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Studies on the Performance of Pipelines Subjected to Differential Settlements: Numerical Study

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Abstract: This paper details the mechanical behaviour of buried steel pipeline crossing differential settlement zone. The investigation is based on numerical simulation of the non-linear response of the pipeline-soil system, through finite element method. The numerical simulation considers geometric (large strain and displacement), material (non-linear material behaviour of soil and pipeline) and boundary (interaction between buried pipeline and the surrounding soil) non-linearities. The effects of parameters, like diameter to thickness ratio, embedment depth and internal pressure, friction coefficient, settlement rate and soil properties on pipeline behaviour is investigated in terms of cross-sectional distortion, axial tensile and compressive strain. The results show that the maximum strain appears on both side of the settlement section in the pipeline. In ground settlement zone, axial strain on the top of the pipeline is compressive strain and axial strain on the bottom of the pipeline is tensile strain, reverse behaviour is observed in the no settlement zone of pipeline. The results from the present study can be used for the development of performance envelope, which can be used for better design of pipelines.

Keywords: Pipeline, Soil Settlement, Numerical Modelling, Differential Settlements.

1 Introduction

Pipelines are the lifeline for a country and efficient pipeline network helps in many ways, e.g. economical and reliable transport of oil & gas, water supply and waste management network etc. Pipeline failures not only cost unnecessary remedial works and huge financial losses, but in some circumstances may lead to gas explosions and spillage, resulting in severs environmental damage and loss of life. Permanent Ground

Deformation due to geo hazard represents the fourth major cause of pipeline failures [1].

Settlement is one of the types of a Permanent Ground Deformation and is defined as, the vertical movement of the ground, generally caused by changes in stresses within the earth. Subsidence is a term often used to describe caving or sinking of the ground, which may not be associated with changes in soil stresses. Hence, the distinction between subsidence and settlement is not always apparent. In both conditions, pipeline is primarily subjected to vertical loading along the pipeline length due to soil vertical movement. Most anthropogenic subsidence observed all over the world are caused by the withdrawal of subsurface fluids from porous granular media, mining of coal and minerals, and drainage of organic soils.

Pipeline subjected to differential settlement is a unique loading condition, in which pipeline is subjected to vertical movement along the pipeline length embedded in soil. Hence, it can be referred as pipeline subjected to a continuous differential settlement. The effect of differential settlement on pipeline can be observed at pipeline traversing hard to soft foundations at pumping station/pipeline interfaces, change in soil strata along pipeline length, crossing of landfill areas etc. Fi shows the effect of differential settlement on pipeline and structure.

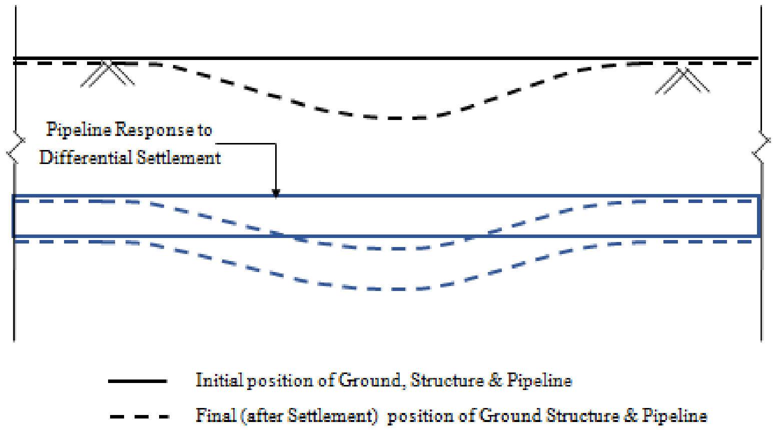

Fig.1. Effect of Differential Settlement on Pipeline & Structure

Predominant effect of differential settlement on pipeline is in a longitudinal direction. Hence, even though differential settlement is detrimental for structures, it can be accommodated effectively in pipeline, by detailed investigation. Proper attention to potential settlement and design is necessary to make pipelines function reliably as a safe, integral part of a conveyance system. Flexibility is important with design of large diameter pipelines, because they are much stiffer and less tolerant to movements, than smaller diameter pipelines. In similar aspects, number of pipeline parameters (diameter, thickness, material, surface effect, buried depth) and soil parameters (types of soil, saturation condition) affects the pipe soil interaction. Hence, each pipeline possesses unique challenges.

