A Parametric Study on Seismic Behavior of Continuous Buried Pipelines Due to Wave Propagation

F. R. Rofooei[1] and R. Qorbani[2]

[1] *Professor, Dept. of Civil Engineering , Sharif University of Technology, Tehran, Iran*
[2] *Msc., Dept. of Civil Engineering , Sharif University of Technology, Tehran, Iran*
Email: rofooei@sharif.edu, r.ghorbani55@gmail.com

ABSTRACT :

Due to their efficiency, buried pipelines are being widely used to transfer water, crude oil and other petrochemical liquid products in large quantities and far distances. Since ground displacement can cause serious damages to these facilities, it is necessary to investigate the seismic behavior of the buried pipelines under severe earthquakes. In that regard, attempts have been made for mathematical modeling of the buried pipelines to capture their true response under earthquake excitations. Using the concept of beams on elastic foundation, a number of 3-D finite element models are prepared for a portion of a continuous pipeline system. In these models, the slippage between the surrounding soil and the pipe is observed by means of nonlinear elastoplastic springs in three orthogonal directions. Nonlinear dynamic time history analyses have been carried out using the displacement time history of the strong ground motions in three normal directions as an input. An extensive parametric study is performed to investigate the seismic behavior of the system, considering different parameters such as pipe's diameter and modulus of elasticity, the burial depth, internal pressure, and the surrounding soil type. Also, the seismic behavior of the buried pipelines with bends is studied, considering different bend angles and distance to the bend parameter. As the results indicate, the induced axial and bending stresses to the straight buried pipelines in severe earthquakes are much less than pipelines with bends. Furthermore, increasing the bend angle will lead to larger stress concentration around the bend area.

KEYWORDS: Pipelines, Ground Displacement, slippage, Nonlinear Dynamic Analysis

1- INTRODUCTION:

Seismic behavior of the underground pipelines is different from those located above ground caused by the interaction between the pipe and soil. Therefore, attempts have been made for mathematical modeling of the buried pipelines to capture their true response under earthquake excitations. A simple method for seismic analysis of these types of structures was based on considering the pipeline axial strains caused by ground displacement, thus neglecting the bending strains produced by the ground motion curvature [1]. Another simplified method for seismic analysis of these types of structures was based on equalizing the strain and curvature of the pipeline with those of its surrounding soil [2]. However, this simple approach could lead to conservative results.
Sakurai and Takahashi developed a simple analytical model for a straight pipeline surrounded by an infinite elastic medium without taking into account the slippage at the pipe-soil interface [3]. Shinozuka and Koike proposed a more comprehensive model by considering the relative displacement at the soil-pipe interface. Neglecting the effect of inertia, they also developed a conversion factor between ground and pipe strains [4]. M. O'Rourke and El Hmadi used a different approach for considering the relative displacement at the soil-pipe interface. They modeled the soil's resistance to axial movement of the pipe by a linear spring and a slider which limits the soil spring force to a maximum frictional resistance at the pipe-soil interface [5].
In this study, the seismic behavior of a continuous buried steel pipeline is investigated. A portion of the pipeline which length is to be determined with fixed end conditions is modeled using beam elements, while their interaction with the surrounding soil is represented by a number of nonlinear springs in three orthogonal directions. Then, the 3-D models of the pipeline with predetermined lengths are subjected to the earthquake components in three orthogonal directions. An extensive parametric study is performed to evaluate their seismic behavior using different parameters.

2- PROPOSED MODELING:

Using ANSYS program, the 3-D pipe20 element is used for modeling the pipeline segments [6]. As it is mentioned before, the interaction between the soil and the pipe has been considered using elastoplastic springs in the orthogonal directions. Figure 1 shows the force-displacement behavior for axial, horizontal, and vertical direction springs proposed by O'Rourke M. J. and Liu X [7]. Based on their model, the transverse horizontal and axial springs behave symmetrically in tension and compression, while that is not the case for the transverse-vertical springs. The contact element Combin39, which is a nonlinear spring and has the capability to model different force-displacement behaviors in tension and compression, is selected for modeling the pipe-soil interaction. Assuming classical (Rayleigh) damping for the soil-pipe system and as it is suggested by Kishida H. and Takano, 6% damping ratio is considered for the first two modes of the system to compensate for the dissipated energy caused by the interaction between soil and pipe [8].

