas of saturated soft or expansive soils. Under those settlements, the steel pipeline should be capable of accommodating the imposed ground displacement while maintaining its integrity and fulfilling its water transmission function without leaks. Connections to rigid structures may introduce stresses and strains well beyond the elastic limit of the pipe material, which may cause local buckling of pipeline wall associated with large strains.

The present paper describes the application of the IJS as a simple and efficient methodology for accommodating settlement displacements in buried pipelines using the GRSP concept. This joint system has been developed for use in engineered steel pipe systems, aimed at absorbing small to large ground-induced deformations, preventing water leakages, and safeguarding overall pipeline integrity. With this concept, water containment is maintained, even if unexpected significant ground settlement occurs. It has been presented in its initial form in previous ASCE Pipeline conferences and other publications (Keil *et al*. 2020b, 2022), and has been validated with full-scale physical experiments and extensive numerical simulations. It consists of implementing pipe wall projections at specific locations and is based primarily on the capability of the steel material to sustain significant amounts of local plastic deformation in a controlled manner without rupture or leaking.

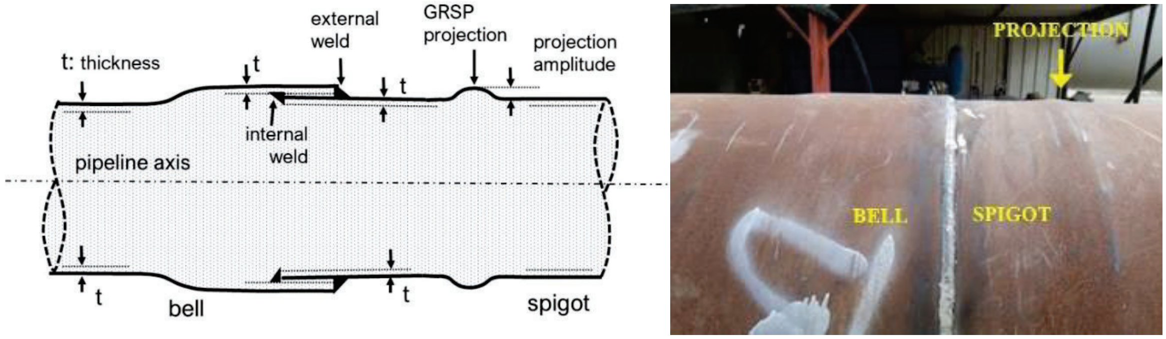
To absorb ground-induced action, the buried pipeline should be able to deform in a way that is compatible with the imposed action. Towards this purpose, the IJS is introduced into buried steel water pipelines by providing factory-installed projections onto the spigot end of pipe wall sections. The projections are subjected to differential settlements when connected to stiff structural systems or existing pipelines. The projections have an optimized size and are placed in appropriate locations along the IJS section of the pipeline so that pipe deformations occur at specific locations in a predictable and controlled manner, which allows the pipe to accommodate the differential movement, absorbing the deformation while not imposing a threat on pipeline structural integrity.

In the 2022 ASCE Pipelines Conference, Vazouras *et al*. (2022) presented initial numerical results from settlement analyses on 84-inch-diameter buried steel pipelines connected to rigid structures. It was shown that, when using this system with projections at an appropriate location, the pipeline deforms in a controlled manner, accommodating the ground-induced action. The present paper is a continuation of the 2022 paper and refers to a wide range of soil and pipe parameters for the purpose of developing relevant design guidelines and design tables. Advanced finite element models are employed for simulating pipeline response to settlements, with 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 propose simple-to-use design tables and guidelines that improve pipeline resilience against differential settlements without leaks, thereby safeguarding pipeline integrity in an efficient, economical, and reliable manner.

SHORT DESCRIPTION OF THE IJS SYSTEM

The main purpose of IJS 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), supported by finite element calculations (Keil *et al*. 2018, 2020a; Chatzopoulou *et al*. 2018; Sarvanis *et al*. 2020) on lap-welded joints subjected to axial compression and bending, indicated that the introduction of a small initial geometric perturbation at the spigot in the form of a projection near the weld enforces the buckle to occur at this specific location in a controlled manner, protecting the bell or the weld region from excessive deformation (Figure 1a).

