DEFORMATION OF STEEL PIPES WITH INTERNAL PRESSURE UNDER AXIAL COMPRESSION AND BENDING LOAD UNDER SEISMIC ACTION

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ABSTRACT :

In the high risk zones in Mexico have been observed that the ground motions often show large horizontal displacements. Those displacements cause large deformations of buried pipelines. Then, the knowledge of study and design recommendations related to deformability of the pipes has not been sufficiently provided. A grand number of studies have been reported concerned about the plastic deformations or buckling of the straight pipe. Most of them are performance of column pipe without internal pressure. Therefore, the purpose of this study is clarifying the deformations; steel pipes with internal pressure, axial compression and bending are analyzed. Effect of internal pressure on deformability of pipe is investigated both under compressive or load bending. Stress analysis using FEM is performed in order to simulate the large deformations of the pipes.

Consequently, this research has focused on the behavior and study under seismic conditions, of already existing pipelines, located in high risk zones. The seismic actions induced a flexion pattern, causing deformations, strain, curvatures and ovalization along of the pipelines. This research describes in-plane bending the behavior in closing and opening mode to evaluate the response of the pipelines. The study involved a typical 20” internal diameter, API 5L X52 steel pipeline.

KEYWORDS: PIPES, PIPELINES, STEEL PIPES, BURRIED PIPES, MECHANICAL BEHAVIOR

1. INTRODUCTION

In the word many seismic movement had caused damage in the superficial and buried system oil pipes. Then with the purpose to reduce the damage of the buried pipes has been many researches to create new and better tools to seismic design that allow a theses pipes give service yet after an earthquake. The earthquakes effect on the buried pipes is the pattern deformations imposed by the seismic wave propagation.

The seismic analysis on the buried pipes is different to the other structures such as: buildings; in the pipes the inertial forces are resisted by mass of the soil around of then, while the inertial forces of buildings are a basics parameters of seismic design.

Consequently the paper described a procedure based on a FEM modeling that was performed to simulate the deformation behavior of pipeline using solid elements to represent the soil and shell elements the pipe walls, where the mechanic characteristics of the materials and the real geometries have been considered, also the characteristic of the soil are modeled together. Real seismic record of seduction originated in the Mexican Pacific Ocean has been used by a time history analysis. Finally, the results obtained of the real structures are considered to be used to determine new design, as well in the regulations environment in our country.

2. GROUND SHAKING EFFECTS ON BURIED PIPELINES

Much of the current research on buried pipelines has dealt with ground shaking effects. The approaches proposed for dealing with this problem range from simple approximations to complex computer models requiring a seismic time - history record as input. The unknowns confronting the designer who attempts to model ground shaking lie in two general areas. One area is the model used to represent the seismic waves and the mechanism through which they propagate from a focal zone. Various types of analysis differ in the assumptions made in modeling these areas of uncertainty. The purpose of this work is to evaluate by numerical models a procedure currently used to analyze and design buried gas and liquid fuel pipelines to resist ground shaking effects that normally are not of major significance and design except for affects associated with large earthquakes (*see figure 1*).

Figure 1 Buried pipe damage by ground shaking effects

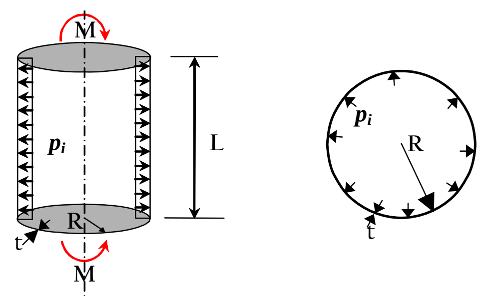


Figure 2 Segment buried steel pipe studied, using a typical steel pipe with 20" external diameter, API 5L X52 (L=10m), submitted to combined mechanical actions

2.2. Soil-pipeline interaction

The soil around a pipeline plays a very important role in relation to its seismic behavior; if it is cohesive soil, the softer it is, the greater differential settlements there will be due to consolidation or higher amplification effects; if it is granular material, the probability of liquefaction becomes higher the looser it is. However, when we talk about soil-pipe interaction, it is supposed that the soil will not fail, but the soil displacements will produce friction-like forces at the soil-pipe interface. The maximum axial force per unit of length depends on the type of soil surrounding the pipe and the method of pipe installation (i.e., the compaction control of the back-fill).