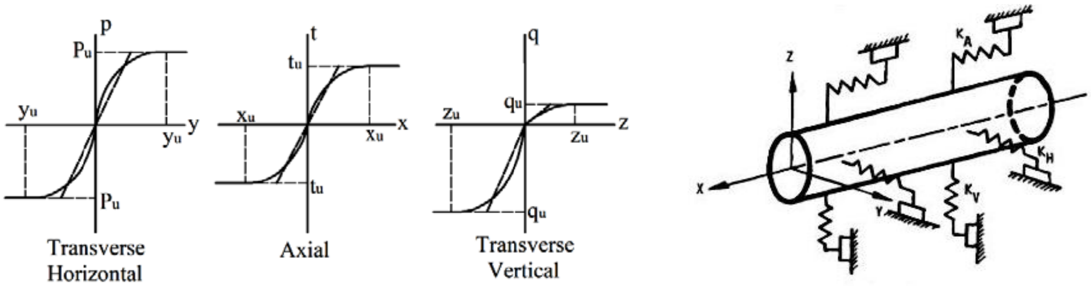

Figure 1- Soil-Pipe Interaction Modeling [7]

3- MODEL PROPERTIES:

The specification of the pipe segments which are presumably made of steel and X65 type are as following:

Outside Diameter: 0.8, 0.9 and 1 m
Modulus of Elasticity: 210 MPa
Yield Stress: 490 MPa

Thickness: 10, 11, 12 mm
Mass Density: 7850 N/m^3
Rupture Stress: 531 MPa

In the parametric study, six different types of surrounding soils including dense, medium, and loose sand, and stiff, medium, and soft clay with the parameters shown in Tables 1 and 2, are considered. The stiffness coefficients of the soil springs in three orthogonal directions are determined using the relations provided by O'Rourke M. J. and Liu X [7]. Nonlinear dynamic analyses were carried out by applying the displacement time history of the earthquake records to the end of soil springs. A parametric study is carried out considering pipeline parameters such as the diameter and modulus of elasticity of the pipe, burial depth, internal pressure, stiffness and damping coefficients of the surrounding soil.

Table 1- Needed Parameters for Modeling Related to Sands

Type of Soil	Angle of Shear Resistance	Unit Weight $N/m3$	Coefficient of Friction	K_0
Loose Sand	30°	18000	0.5	0.5
Medium Sand	32°	20000	0.6	1.0
Dense Sand	35°	21000	0.7	1.5

Table 2- Needed Parameters for Modeling Related to Clays

Type of Soil	Undrained Shear Strength N/m^2	Unit Weight $N/m3$	Coefficient of Friction	K_0
Soft Clay	40000	19000	0.5	0.5
Medium Clay	80000	20000	0.6	1.0
Stiff Clay	160000	21000	0.7	1.5

The Kobe earthquake components with PGA=0.86g, 0.63g and 0.39g in axial, horizontal and vertical directions respectively, are used for nonlinear time history analyses. The peak ground acceleration of selected components are amplified in order to study the nonlinear interaction between the pipe and the soil. Also, K_0 is the coefficient of lateral soil pressure at rest.

4-THE NUMERICAL RESULTS:

4-1-Pipeline length considered for modeling:

In order to evaluate the influence of the boundary conditions on the pipeline response, a number of models with different lengths, free and fixed end conditions have been analyzed using different soil types. As it is obvious from figure 2, in models with 900m length or more, and for the given soil types, the axial displacement of the middle element is independent from the pipe end conditions. Thus, a 1000m long model of the pipeline with fixed ends conditions is used for the parametric studies.