This geometric projection constitutes the basis of implementing IJS in a GRSP system, aimed at increasing the pipeline resilience in geohazard areas. The projection amplitude (Figure 1b) has been determined using rigorous numerical tools and has been verified through extensive experimental testing (Keil *et al*. 2020b, 2022). The present paper extends the application of the IJS in differential settlement areas for the purpose of providing a simple and efficient solution for safeguarding the integrity of buried welded pipelines.



(a) (b)

Figure 1. (a) Schematic representation of the IJS. (b) Projection introduced in a 24-inch diameter pipe (see yellow arrow).

PROBLEM STATEMENT

The physical problem of differential pipeline settlement in buried pipelines connected to rigid structures is shown schematically in Figure 2 (illustrated without GRSP). 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 develop. Increasing the differential settlement, a buckle first occurs at location A, which is quite close to the fixed end conditions imposed by the building wall. Continuing the movement, a buckle occurs at B, on the opposite side of the pipe. In our discussion, we will refer to these local buckling locations in the plain pipe as the "original locations" of the buckles.

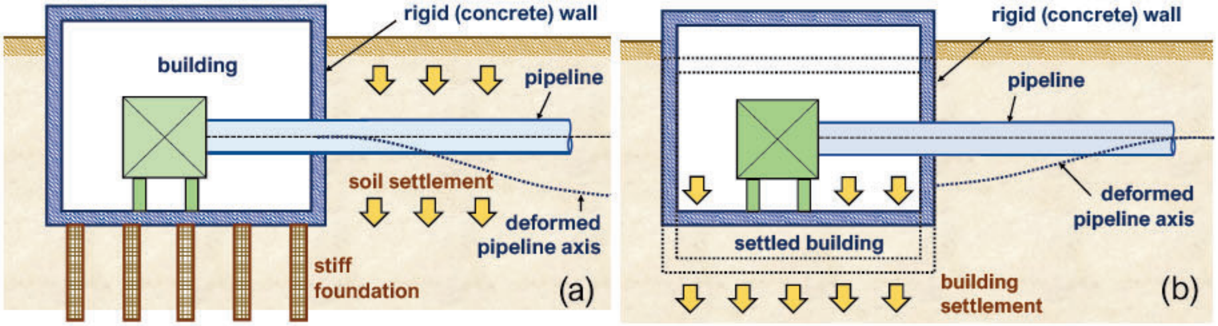


Figure 2. Settlement problem: (a) the ground settles with respect to the building; (b) the building settles with respect to the ground.