3. STRUCTURE STUDIED

This research is focused on the behavior and study under seismic conditions, of the steel straight pipelines semi-buried with internal pressure, located in high risk zones, see figure 3. The seismic actions when arrive in perpendicular direction of the pipeline induced a bending pattern, causing deformations, strain, curvatures and ovalization along of the pipelines. This work shows in-plane bending the behavior in closing and opening mode to evaluate the response of the pipelines. The study involved a typical 20" internal diameter, API 5L X52 steel pipeline (*see figure 2*). Steel pipes are studied considering internal pressure, take into account the self weight (pipe-liquid) and seismic excitation, these condition generate a stress-strain state basically in bending, to estimate the structural response of the semi-buried pipes, the modal configurations is evaluated by numerical approaches such as finite element method (FEM) for steel straight pipes with internal pressure $p_i = 5.888\ Mpa$ ($p_i = 60\ Kg/cm^2$), see figure 2. Derived of this numerical analysis is studied de mechanical behavior.

Geometrical characteristics of the steel pipe studied are:
Diameter D = 50.8 cm (20")
thin wall t = 1.5875 cm (5/8")

E = 206,084.39 Mpa (*2.1 E06 Kg/cm*^{2})
ν = 0.3

3.1. Mechanical characteristics of the soil
The soil around of the pipeline was modeled considering the follow mechanical characteristics of a real soil, see table 3.1.

Table 3.1. Characteristics of the soft soil

Deep (m)	0 - 5.00
E_s (Mpa)	34.495; 351.50 (*Kg/cm*^{2})
G_s (Mpa)	11.498; 117.17 (*Kg/cm*^{2})
ν_s	0.5
SUCS	Hard consistency of clay

4. NUMERICAL MODEL AND ASSUMPTIONS

In this part is described a procedure based on a FEM modeling that was performed to simulate the deformation behavior of pipeline using solid elements, where the mechanic characteristics of the materials and the real geometries have been considered, also the characteristic of the soil are modeled together. Seismic record of seduction originated in the Mexican Pacific Ocean has been used by a time history analysis.

4.1. Statement of the problem
The selected pipes are typical structures employed in oil national industry; therefore in this work they have been used with their real values of the geometric and mechanical properties that constitute it. The investigation is developed in the following way, the soil-pipeline is modeling through a fine mesh composed by elements solids, that represent a wall of the pipe, the fluid and soil respectively and it is analyzed applying the finite element method (FEM), considering different soil-pipeline interaction models. It is studied the flexibility of the thin walls and the interaction effect with soil around it generated by seismic faulting (see figures 3.a and 3.b).

4.2. Numerical model of soil-pipeline interaction

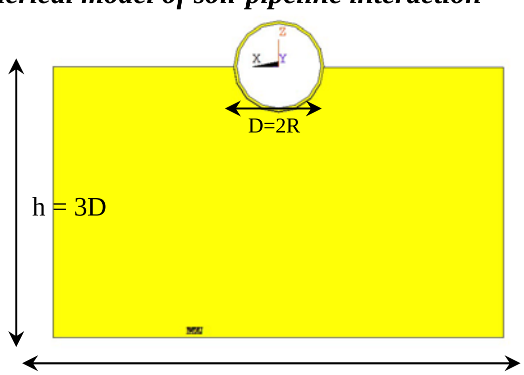


Figure 3.a Geometrical characteristics of the numerical models of soil-pipeline interaction: b=5D, h=3D, L=10m

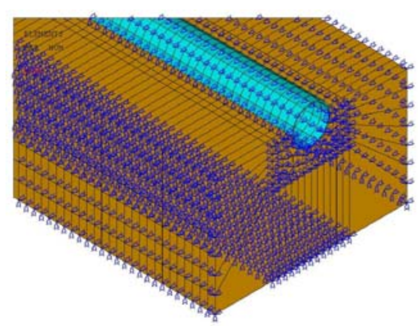
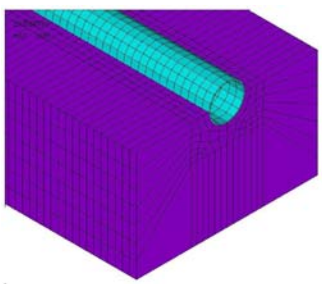
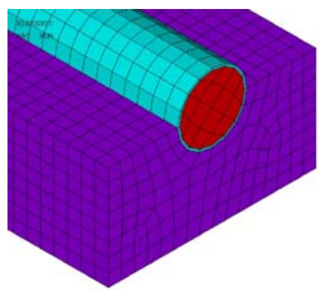
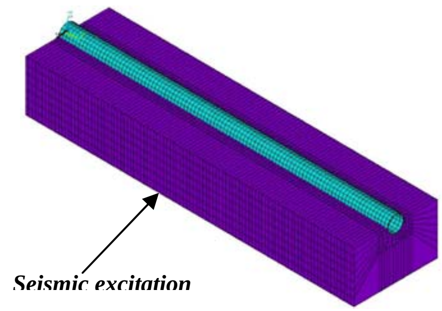


