Strain-Based Design of a Large-Diameter Steel Water Pipeline Crossing Ground Settlement Areas

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ABSTRACT

This paper describes the structural design of a large-diameter buried steel pipeline crossing two areas of substantial soil settlement, which impose fault-type actions in the pipeline. Those ground-induced deformations are associated with the development of high levels of strain, well beyond the elastic limit of the pipe material. The present paper describes the application of "strain-based" design approach, towards economically efficient solution, while increasing pipeline safety and reducing risk. Strain demand is calculated first, using a global analysis, through finite element models, developed for the purposes of the present design. The numerical models employ "pipe elements" to simulate the pipeline and "soil springs" to describe the soil and its interaction with the pipeline. Subsequently, the ground-induced strains are calculated and compared with the allowable values. The design makes use of a newly developed concept, the "projection" concept, which increases pipeline resilience and improves lap welded joint performance. The effects of soil conditions on pipeline performance are also discussed.

INTRODUCTION

Steel water pipelines are usually constructed in areas where substantial ground-induced actions are expected, referred to as "geohazard areas". Seismic prone areas constitute typical examples of geohazard areas, where the pipeline may undergo substantial amount of deformation, stemming from fault movement, liquefaction-induced lateral spreading or soil subsidence, or earthquake-induced landslide motion. These are permanent ground displacements (PGD) and may lead to pipeline failure in the form of excessive local buckling or fracture of pipeline wall and loss of pressure containment (Karamanos *et al*. 2017). Nevertheless, pipelines may experience significant ground-induced deformations in non-seismic areas, due to unstable slope motion or soil subsidence. Those permanent ground-induced actions may be quite severe (Sarvanis *et al*. 2018) and deform the pipeline well beyond the level corresponding to normal operating conditions. More specifically, they are associated with severe inelastic deformation of the steel material and need to be considered in pipeline design (Karamanos *et al*., 2017). Therefore, typical stress design may not be adequate, and strain-based design of the pipeline should be performed.

In geohazard areas, the use of segmental joints may not be recommended, and welded joints are used. In principle, lap welded joints are preferred instead of butt-welded joints, due to their lower construction cost, and their successful proven history of use. For the particular case of pipeline construction in geohazard areas, recent experimental research, supported by detailed finite element simulations, has demonstrated that lap welded joints may offer an efficient and economical solution for buried welded pipelines.

Recent experimental results on lap welded joints under bending and axial loading conditions have been reported by Keil *et al*. (2018, 2020), supported by numerical simulations (Chatzopoulou *et al*., 2018; Sarvanis *et al*., 2019). They referred to two lap welded joints of 25.75-inch outside diameter pipes (24 inch nominal diameter), with thickness equal to 0.135 in and 0.250 in, made of steel grade ASTM A1011 SS GR36 and ASTM A1018 SS GR40, respectively. The main conclusion from those works is that standard lap welded joints are capable of sustaining a significant amount of bending and axial deformation while maintaining water containment, whereas the lap weld joint strength is quite close to the strength of the plain pipe.

More recent research has continued the work presented in the above papers, and reported experimental results of the structural performance of a newly developed seismic resilient steel lap weld joint, referred to as "seismic resilient joint" or simply "seismic joint", subjected to bending and axial compression and tension loadings. The main feature of the new joint is the introduction of a small-amplitude "projection" near the lap welded joint, on the "spigot" side, which enables the formation of local buckling at this specific location, avoiding the development of excessive strain and deformation at the bell or the field weld area (Figurea). Using this "projection", the pipeline is capable of deforming and buckling in a controlled manner, ensuring the strength and deformation capacity of the lap welded joint. In addition to the "seismic projection" used at the vicinity of a lap-welded pipeline joint, this projection has been optimized for the purpose of providing more flexibility at this specific location; the resulting projection is referred to as "projection II" (Figureb). More information on "projection II" is offered in the companion paper (Fappas *et al*., 2021).

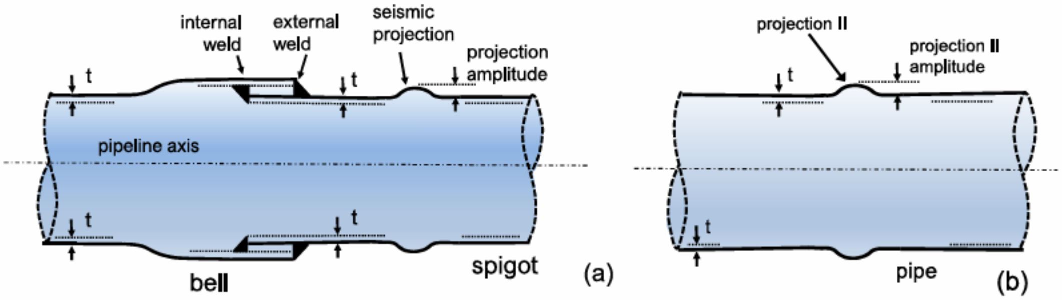

Figure 1: Schematic representation of pipe "projections": (a) seismic projection; (b) projection II