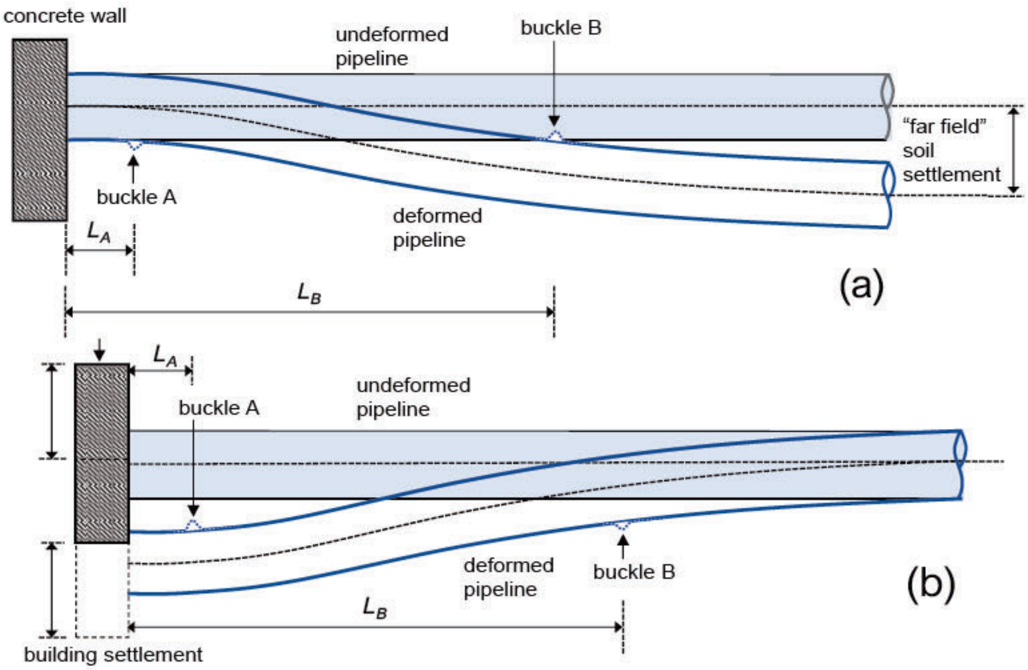


Figure 3. S-shape of deformed pipeline (schematic) with buckles at locations A and B (soil settlement with respect to the building).

The use of 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 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, it is important to know; "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.

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

FINITE ELEMENT MODEL

Nonlinear finite element models, introduced in the paper by Vazouras *et al*. (2022), are employed for performing the numerical simulation of buried pipe settlement. They are developed in general-purpose finite element software ABAQUS/Standard and follow the modeling technique developed by the research team at the University of Thessaly for simulating soil-pipeline interaction problems related to ground-induced deformations. Using this technique, both the pipe and the soil are modeled 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. The numerical model is outlined herein for the sake of completeness, and a general view of the finite element model is shown in Figure 4.

The steel pipe is modeled 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 equal to 20 pipe diameters. The pipe in Figure 4 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 60% of pipe wall thickness 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 in areas where no such phenomena are expected to occur. The element size in the circumferential direction of the pipe is equal to 5 times the pipe wall thickness. The constitutive model for the pipe material is J_2 flow plasticity with isotropic hardening. The yield stress and ultimate stress of the pipe material are 43.9 ksi (303 MPa) and 74.2 ksi (512 MPa), referring to a typical A1018 42 ksi minimum yield steel.

The size of the entire soil block used in the finite element model is 19 diameters long, 4 diameters deep, and 4.5 diameters wide. The soil is modeled with eight-node reduced integration “brick” finite elements, denoted as C3D8R in ABAQUS. The element size in the critical area is 13 in × 16 in× 20 in, whereas away from this area, it increases to 39 in × 16 in × 20 in. The constitutive model of the soil obeys 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.

Table 1. Soil properties considered in the numerical analysis.

Range values of soil parameters	Cohesion c (psi)	Young’s modulus E, psi	Friction angle φ, degrees
Cohesive (clay)	7.25 – 14.50	1,160 – 2,320	0^o
Non-cohesive (sand)	0.7	1,160 – 2,900	$36^o – 40^o$

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 modeled with C3D8R solid elements. The size of the concrete block used in the finite element model is 39.3 in × 393 in × 322 in and the corresponding finite element size is 7.87 in × 16 in × 20 in. 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. The projection is introduced in the pipe model by simulating the corresponding manufacturing process.