ASCE guidelines are generally used for pipeline design, which are based on analytical model. To simplify the problem, analytical model are based on certain assumptions on the soil behavior, geometries and loading conditions. Moreover, the p-y relationship is developed based on 2D soil deformation [2, 3]. Addressing pipe soil interaction with analytical model becomes challenging due to the presence of geometrical, boundary and material nonlinearity. Simulation of 1g physical setup is costly and time consuming, due to the large variation in the input parameters [4].

Finite Element Analysis (FEA) can handle geometric, material and boundary nonlinearity. With verified pipe soil interaction and soil material modeling approach, 3-D FE analysis can provide better visualization and understanding of soil structure interaction for pipe subjected to differential settlements.

2 Analysis Approach and FE Model Details

2.1 Mechanical Analysis of the Buried Pipeline

There are three kinds of mechanical models for the buried pipeline. The first one is beam on elastic foundation model. The second is soil spring model. The surrounding soil was assumed as a series of springs and the spring stiffness is decided by the soil properties. The third one is nonlinear contact model. It is usually in the numerical calculation [5].

Pipeline subjected to differential settlement is a nonlinear problem involving complex pipe-soil interactions. Therefore, it is challenging to solve the realistic pipeline response by analytic methods.

2.2 Finite Element Model

3D finite element analysis approach using ABAQUS is utilized to study stress strain response of the buried steel pipeline under the action of ground settlement. The numerical simulation considers geometric (large strain and displacement), material (non-linear material behaviour of soil and pipeline) and boundary non-linearities.

Half symmetry FE model is considered based on the symmetric nature of the problem (buried pipeline & soil) and loads acting. Fig. **1** shows the finite element model of buried pipeline and soil stratum. The pipeline is embedded in soil along the x-axis. Four noded reduced integration shell elements (S4R) are used to model the pipeline and eight noded reduced integration brick elements (C3D8R) are used to simulate the surrounding soil. The thickness of backfill soil (h) is 1.5 m. The soil model in the x-direction is equal to at least 60 pipeline diameters, where dimensions in directions y, z equal to 7.5D and 15D, respectively. A total of 40 shell elements around the cylinder circumference in this central part have been found to be adequate to achieve convergence of the solution, and surrounding soil is meshed with a smaller size [6, 7].

Initially, in-situ conditions are simulated followed by settlement loading. The analysis is conducted in two steps. In the first step, gravity loading and internal pressure were applied and subsequently, in the second step, displacement was imposed on the ground settlement zone. The nodes on the bottom boundary plane of the stratum remain fixed in the z-direction. Symmetry constraints are imposed on the symmetry planes of buried pipeline and stratum. Fig. **1** shows details of the boundary conditions applied in the analysis.