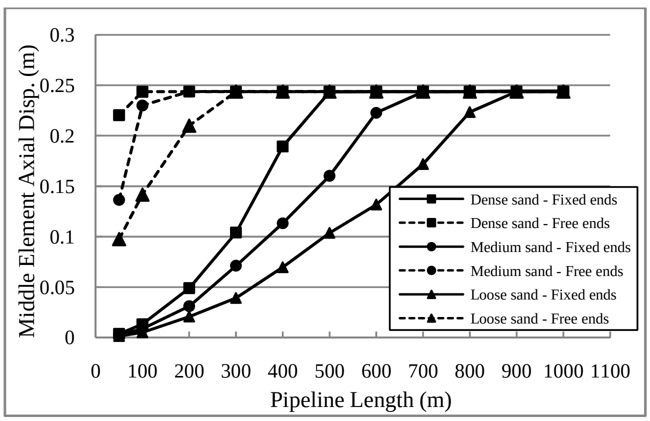

Figure 2- Effect of Boundary Conditions on Maximum Response of Middle Element

4-2-Soil stiffness:

Figure 3 shows the influence of soil stiffness on the relative displacement of pipe with respect to the soil. It can be seen that increasing the soil stiffness reduces the pipe displacement in axial and trans-horizontal directions. In these figures, H and OD represent the burial depth and the outside diameter of the pipeline respectively.

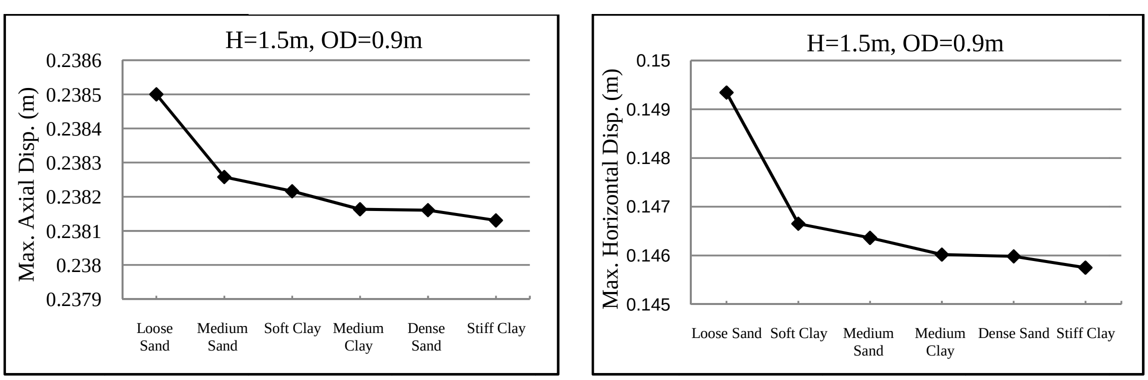

Figure 3- Effect of Soil Stiffness on Response of Middle Element

4-3- Mass of the pipe and the water inside:

Figure 4 shows the effect of the water inside the pipeline on its maximum displacement in axial and lateral directions. It can be seen that by increasing the pipe mass (due to added water), the dynamic interaction between the pipe and soil would increase, leading to larger responses.

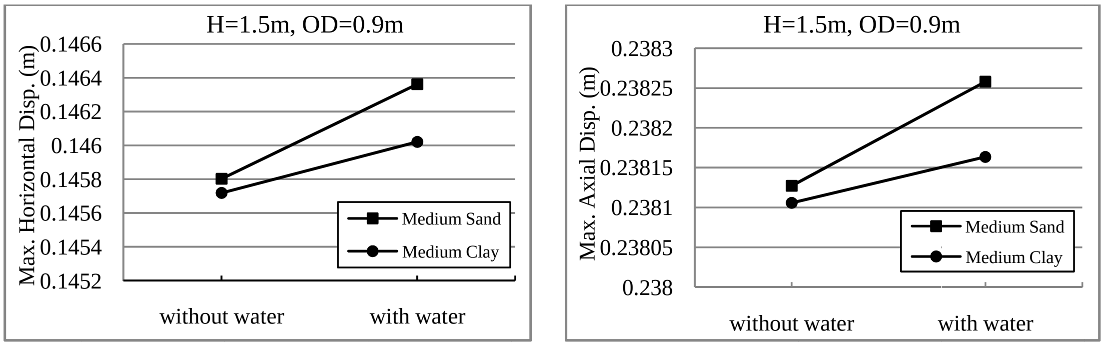

Figure 4- Effect of Existence of Water on Response of Middle Element

4-4- Pipeline burial depth:

In order to study the effect of burial depth on the system's response, 3 different depths are considered for the pipe. For non-cohesive soils, as it is clear from figure 5, increasing the burial depth of the pipe reduces its response in horizontal direction. However, in cohesive soils, any increase in the burial depth, increases the horizontal response of the pipe's middle element. That is because in opposite to cohesive soils, increasing the burial depth in non-cohesive soils, increases the stiffness of the axial soil springs. Also, it is necessary to mention that in considering different burial depth, the specifications of soil are assumed to remain constant.