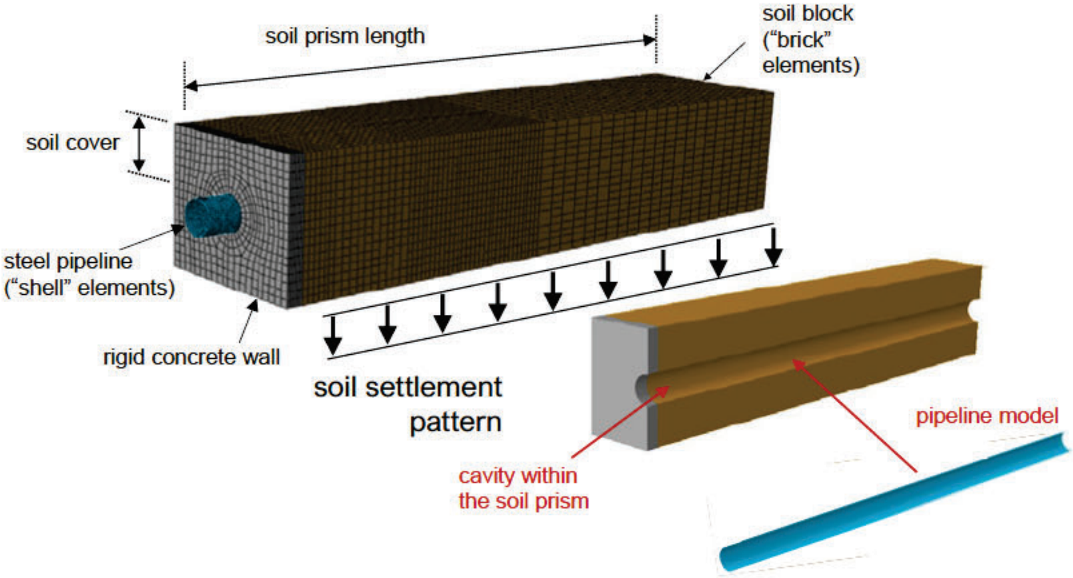


Figure 4. General view of the finite element model for soil settlement; soil block, pipeline, concrete wall, and settlement pattern.

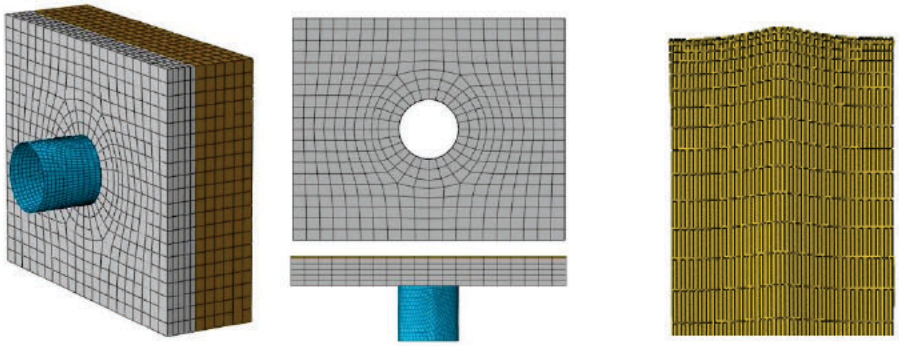


Figure 5. (A) Detailed view of the model at the building concrete wall. (B) Top and side views of the concrete wall. (C) Finite element mesh at the projection area.

The analysis procedure follows a sequence of steps. Considering that the projections are fabricated at the pipe factory, the projection is first imposed. 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 is 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

Three pipes made of A1018 42 ksi minimum yield steel with diameters equal to 86.25 in (nominal: 84 in, denoted as Pipe I), 43.875 in (nominal: 42 in, denoted as Pipe II) and 25.75 in (nominal: 24 in, denoted as Pipe III) are considered. Pipe wall thickness for Pipe I ranges between 0.375 in and 0.75 in and for Pipe II ranges between 0.175 in and 0.25 in. Finally, two wall thickness values were considered for pipe III, 0.135 in and 0.25 in. Soil conditions for cohesive (clay) and non-cohesive (sand) soils are considered with parameters as shown in Table 1. Two values of pipe cover depth are considered: 4 ft and 10 ft. Additional analyses are performed for Pipe I with 20 ft depth of cover. Furthermore, both settlement types were considered, namely the case where the soil settles with respect to the building and the case where the building settles with respect to the surrounding soil.