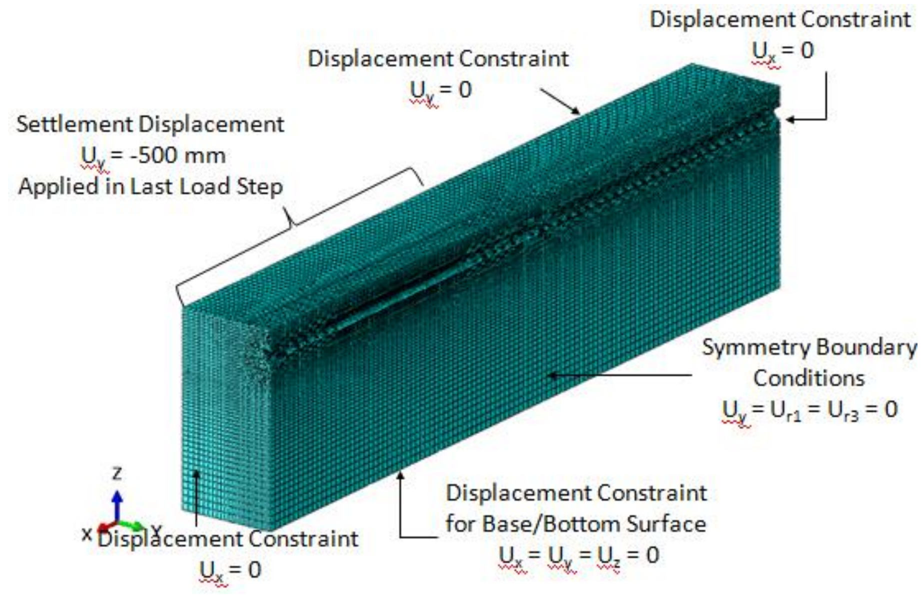

Fig. 1. Finite Element Model and Boundary Condition for Differential Settlement Study

Mechanical behaviour of the soil material is simulated through an elastic perfectly plastic Mohr-Coulomb constitutive model. Zero friction angle was assumed to essentially consider Tresca failure criteria. Materials of backfill soil and the stratum are the same, with undrained cohesive strength c = 10 kPa at base & 0.02 kPa at top, modulus of elasticity E = 5 MPa at base & 0.01 MPa at top, Poisson's ratio μ = 0.49 and density ρ = 1510 kg/m^3.

Steel pipeline of X65 grade is simulated with a large strain von Mises plasticity model with isotropic hardening. The pipeline diameter (D) is 0.762 m, which is a typical size for hydrocarbon transmission pipeline. The pipeline wall thickness (t) is considered equal to 25.4 mm. Pipeline material yield stress σ_y is 449 MPa. Young's modulus of the steel material is 210 GPa, Poisson's ratio is 0.3 and density is 7800 kg/m^3. The dependency of soil properties (i.e. Young's Modulus and un-drained Cohesion Strength) with depth is considered by defining a field variable.

Deformations behaviour of the buried pipeline and surrounding soil influence each other. The interface between the outer surface of the pipeline and the surrounding soil is simulated with contact algorithm, which allows separation of the pipeline and soil and accounts for contact friction. Isotropic coulomb friction is applied with a value of friction coefficient μ as 0.5.

2.3 Response of the Pipeline under Settlements

Figures 3-4 show displacement plots for soil and pipeline, at the end of soil settlement load step i.e. settlement displacement of 500 mm. Figures 5-6 shows von Mises stresses in the soil and pipeline respectively, at the end of soil settlement - settlement of 500 mm.