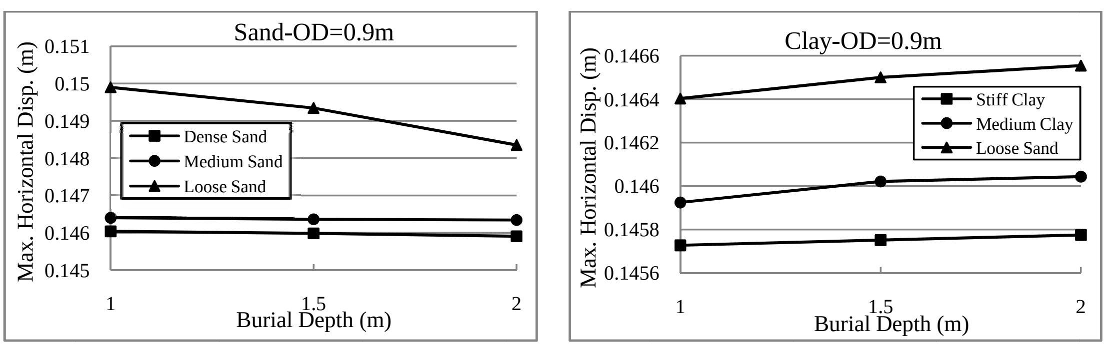

Figure 5- Effect of Burial Depth on Response of Middle Element in horizontal Direction

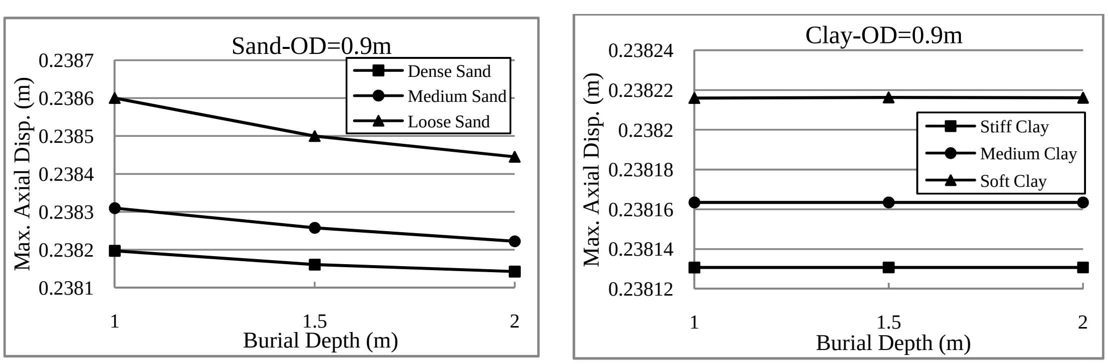

Figure 6- Effect of Burial Depth on Response of Middle Element in Axial Direction

Figure 6 shows the same results for the middle element displacement in axial direction. Again, in non-cohesive soils, increasing the burial depth, causes the responses in axial direction to reduce. But, in cohesive soils, it has no considerable effect on the pipe's axial response.

4-5- Pipe diameter:

The effect of pipe diameter on the horizontal response of the middle element is shown in figure 7 for the non-cohesive and cohesive soils. As the results indicate, increasing the pipe diameter in general would lead to an increase in the response in lateral (horizontal) direction. This is due to the fact that any increase in the pipe diameter increases the soil lateral spring stiffness as well as the mass of the pipeline. The results show that the influence of the latter is more prominent than the first one.