The results in Figure 6 refer to pipe with 43.875 in diameter and pipe wall thickness equal to 0.20 in without projections and soft to firm cohesive soil conditions. The analysis considers a plain pipe under soil settlement, and the deformed pipeline shape is shown in Figure 6 for three values of settlement: 0.8 in, 1.46 in, and 4.06 in. These values refer to “free field” settlement (Figure 3) and is different than the resultant vertical displacement of the pipeline. Furthermore, the value of 4.06 in is relatively large and should be considered as a maximum value of settlement associated with normal operating conditions. As expected, the pipeline exhibits local buckling at two cross-sections, located at a distance of 0.26 ft (A: bottom side of the pipe) and 14.44 ft (B: top side of the pipe) from the building wall; these two locations are the “original locations.” The buckle in A is very close to the building wall and occurs at settlement 1.46 in. The second buckle in B occurs at settlement 4.06 in. Upon buckling, pipe deformation localizes at A and B. Those two locations act as “plastic hinges,” where the pipe exhibits significant local rotation absorbing pipeline deformation imposed by the differential settlement.

Subsequently, the pipe under consideration with the same soil conditions is subjected to differential settlement with a maximum value equal to 13.5 in, where the building settles with respect to the surrounding soil. The deformed shape of the pipeline is shown in Figure 7 for three values of building settlement: 0.8 in, 1.50 in, and 3.62 in. First, a buckle occurred at a distance of 0.295 ft from the building wall (location A) at 1.50 in building settlement, whereas a second buckle occurred at a distance of 14.44 ft from the building wall (location B) at 3.62 in building settlement.

In total, 116 cases have been analyzed, considering a wide range of pipe and soil parameters. In each case, the imposed settlement was gradually increased up to a maximum value of approximately 13.5 in. At each step of the analysis, stress and strain within the pipe were recorded, and the formation of buckling was monitored.

In this paper, the main conclusions from the extensive analysis of IJS are as follows:

1. All cases examined exhibited local buckling at location A, nearest to the rigid wall. The distance of buckle A from the pipe wall is less than 1ft. The settlement size corresponding to the occurrence of this local buckle was relatively small, usually less than 10% of the pipe diameter.

2. The location of buckle point at B and the soil displacement corresponding to the formation of this buckle, i.e., the values of L_B and u_B, have a much greater scatter. The following observations can be made:
   (a) In several cases, especially in large-diameter pipes (D=84 in), a second buckle at B did not occur even for soil displacement that reached 13 in. In those cases, bending and stretching were accommodated by the pipeline without the occurrence of local buckling.
   (b) Normalization of u_B and L_B scatter with respect to the pipe diameter D helps in better interpretation of the numerical results.
   (c) Pipe wall thickness influences the u_B value; the larger the thickness, the larger the value of u_B. On the other hand, the influence of pipe wall thickness on the value of L_B is significantly smaller.
   (d) Both values of L_B and u_B depend on the type of settlement. Building settlement appears to be more severe for the pipeline.
   (e) The level of internal pressure influences pipeline behavior by a small amount. Results for unpressurized pipes show that those pipes behave slightly better compared with the pressurized cases. The level of internal pressure has minimal effect on the value of L_B.
   (f) Soil stiffness appears to have a beneficial effect on pipeline behavior, indicating the soil resistance increases the value of u_B.
   (g) The value of L_B increases with the increase of pipe thickness and decreases in terms of increasing soil stiffness and soil cover.