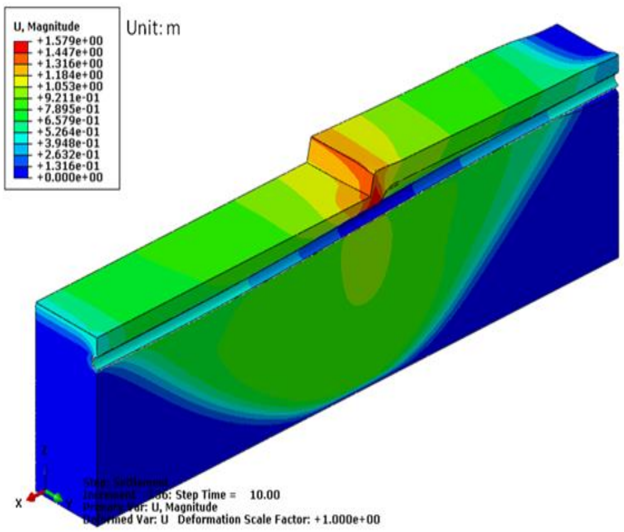

Fig. 2. Displacement Plot - at the End of Settlement Condition

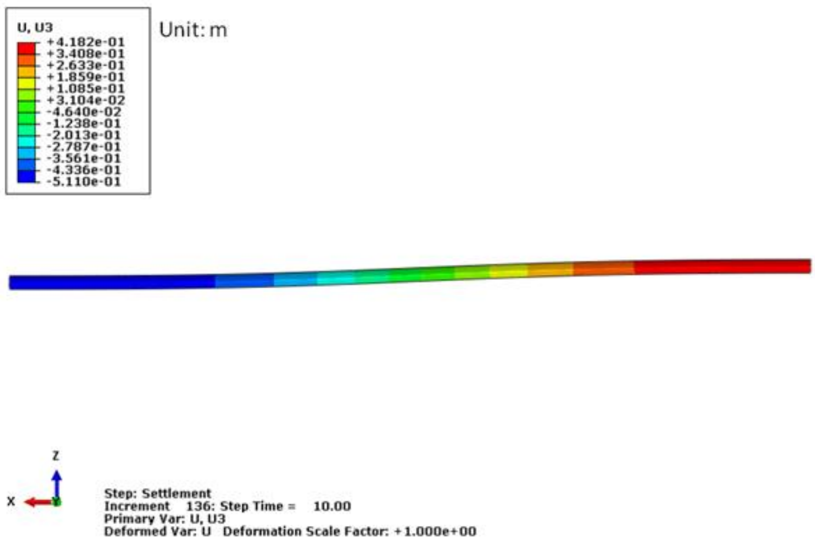

Fig. 3. Displacement Plot for Pipeline in Vertical Direction - at the End of Settlement

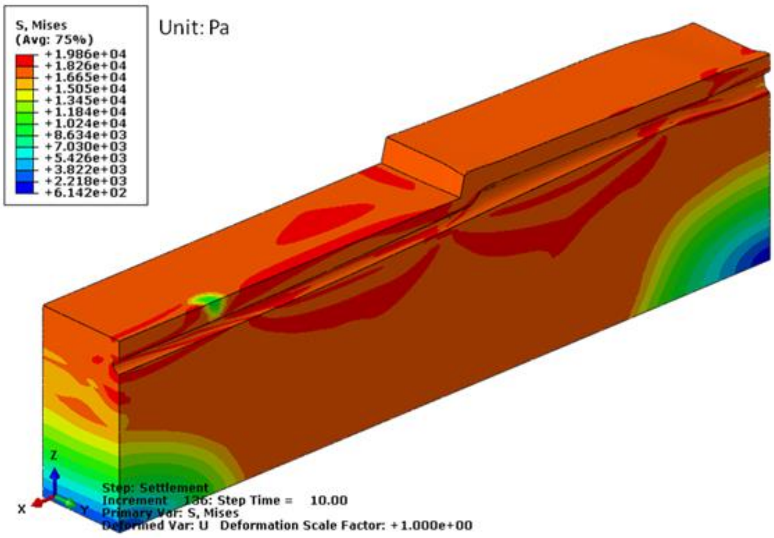

Fig. 4. Von Mises Stress Plot for Soil - at the End of Settlement Condition

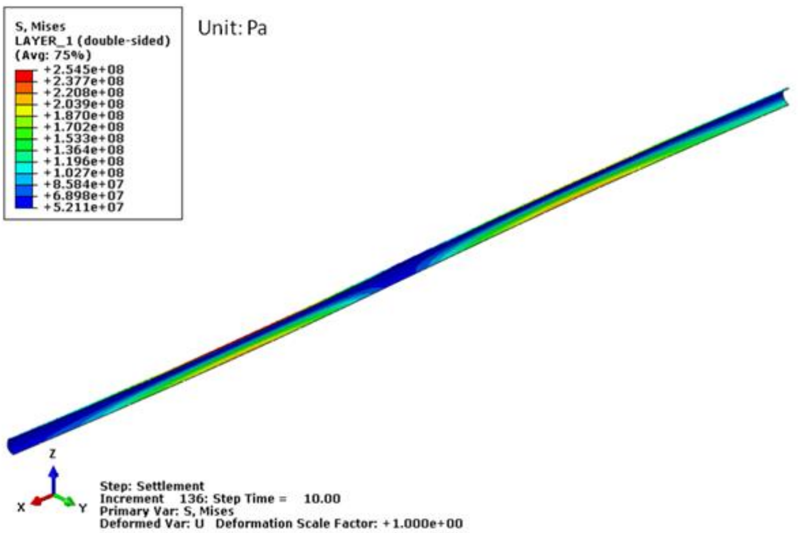

Fig. 5. Von Mises Stress Plot for Pipeline - at the End of Settlement Condition

The pipeline response to the soil settlement is affected by the pipe soil interaction, which in-turn affects the soil deformation surrounding the pipeline. In the no-settlement zone pipeline shows the upheaval movement and in settlement zone pipeline compress the soil. This behaviour results in void formation near the dividing plane or soil interface at settlement and non-settlement.