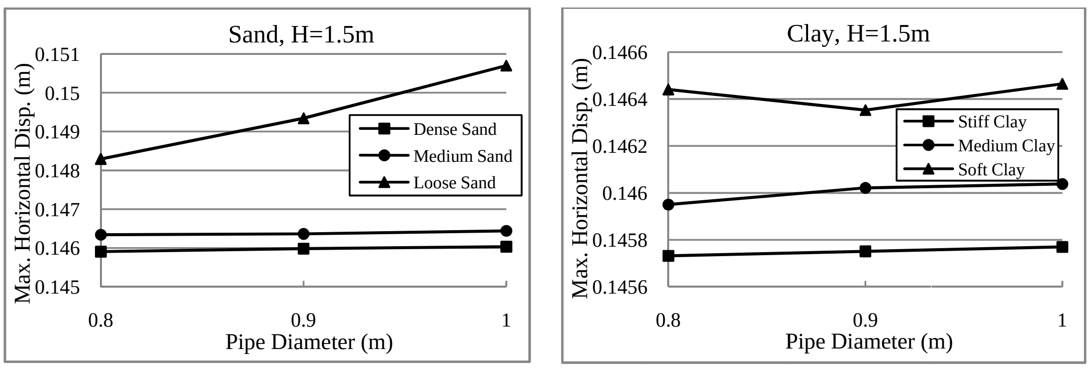

Figure 7- Effect of Pipe Diameter on Response of Middle Element in Horizontal Direction

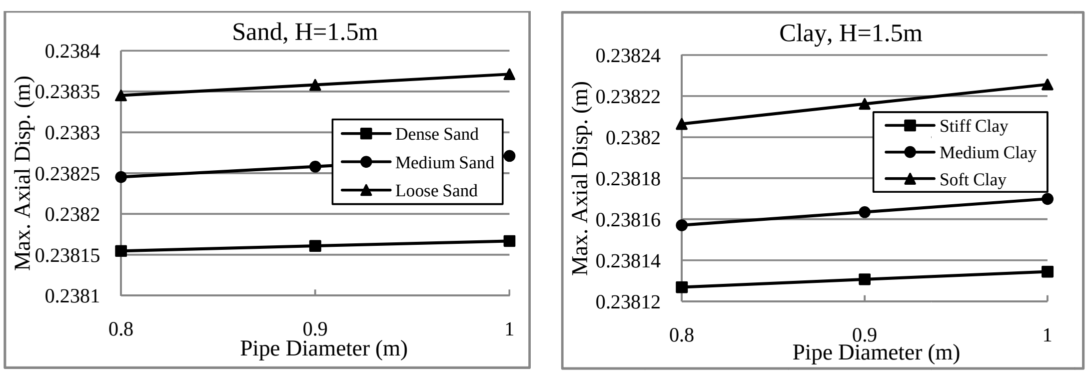

Figure 8- Effect of Pipe Diameter on Response of Middle Element in Axial Direction

With regard to the effect of pipe diameter on the axial response of the pipeline, as figure 8 illustrates, an increase in the pipe diameter, causes the pipe's axial response to increase.

4-6- Soil Damping:

Figure 9 shows the influence of soil damping ratio on the pipe response for cohesive and non-cohesive soils. One could observe that, increasing the damping ratio up to a certain limit would reduce the response parameters of the system. However, for larger dampings (larger than 10% in this example) no significant change in results would occur.

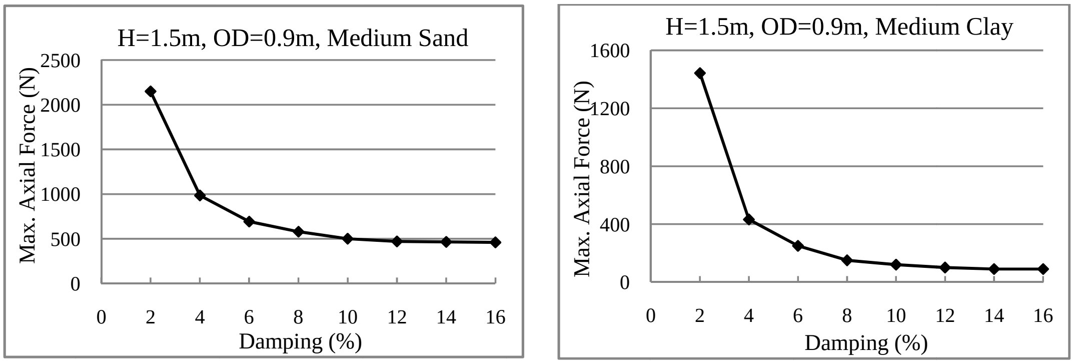

Figure 9- Effect of Soil Damping on Response of Middle Element in Axial Direction

4-7- Slippage between Soil and Pipe:

One of the main parameters affecting the axial slippage of the pipelines is the relative stiffness between the soil and the pipe in the axial direction. Any increase in the pipe stiffness in comparison to soil springs stiffness, would increases the axial force in the soil springs, thus raising the possibility of slippage between pipe and soil. Figure 10 presents the time history of the axial force in soil springs for a pipe of 0.8m diameter surrounded by 3 types of non-cohesive soil. As these figures show, increasing the pipe to soil stiffness ratio, causes the axial force of the springs to increase. For the case of loose sand, the soil spring force has reached its maximum value and slippage has occurred.