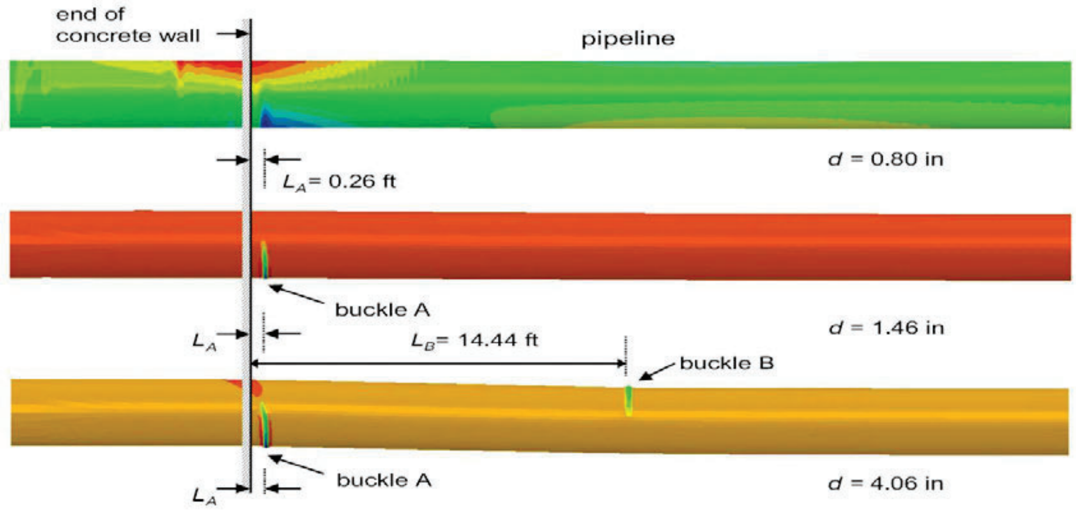


Figure 6. Deformed shapes of a 43.875-in pipeline (D/t=219) at three levels of settlement amplitude (u_B =0.8 in, 1.46 in, and 4.06 in) without projections, shown the formation of buckles at points A and B; type of settlement: soil settlement.

DESIGN GUIDELINES AND TABLES

Based on the numerical results of plain pipe presented above, a set of guidelines have been developed for the structural design of buried steel water pipelines utilizing the IJS when connected to rigid structures, subjected to differential settlement of up to 13.5 inches.

1. It will always be necessary to locate one projection near the building wall (location A). The distance from the projection to the wall should be up to 40% of pipe diameter (0.4D), or less , if possible.
2. When the building settles with respect to the pipe envelope, a second projection at location B should be placed at four (4) pipe diameters (4D) from the building wall. If settlement is expected to be less than 6% of pipe diameter D, there is no need for a second projection at B.
3. When the soil around the building settles with respect to the building, it is suggested that:
   (a) If the expected settlement is less than 6% of the pipe diameter D (0.06D), there is no need to introduce a second projection.
   (b) If the expected settlement size is between 6% and 16% of the pipe diameter D, a second projection (location B) should be placed at a distance of four (4) pipe diameters (4D) from the building wall.
   (c) If the expected settlement size is greater than 16% of the pipe diameter D (0.16D), three projections should be used to cover all possible cases of soil type and stiffness, pipe diameter and thickness, and cover depth. The locations of the second and third projections should be at a distance of four (4) diameters from each other and six and a half (6½) diameters from the building wall, respectively.
4. Wall thickness should not be increased in the IJS areas.
5. Very stiff backfill materials such as flowable fill or concrete should not be used.

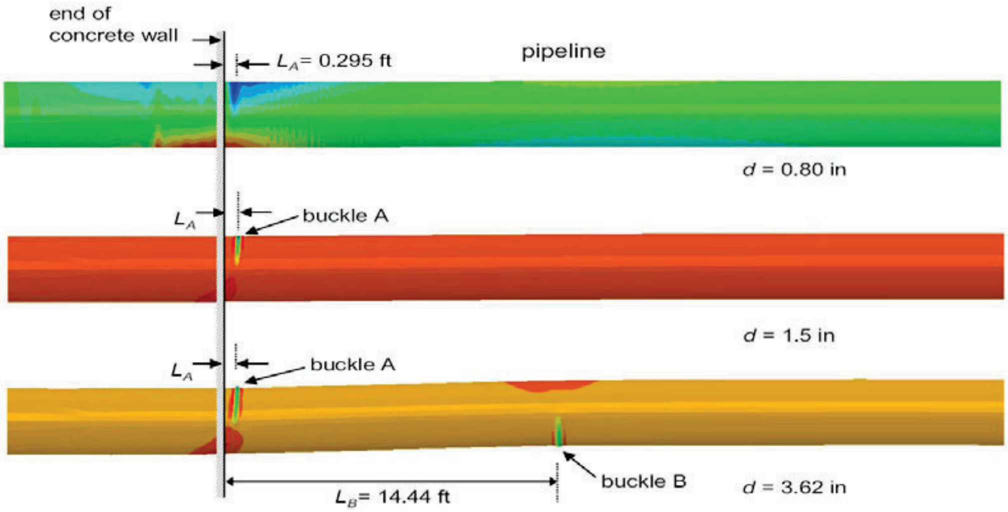
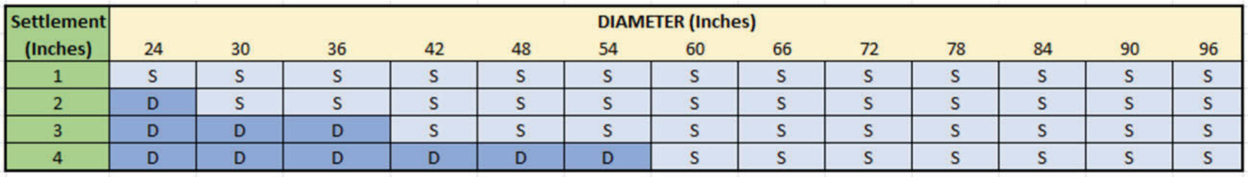