From the analysis, it is observed that the von Mises stress and high stress area increase with increasing settlement. There are two oval shape high stress areas near the dividing plane. In no-settlement zone, pipeline upper section is in tension (higher stress location) and bottom section is in compression, inverse behaviour for stress nature and location is observed in the settlement zone. The distance between the high stress areas is increased with increase in settlement. The middle section of the pipeline is having low stresses.

3 Effect of Pipeline Parameters

3.1 Diameter to thickness ratio (D/t)

For the ground settlement of 300 mm and internal pressure is $0.2P_{max}$, stress and axial strain responses of the pipeline under different diameter to thickness ratios are shown in Figs. 7-8 respectively. As seen in Fig.6, von Mises stresses and higher order stress area decrease with decreasing diameter to thickness ratio, because the larger diameter to thickness reduces the pipeline stiffness. Under the joint action of the ground settlement and internal pressure, the overall stress and local stress increase with the increase in diameter to thickness ration. Fig. **7** shows the axial strain of the pipeline, the maximum axial strain increases with the increase in the diameter to thickness ratio.

Fig. **8** shows the bending curves of the pipeline. The reduction in curvature radius near the dividing plane in the settlement zone indicates that, thin walled steel pipeline is prone to buckling under ground settlement near the dividing plane.

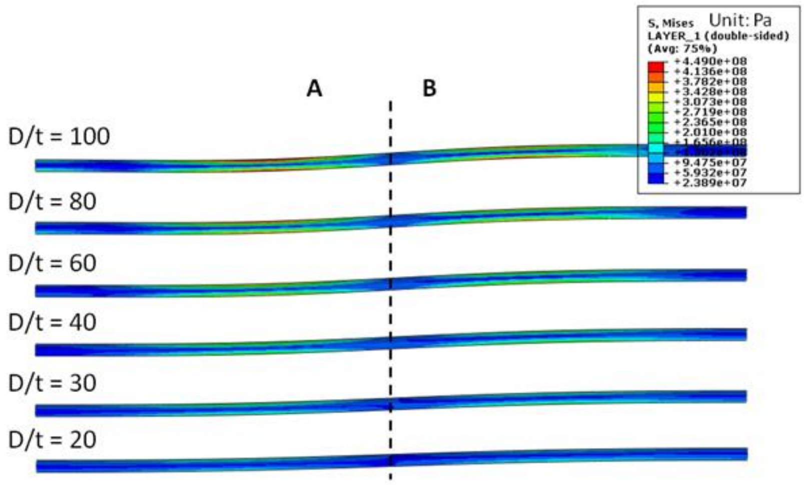

Fig.6. Von Mises Stress Plot of Pipeline for Different D/t Ratio

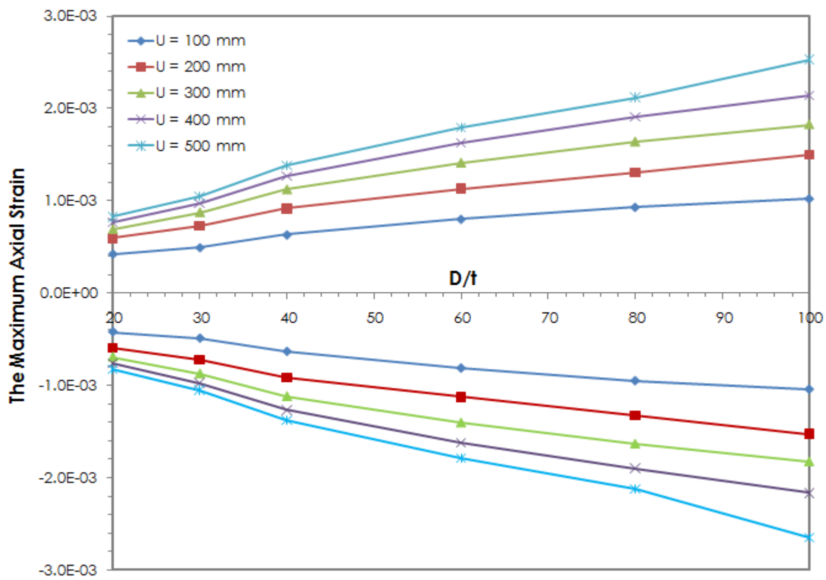

Fig. 7. Axial Tensile and Compressive Strain Plot of Pipeline for Different D/t Ratios