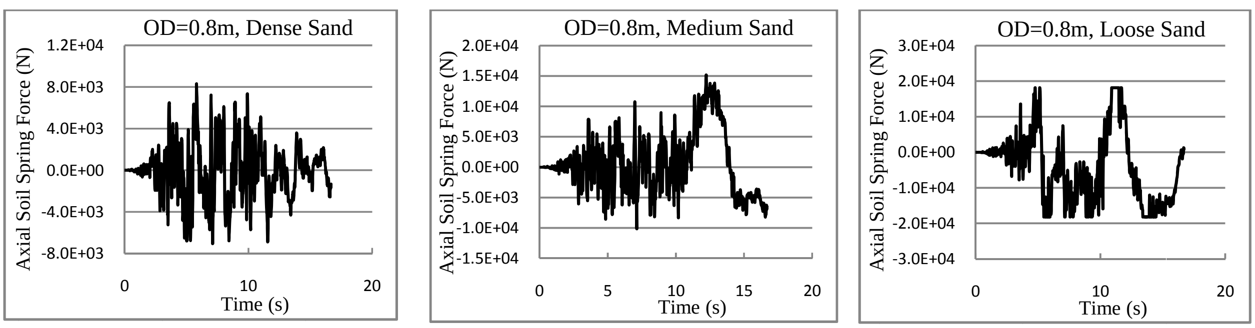

Figure 10- Effect of Soil Damping on Response of Middle Element in Axial Direction

Also, figure 11 shows the maximum axial force in soil springs for different soil types and various pipe diameters. The results indicate that for a specific soil type, increasing the pipe diameter which increases its stiffness, would raise the axial force of soil springs.

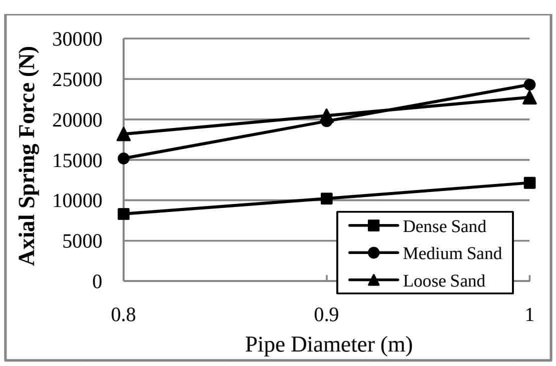

Figure 11- Time History Diagram of Axial Soil Springs

4-8-Pipelines with bends:

Generation of high stress concentration near the bends of a pipeline network that results from the wave propagation phenomenon is among other important issues to be addressed. In order to evaluate the behavior of buried pipelines with bends, a number of pipeline models with different bend angles (in the horizontal plane) have been prepared. In this study, the effect of distance to the bend and the angle of bend on the pipeline responses have been studied.

Figures 12 & 13 show the effect of pipeline bend angle and distance to the bend on the maximum stresses and strains generated in the pipeline. Medium sand has been chosen as the surrounding soil in this study. As it is clear from these figures, with approaching toward the bend in a pipeline, the stresses and strains will increase. Another important parameter is the angle of bend in buried pipelines. As one could observe, increasing the bend angle will change the induced stresses and strains. For this specific example, the maximum axial stresses and strains occur for a 30 degree bend angle, while, the maximum bending and sum of axial and bending stresses occur for a 75 degree bend angle.