Figure 7. Deformed shapes of a 43.875-in pipeline (D/t=219) at three levels of settlement amplitude (u_B = 0.8 in, 1.5 in, and 3.62 in) without projections, shown the formation of buckles at points A and B; type of settlement: building settlement.

In most applications, the amount of settlement does not exceed 4 inches. For these particular cases, with diameters of 24 in through 96 in, refer to Table 2 to determine the need for either a single projection near the structure, noted as “S” in the table, or two projections, noted as “D” in the table, based on the total differential settlement. Using Figure 8, the joint length extending from the structure wall “A” is 1.5 feet for 24- and 30-inch diameter pipe and 2 feet for larger diameters (36 through 96-inch). When two projections are prescribed in Table 2, the second joint length “B” is four (4) pipe diameters (4D).

Table 2: Determination of one or two InfraShield® projections based on settlement and pipe diameter. Applicable for SC1, SC2, or SC3 soil embedment as defined in AWWA M11 (2017).



Settlement	DIAMETER (Inches)												
(Inches)	24	30	36	42	48	54	60	66	72	78	84	90	96
1	S	S	S	S	S	S	S	S	S	S	S	S	S
2	D	S	S	S	S	S	S	S	S	S	S	S	S
3	D	D	D	S	S	S	S	S	S	S	S	S	S
4	D	D	D	D	D	D	S	S	S	S	S	S	S

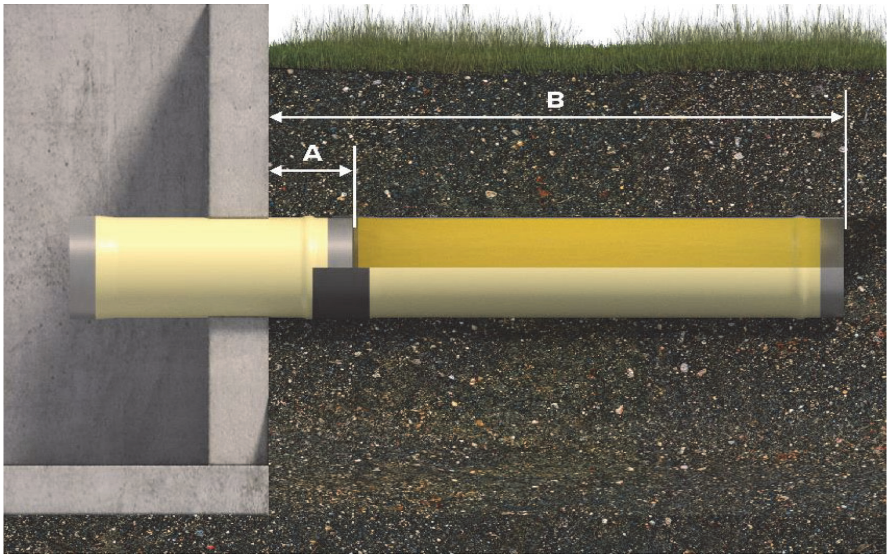


Figure 8: Pipe joint length from the rigid structure.