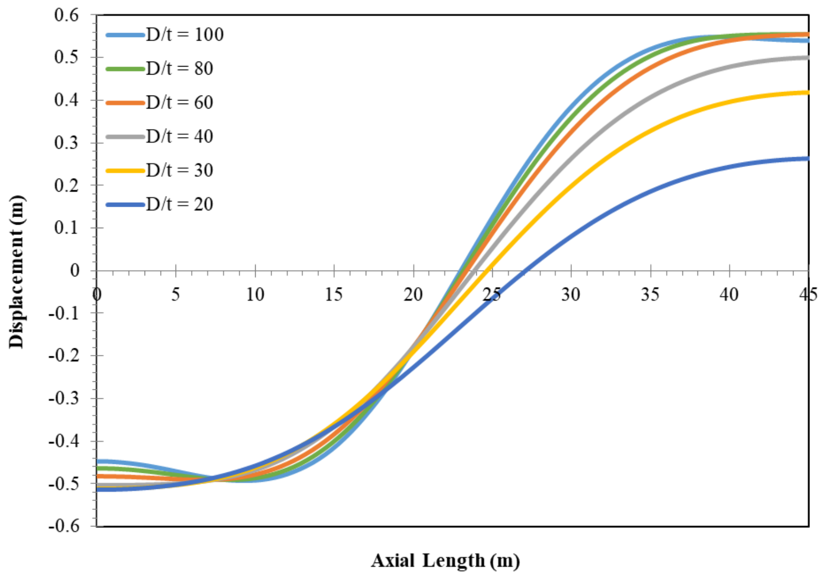

Fig. 8. Pipeline Displacement due to Settlement Load along Pipeline Length

3.2 Internal Pressure (P/P_{max})

For the ground settlement of 300 mm, stress strain responses of the pipeline with increasing P/P_{max} ratios are shown in Figs. 10-11. As shown in Figure 9, under the joint action of the ground settlement and internal pressure, the overall stress and local stress increase with the increase in P/P_{max} ratio. The increase in induced stress is directly proportional to the increase in internal pressure. Fig. **10** shows the axial strain of the pipeline, the maximum axial strain increases with the increase in the P/P_{max} ratio. With the increase in ground settlement, change rate of the maximum axial strain decreases. Fig.11 indicates that, P/P_{max} ratio doesn't affect the bending deformation of the buried pipeline. No case has shown the plastic strain in pipeline.