The present paper describes the application of "strain-based" design in conjunction with the above "projection" concept in a geohazard area, where ground-induced actions are expected in a large-diameter steel water pipeline due to soil subsidence. More specifically, the study refers to a large-diameter steel pipeline that is part of a $1.2B surface water supply project currently under design for the West Harris County Regional Water Authority in Houston, Texas. This major pipeline crosses two areas of substantial long-term soil settlement, which impose a fault-type ground-induced action in the pipeline, associated with maximum value of soil subsidence that exceeds 3 ft and the development of high levels of strain, well beyond the elastic limit of the pipe material. The design process is assisted by finite element models, which account for internal pressure effects, cross-sectional deformation, inelastic behaviour of the steel material, and soil-pipe interaction effects. Furthermore, the presence of projections is taken into account in the model using special-purpose “connector” elements.

OUTLINE OF STRAIN-BASED DESIGN

Basic pipeline design refers to integrity against pressure containment. In this case, internal pressure is the main loading condition, and the design consists primarily in keeping the hoop stress below the allowable stress of the steel material. Longitudinal stress is also considered in this design process. In all this design process, elastic behavior of steel material is assumed.

On the other hand, during a severe ground-induced action, the pipeline is subjected to substantial amount of deformation, associated with large inelastic strains. Adopting a stress-based approach would lead to an economical design that penalizes the design significantly and may not account properly for the special features and advantages of the steel material. Therefore, a strain-based design should be adopted, allowing for the pipeline to deform beyond the elastic limit of the steel material. Strain-based design has been adopted by oil and gas pipeline industry in geohazard areas, and a lot of research has been conducted for establishing reliable design procedures so that the structural integrity of buried pipelines is safeguarded in the course of a severe ground-induced action.

Strain-based design consists of two main parts, namely (a) soil-pipe interaction, sometimes referred to as “strain demand”, and (b) pipeline resistance. Those parts are outlined below:

Soil-pipe interaction. The interaction between soil and pipe is a paramount issue in determining the forces and strains induced by the moving ground to the pipeline. There are several ways to account for soil pipe interaction through analytical or numerical model. Analytical models can provide some initial results which may be very useful for early stages of the design however numerical models are necessary when the structural integrity of a major pipeline that crosses a geohazard area is examined. Numerical models are categorized as “beam-type” or “three-dimensional”. The latter are special-purpose models, employ shell elements for simulating the pipeline, three-dimensional solid elements for the soil, and appropriate interface conditions to account for the soil-pipe interaction; they are quite accurate but are computationally expensive and require advanced modelling skills, therefore, they are used only in special cases (Sarvanis *et al.*, 2018). The former models are used almost exclusively in pipeline engineering practice, they employ beam-type elements for the pipeline (“pipe” or “elbow” elements), and “springs” for the soil and soil-pipe interaction (Karamanos *et al.*, 2017).

Pipeline resistance. This is the second part of the design process and refers to the capability of the pipeline to sustain the ground-induced actions calculated in the first part of the design process. In buried steel water pipelines, joints are the most vulnerable locations. In those geohazard areas, welded pipelines should be employed. Lap welded joints have been shown to be very efficient; recent experimental results (Keil *et al.*, 2018; 2020) have shown that lap welded joints are capable of sustaining a significant amount of inelastic deformation without loss of containment associated with fracture of the pipe wall. Although a universal value for the maximum allowable strain in lap welded joints has not be established yet, a 2% strain limit is a widely accepted value (ALA 2005; Nervik *et al.* 2020). For increased safety of the pipeline a new concept has been proposed recently consisting of introducing a small projection near the joint on the spigot side. Therefore, under severe bending or axial compression, buckle will occur at the projection location in a controlled manner away from the weld and the bell, which are considered to be more vulnerable.