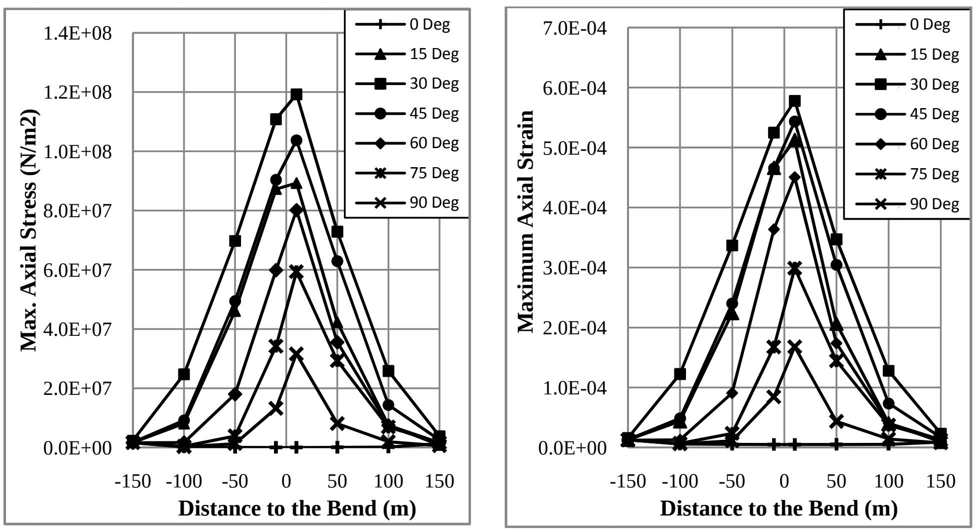

Figure 12- Maximum Axial Stress & Strain for Models with Different Bend Angles

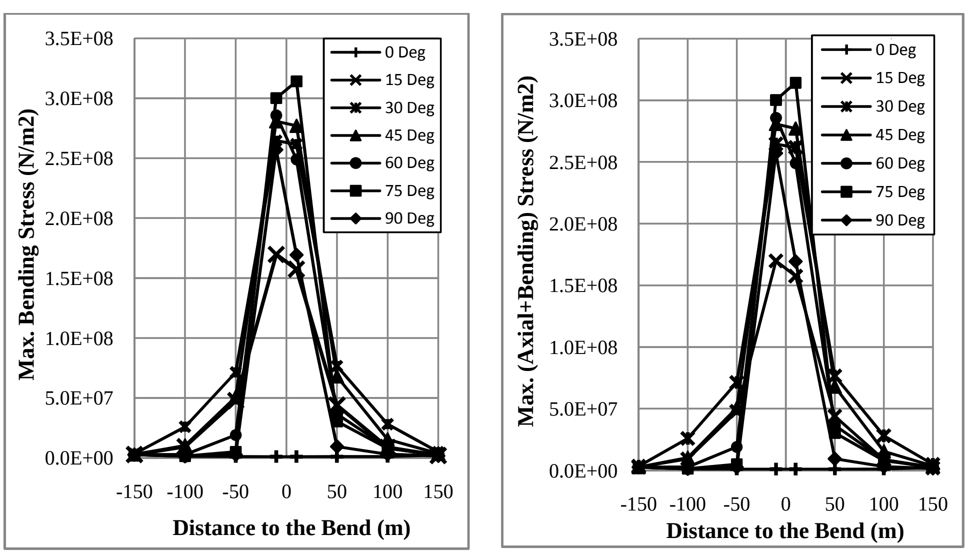

Figure 13- Maximum Axial Stress for Models with Different Bend Angles

5- CONCLUSIONS:

1- Decreasing the surrounding soil stiffness, raises the interaction between soil and pipe and in turn increases the pipe response parameters.
2- In pipelines with larger diameters, the effect of mass on dynamic interaction between pipe and soil is important and cannot be neglected.
3- Increasing the soil damping up to a certain limit would cause a considerable reduction in responses. However, any further increase in the damping ratio would have no significant effect on the results.
4- Soil-pipe relative stiffness has a considerable influence on slippage between the soil and the pipe as well as on the response parameters. Increasing the pipe to soil stiffness ratio, raises the force generated in the soil springs thus increasing the possibility of slippage between the soil and pipe.
5- Approaching toward a bend in a pipeline, increases the induced stresses and strains due to wave propagation. For the specific example considered here, the maximum axial stresses and strains occur for a 30 degree bend angle, while, the maximum bending and sum of axial and bending stresses is obtained for a bend with 75 degree angle.

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