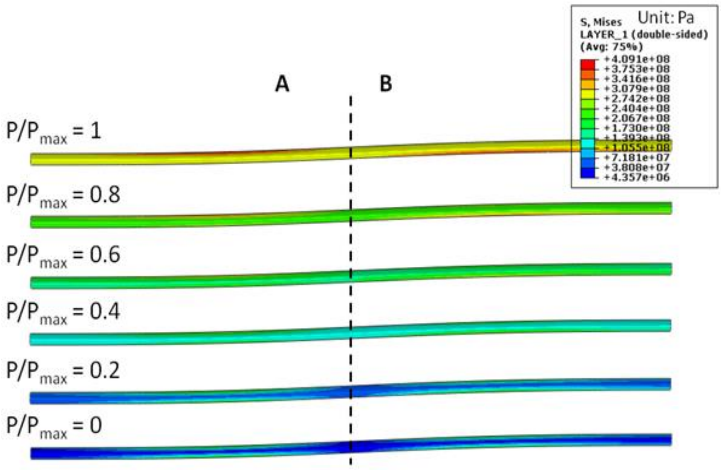

Figure 9: Von Mises Stress Plot of Pipeline for Different D/t Ratios

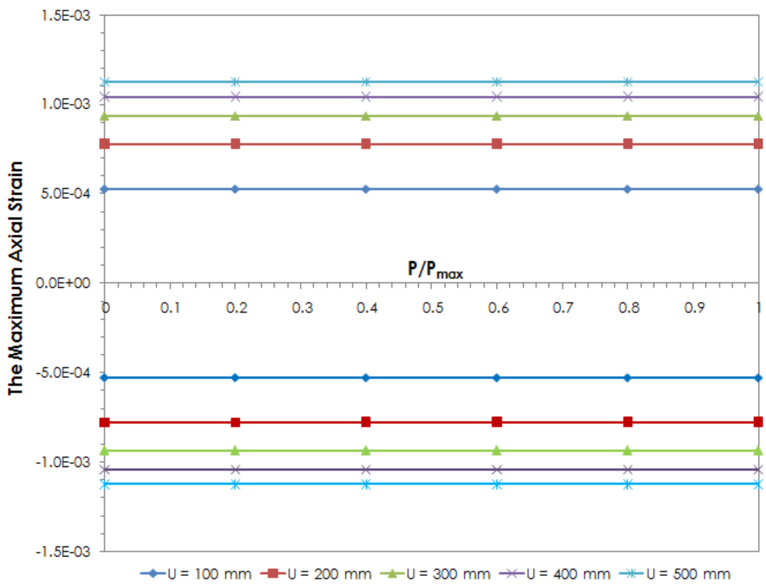

Fig. 10. Axial Tensile and Compressive Strain Plot of Pipeline for Different D/t Ratios

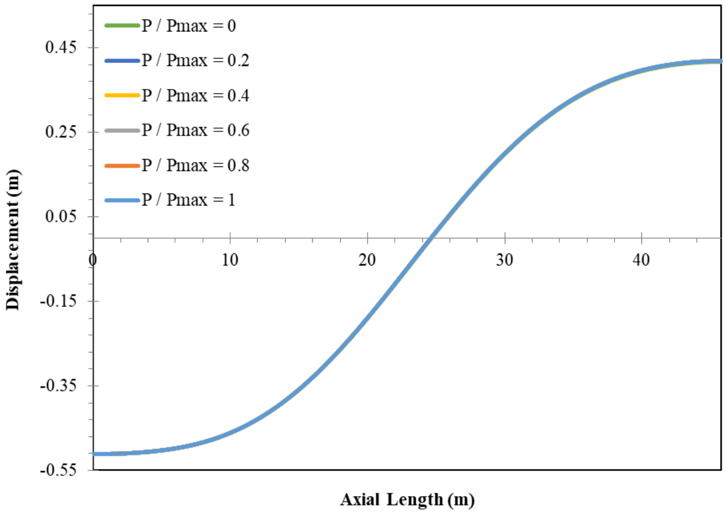

Fig.11. Pipeline Displacement due to Settlement Load along Pipeline Length

3.3 Normalized Depth of Burial (h/D)

When the ground settlement is 300 mm, internal pressure is $0.2P_{max}$, stress strain response of the pipeline under different buried depth to pipeline diameter ratios is shown in Figs. 13-14. As shown in Fig.12, the overall stress and local stress decrease with the increase in buried depth to pipeline diameter ratios. Fig. **13** shows the axial strain of the pipeline, the maximum axial strain decreases with the increase in the buried depth to pipeline diameter ratio. With the increase in ground settlement, rate of change of the maximum axial strain decreases. Figure 14 shows the considerable upheaval bending deformation of buried pipeline in no-settlement zone.