DESCRIPTION OF GEOHAZARD ACTION

The large-diameter steel pipeline under consideration crosses two settlement areas that are identified as Brittmoore and White Oak areas. In the former area, the pipeline has 84-inch nominal diameter, and the total expected settlement is 3.14 ft. In the latter location, the nominal pipeline diameter is equal to 96 inches and "faults crossing" is expected to occur at two specific locations (West Little York and Repump Station), with a maximum displacement equal to 1.1 ft. The soil differential displacements in the three directions at each crossing location (75-year values), over a pipeline length of 30 ft, are shown in Table 1. In both settlement areas (Brittmoore and White Oak), due to the imposed ground displacement, the pipeline is subjected to significant bending and stretching (tension). Furthermore, the Brittmoore location is particularly critical for pipeline integrity, due to an 84-inch pipeline riser, located very close to the fault.

PIPELINE DESIGN AND ANALYSIS

General considerations. In both settlement crossings (Brittmoore and White Oak), a preliminary pipeline design is performed, to assess the structural performance of the steel pipeline. This preliminary design follows a "strain-based" approach. First, strain demand is calculated using a global analysis, through finite element models, developed for the purposes of the present design. Ground-induced strains are calculated and compared with the allowable values. The effects of soil conditions are considered in detail, based on real geotechnical measurements. Furthermore, the design makes use of the "projection" concept, which increases pipeline resilience and improves lap welded joint performance.

Numerical modelling. Finite element models for the Brittmoore fault and the two White Oak locations have been developed in ABAQUS/Standard. The models use "elbow" elements to simulate the pipeline, and special-purpose PSI (pipe-soil interaction) elements to account for the soil conditions and the soil-pipe interaction. The pipeline material is ASTM A1011 SS GR36, and it is modelled as elastic-plastic. Soil resistance in all three directions (axial, transverse lateral and transverse vertical) is considered as bi-linear, according to the ALA design guidelines, using the soil properties provided by the geotechnical report. Finally, the projections are introduced in the model using the special-purpose "connector" elements, with appropriate stiffness, calculated on the basis of detailed finite element simulations, which account for the nonlinear local behavior of the projection under axial tension and bending (Fappas *et al.* 2021).

White Oak fault. The pipeline configuration at the two White oak crossings is shown in Figure 1. At the two crossings, the pipeline is nearly parallel to the fault orientation. The pipeline diameter is 98.75 in, and the initial design verification has been performed for a ¾ in wall thickness. The soil displacements are depicted in Table 1. The soil conditions are described in the geotechnical reports (Boone and Flores, 2019a), and the corresponding soil springs have been calculated using the provisions of ALA (2005) Guidelines. To account for the uncertainty associated with the definition of the soil parameters, the sensitivity of the numerical results with respect to soil stiffness has been examined.

Using the above approach, the calculated maximum tensile and compressive strain at the White Oak fault are equal to 0.90% and -0.10% respectively. Those values are considered small, and therefore no additional special measures beyond the standard "seismic projection" in the pipeline are required for the White Oak area. Those small values of strain have indicated that the pipe wall thickness may be reduced, without threatening the structural integrity of the pipeline. Further analysis, considering pipe thickness equal to ⅝ in, indicated that the corresponding maximum tensile strain is equal to 1.25%, which is an acceptable value with the use of “seismic joint” at every lap-welded pipeline joint in this area, so that if local buckling occurs, it may not occur at the bell or at the weld area, increasing pipeline safety.

Table 1: Differential soil displacement over a length of 30 ft (75-year values) at the three crossing locations.

	vertical (ft)	horizontal transverse (ft)	extensional (ft)
Brittmoore	3.14	0.87	0.70
White Oak (West Little York)	1.04	0.11	0.36
White Oak (Repump Station)	0.76	0.26	0.51

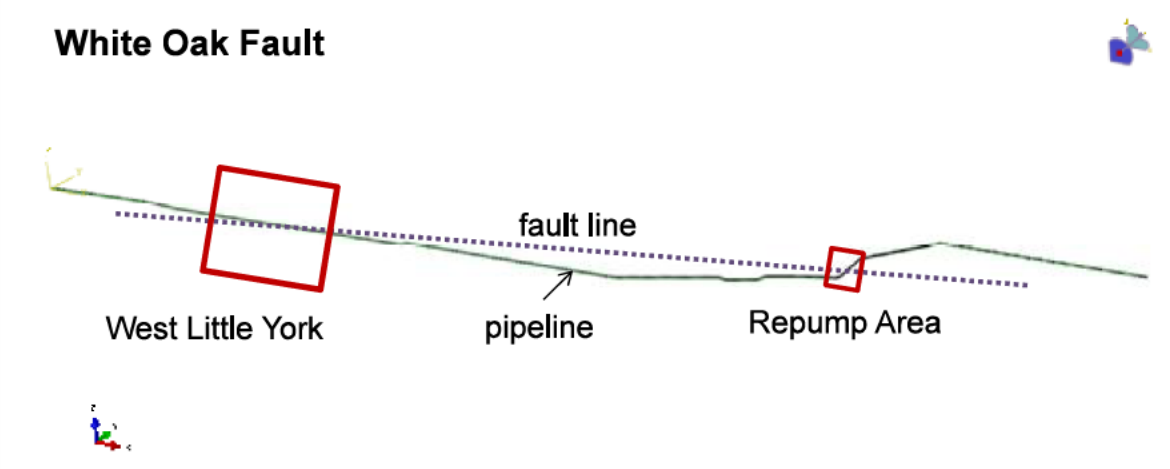

Figure 1: Pipeline fault crossings at White Oak area (finite element model).