Figure 3.b Boundary conditions of the numerical model of soil-pipeline interaction considering the semi-buried pipe

In figures 3.a, 3.b, 4.a and 4.b. are shown a numerical models of soil-pipeline interaction, builds and used to know the seismic response, these models have the follow geometrical characteristics, large B=5D, height h=3D, and long L=10m, in this work is exposed the numerical results for the case of the semi-buried steel straight pipes with internal pressure and seismic actions arriving in the perpendicular and longitudinal directions of the pipeline which induced a bending pattern. The boundary conditions of the soil are: at the bottom in the direction *z*, the vertical displacements are restraints, at the lateral faces (direction x; *x=±2.5D*) the horizontal displacements are restraints and finally at the transversal faces (direction y; *y=±500cm*) the horizontal displacements are restraints, with relation to the soil surrounding with the pipe the boundary conditions are represented by contact elements in each node, allowing the uplift of the pipe to the soil when appear tension stresses (see figure 3.b). The figures 4.a. and b. show the numerical models of soil-pipeline-fluid interaction, taking into a count the self-weight and the fluid actions. The figure 5 exposed the numerical model used in the seismic analysis; the signal is applied at the bottom of the soil, which induced a bending pattern, to know the response of the interaction system soil-pipe.







Numerical model of soil-pipeline interaction (*semi-buried pipe*)

Figure 4.a Self-weight   Figure 4.b Self-weight and fluid   Figure 5 Self-weight

5. NUMERICAL RESULTS OF THE PIPES STUDIES

5.1. Full and pressurize condition

In this part, it carried out the gravitational analysis considering the full condition, self weight and internal pressure of the steel pipe segment; the goals were to adjust the numerical model of the analysis by FEM.

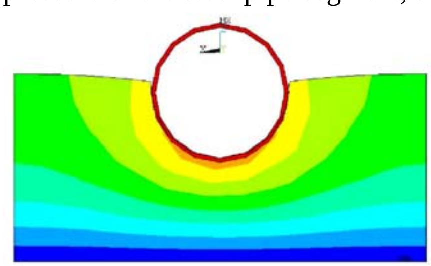


Figure 6.a Numerical model ***1*** of soil-pipeline interaction of the semi-buried pipe

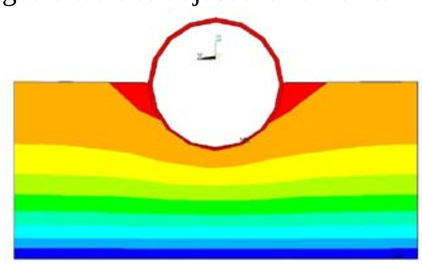


Figure 6.b Numerical model ***2*** of soil-pipeline interaction of the semi-buried pipe, without fluid

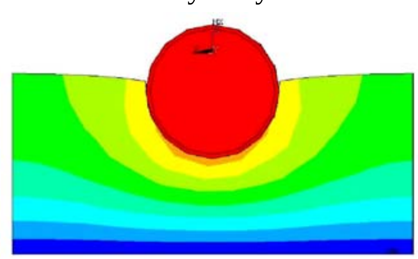


Figure 6.c Numerical model ***3*** of soil-pipeline-fluid interaction of the semi-buried pipe

Table 5.1. Results of the numerical model

Numerical Model	Figure	Vertical displacement (cm)	Characteristics of the three models
1	6.a	0.014668	self weight + fluid integrated
2	6.b	0.009810	empty
3	6.c	0.014592	self weight + full

In the figures 6.a to 6.c and table 2 are shown the numerical results of the gravitational analysis considering the full condition of the steel pipe segment, for three different models.

5.2. Dynamic analysis

In this part, with the purpose to know the dynamic characteristic and their influence on the bending pattern in the structural response of the pipe, before to carry out the seismic analysis, it accomplished the dynamic analysis; the figures 7.a to 7.d and table 3 shown the most representative natural periods, frequencies and modal shapes of the numerical model of soil-pipeline interaction.