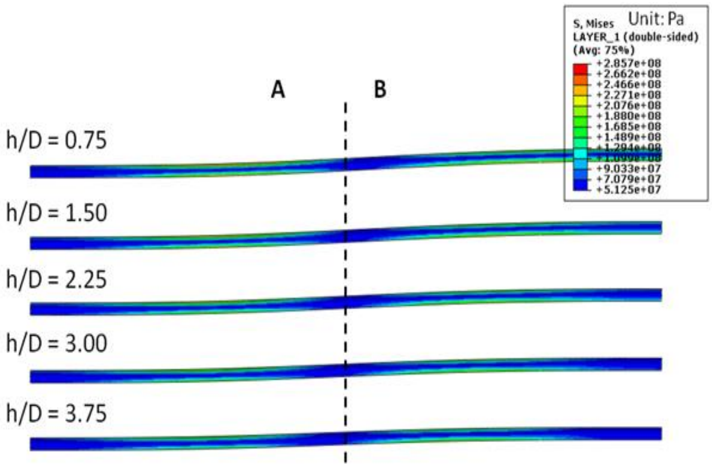

Fig.12. Von Mises Stress Plot of Pipeline for Different D/t Ratios

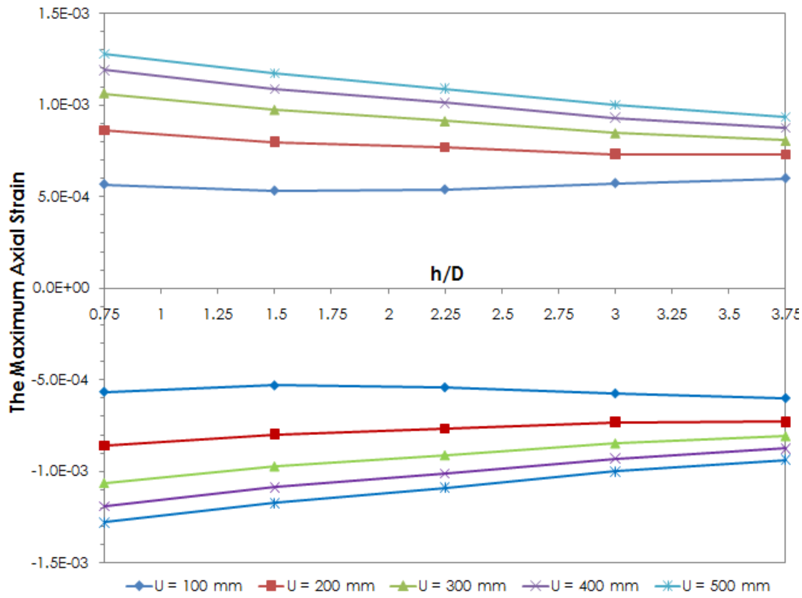

Fig. 13. Axial Tensile and Compressive Strain Plot of Pipeline for Different D/t Ratios

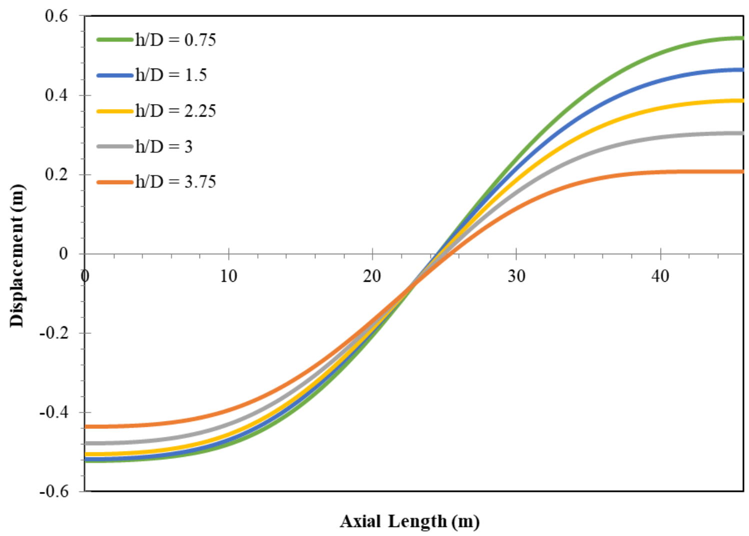

Figure 14: Pipeline Displacement due to Settlement Load along Pipeline Length

4 Conclusions

In a pipeline subjected to continuous differential settlements, two higher stress locations are formed each one in settlement and no-settlement zone, near the interface plane. In no-settlement zone, pipeline upper section is in tension (higher stress location) and bottom section is in compression, inverse behaviour for stress and location is observed in settlement zone. The pipe-soil interaction results in soil compression and void formation near the settlement and no-settlement zone, respectively.

From the interpretation of analysis and pipeline parameteric studies following conclusions can be drawn:

1. With the increase in diameter to thickness ratio, pipeline becomes prone to local buckling near the dividing plane.
2. Internal pressure variation does not affect the pipeline deformation behaviour.
3. With the decrease in buried depth to diameter ratio, pipeline may get exposed in no-settlement zone.

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