Brittmoore fault. This location is more critical that the White Oak location, mainly because the larger value of settlement, and the proximity of the differential settlement (fault) area to a pipeline riser. In this case, the main challenge consists of reducing the force exerted by the pipeline on the riser, while keeping the pipeline strain within an acceptable level. The configuration of the Brittmoore fault crossing is shown in Figure 2, indicating a nearly perpendicular crossing pattern between the pipeline and the direction of the fault. The riser is depicted in the left end of the pipeline segment under consideration. The soil settlements for Brittmoore fault area are shown in Table 1.

The pipeline diameter at the Brittmoore is equal to 86.25 in, with thickness equal to ⅝ in. Based on the geotechnical report (Boone and Flores, 2019b), two backfill cases are considered in the present analyses: (a) a “hard” CLSM (Controlled Low Strength Material) soil material with unconfined compressive strength (UCS) of 100 *psi* and uncoated steel pipe, modeled as undrained material and (b) a soft soil of “pea gravel” with an effective friction angle of 30° and a total unit weight of 110 *pcf*, with polyethylene coated pipe wrapped in a geotextile. In both cases, the soil springs are calculated from the ALA (2005) Guidelines. In the geotechnical report, to account for the uncertainty on soil properties, the soil springs have been evaluated using a wide range of values for the main soil parameters, so that upper and lower limits were established corresponding to 5% and 95% probability of exceeding soil stiffness respectively. Further uncertainty refers to the location of the fault and therefore, in the present analysis two fault locations are considered, denoted as Fault Location 1 and 2 in Figure 2. The numerical results have demonstrated that Fault Location 1, nearest to the riser, is the most critical location in terms of the strain level developed in the pipeline.

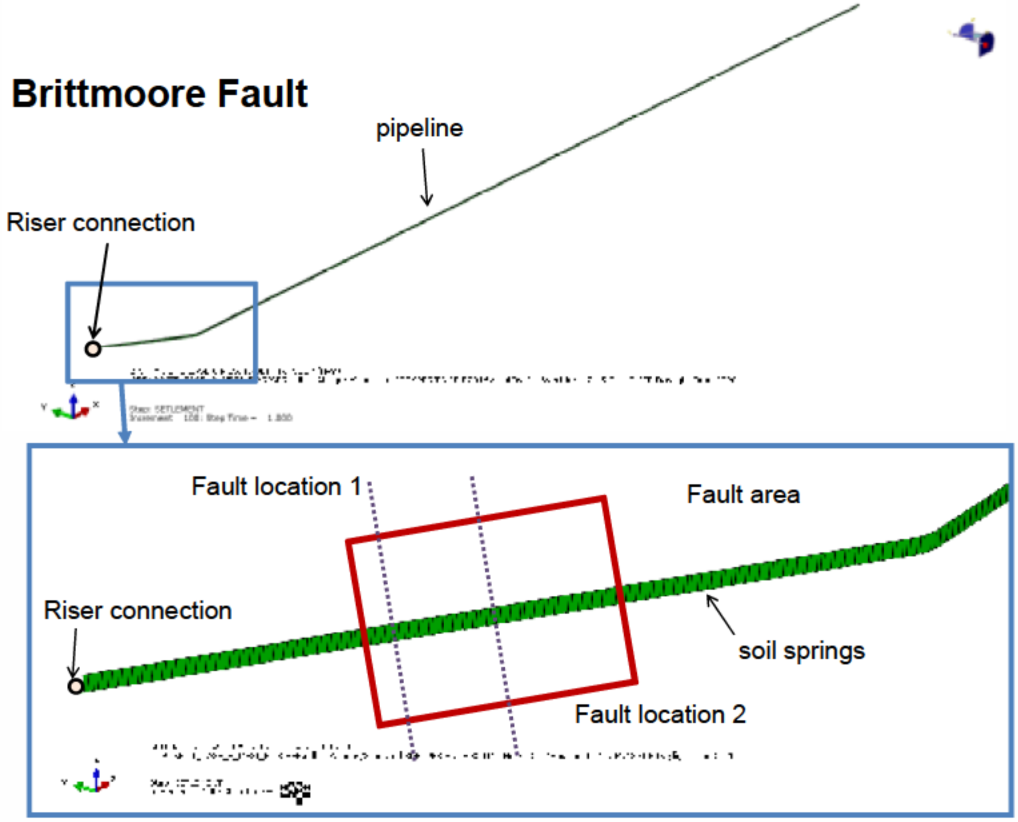

Figure 2: Pipeline fault crossings at Brittmoore area (finite element model).