Table 3. Dynamical parameters of the numerical model

Mode	Frequencies (hertz)	Periods (sec)
1	0.09528	10.49503
2	0.17321	5.77322
3	0.19803	5.0498
4	0.2213	4.51882
5	0.23107	4.32769
6	0.24966	4.0054
7	0.25539	3.91554
8	0.27324	3.65984
9	0.27574	3.62666
10	0.27792	3.59813

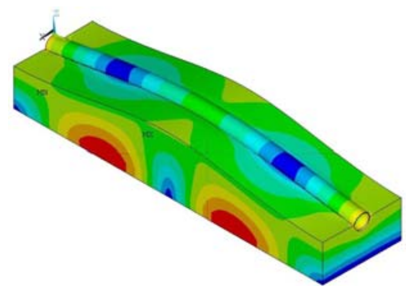


Figure 7.a Modal configuration, mode 2

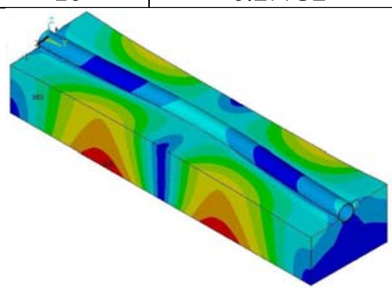


Figure 7.b. Modal configuration, mode 4

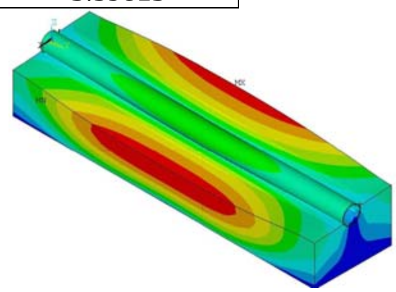


Figure 7.c Modal configuration, mode 6

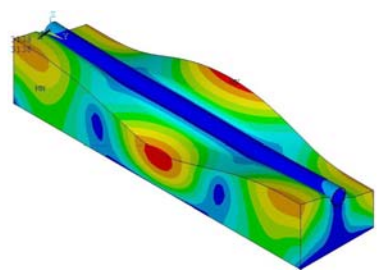


Figure 7.d Modal configuration, mode 9

The dynamical results revealed that the first periods and their respective modes 2 to 6 have an important influence of the bending pattern behavior on the seismic response.

5.3. Seismic analysis

The seismic analysis were carried out employing a seismic record at Mexico City, obtained of the earthquake originated at the Subduction zone of Mexican Pacific Coast, in 1985 (see figure 8); of this record was applied at the base of the models pipe-soil, in the two horizontal direction (*x, y)*.

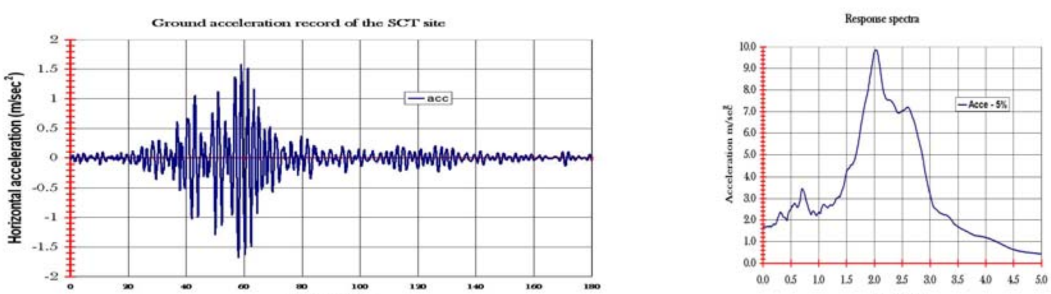


Figure 8 Horizontal ground acceleration record and response spectra, Mexico City

In order to study the structural response of soil-pipeline interaction and the mechanical behavior of the pipe, owing to the propagation waves generated by seismic faulting that cause the curvature in the straight pipes due to traveling wave effects, the acceleration record (figure 8) was integrated in the dominion of the time to obtain the displacement record which was applied to the numerical model perpendicular and longitudinal directions to the straight semi-buried pipelines (*see figures 9 and 10*).