SUMMARY AND CONCLUSIONS

An extensive numerical study was performed on buried steel pipelines connected to rigid structures subjected to differential settlement. The study was aimed at providing design guidelines for the use of the InfraShield® Joint System (IJS) in Geohazard Resistant Steel Pipe (GRSP) applications that will improve the structural performance of buried pipes in settlement areas. The numerical results extend the results presented by the authors in previous ASCE Pipelines 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). The numerical results show that, when introducing IJS projections at appropriate locations, the pipeline deforms in a controlled manner, absorbing the ground-induced action and safeguarding pipeline integrity in an efficient, economical, and reliable manner. For the case of settlements not exceeding 4 inches, a simple and efficient methodology is provided with the use of a design table.

REFERENCES

AWWA (American Water Works Association). (2017). Steel Pipe - A Guide for Design and Installation. AWWA M11, 5th Edition.

Chatzopoulou, G., Fappas, D., Karamanos, S. A., Keil, B., and Mielke, R. D. (2018). “Numerical simulation of steel Lap welded pipe joint behavior in seismic conditions.”, *ASCE Pipelines Conference*, paper No. 387141, Toronto, ON, Canada.

Fappas, D., Sarvanis, G. C., Karamanos, S. A., Keil, B. D., Mielke, R. D., and Card, R. J. (2021). “Safeguarding the integrity of large-diameter steel pipelines subjected to differential ground settlements”, *ASCE Pipelines Conference*, paper No. 932722, Calgary, AL, Canada.

Keil, B. D., Gobler, F., Mielke, R. D., Lucier, G., Sarvanis, G. C., and Karamanos, S. A. (2018). “Experimental Results of Steel Lap Welded Pipe Joints in Seismic Conditions.”, *ASCE Pipelines Conference*, paper No. 386906, Toronto, ON, Canada.

Keil, B. D., Lucier, G., Karamanos, S. A., Mielke, R. D., Gobler, F., Fappas, D., Sarvanis, G. C., Chatzopoulou, G., and Card, R. J. (2020a). “Experimental Investigation of Steel Lap Welded Pipe Joint Performance Under Severe Axial Loading Conditions in Seismic or Geohazard Areas”, *ASCE Pipelines Conference*, paper No. 744005, San Antonio, TX, USA.

Keil, B. D., Mielke, R. D., Gobler, F., Lucier, G., Sarvanis, G. C., Chatzopoulou, G., Fappas, D., and Karamanos, S. A. (2020b). “Newly Developed Seismic Resilient Steel Pipe Joint Safeguards Pipeline Structural Integrity during Severe Geohazard Events”, *ASCE Pipelines Conference*, paper No. 744041, San Antonio, TX, USA, August 2020 (Virtual).

Keil, B. D., Fappas, D., Gobler, F., Sarvanis, G. C., Chatzopoulou, G., Lucier, G., Mielke, R. D., and Karamanos, S. A. (2022). “A New System for Improving the Structural Resilience of Lap-Welded Steel Pipeline Joints”, *Thin-Walled Structures*, Vol. 171, article 108676.

Sarvanis, G. C., Chatzopoulou, G., Fappas, D., Karamanos, S. A., Keil, B. D., Lucier, G., Gobler, F., and Mielke, R. D. (2020). “Bending Response of Lap Welded Steel Pipeline Joints”, *Thin-Walled Structures*, Vol. 157, Article 107065.

Vazouras, P., Keil, B. D., Dakoulas, P., Mielke, R. D., and Karamanos, S. A. (2022). “A novel concept for assuring the performance of steel water pipelines in ground settlement areas”, *ASCE Pipelines Conference*, paper No. 71, Indianapolis, IN, USA.