The numerical results indicated that using the CLSM stiff backfill between the fault and the pipeline riser, the reaction force on the riser is rather low, but this results in the development of tensile strains in the pipeline that may exceed the 2% tensile strain limit. On the other hand, the use of the "pea gravel" soil trench reduces the strain in the pipeline, but the force transmitted to the riser is significantly increased; in such a case, the use of a concrete block near the riser may be necessary, to account for this increased value of force.

The numerical results also show that the introduction of several "projections Π" on either side of the fault, are beneficial for pipeline structural performance (Figure 3). Those projections act as an additional mitigation measure for the effects of soil settlement at the Brittmoore location, accommodating pipeline stretching, and leading to a reduction of tensile strain and the axial force on the nearby riser.

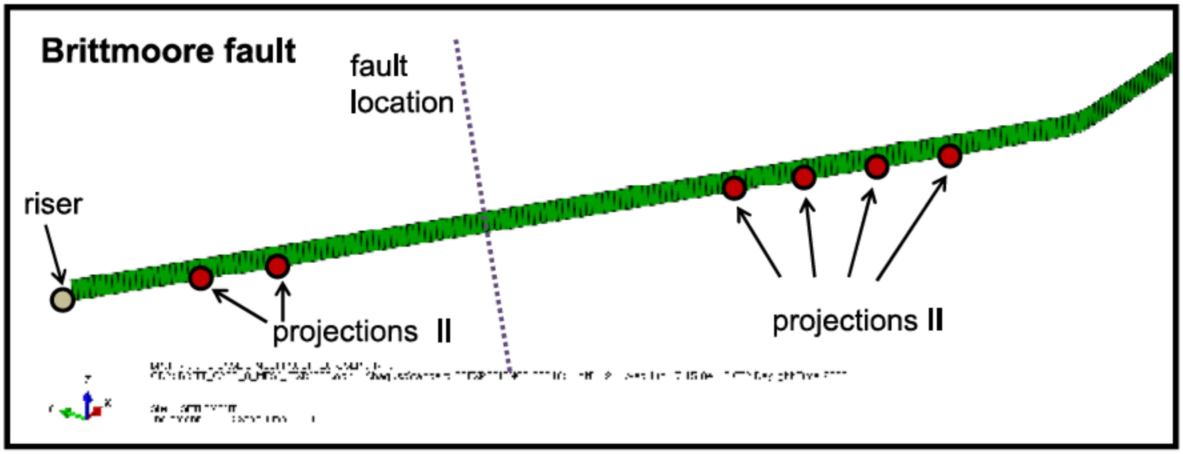

Figure 3: Pipeline crossing at Brittmoore area (finite element model); location of projections II.

CONCLUSIONS

The paper discusses the preliminary design of a large-diameter steel pipeline at two geohazard locations, where a substantial amount of ground settlement is expected to occur. The strain-based design procedure follows the in the present study employs finite element tools, capable of calculating the strains developed in the pipe wall and the reaction forces at the nearby riser, considering a variety of geotechnical and structural parameters. The main conclusions and recommendations may be summarized briefly as follows:

- The authors suggest the use of “seismic joint” at every lap-welded joint in both areas (Brittmoore and White Oak). Therefore, if local buckling occurs, it may not occur at the bell or at the weld area, increasing pipeline safety.
- The calculated strains at the White Oak fault are rather small compared to Brittmoore, and therefore the use of standard “seismic joints” in the area alone is recommended. Furthermore, strain-based design results suggest that the use of a ⅝ -inch pipe thickness, instead of a ¾-inch pipe thickness, is possible.
- In the Brittmoore fault crossing, the presence of a pipeline riser very close to the fault area, imposes a serious challenge; one has to perform an optimal design, so that the strain in the pipeline is minimized, whereas the force exerted on the riser due to pipeline stretching.
- The introduction of a series of projections II on either side of the Brittmoore fault, as well as the use of low-friction geotextile around the pipe, are beneficial for pipeline performance, reducing further the maximum induced strains in the pipe.

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