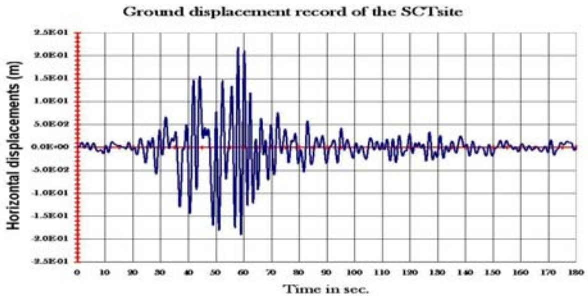


Figure 9 Input seismic displacement record

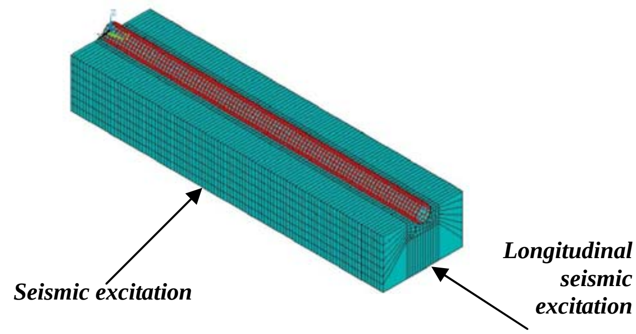


Figure 10 Soil-pipeline interaction numerical model, L=10m

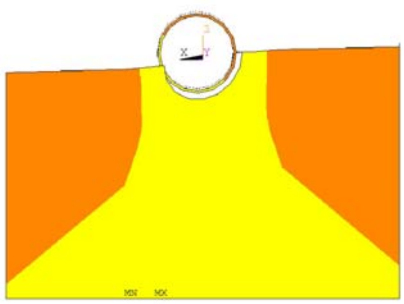
6. TIME HISTORY ANALYSIS AND RESULTS

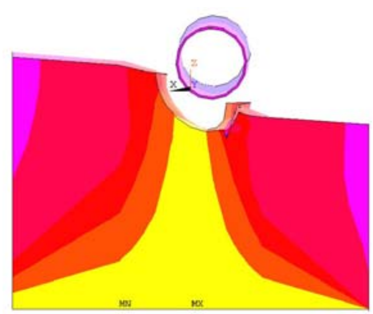
6.1. Seismic response of the pipes, transversal and longitudinal seismic excitation

In this part are presented the numerical results of the historical analysis for the four conditions studied:

Case	Condition of the steel pipe	Horizontal Seismic excitation
a.	*Full and pressurized (p_i=5.89 Mpa)*	*Transversal, dir x*
b.	*Full without pressure*	*Transversal, dir x*
c.	*Full without pressure*	*Longitudinal, dir y*
d.	*Full and pressurized (p_i=5.89 Mpa)*	*Longitudinal, dir y*

The goal is to know the seismic horizontal displacement response in the two horizontal directions (***x** and **y***) of the steel straight pipes and the state of stresses.





Case a, seismic response of the horizontal displacement

Figure 11.a. Transversal displacement, at *28.8sec.* Figure 11.b. Transversal displacement, at *35.68sec.*

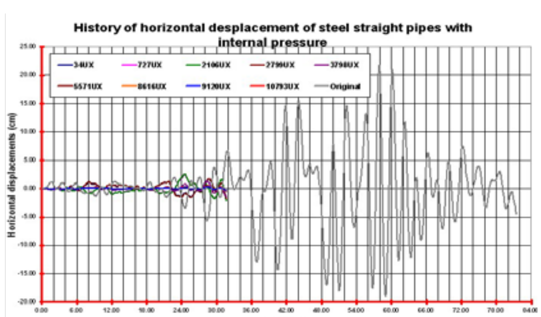


Figure 12.a. – History of the horizontal displacement of the steel pipes segment to L_1=10cm

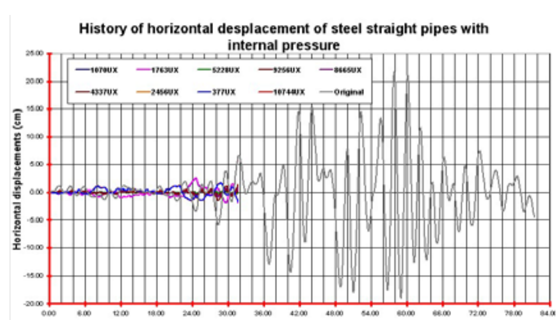


Figure 12.b. – History of the horizontal displacement of the steel pipes segment to L_2=500cm

Case a. *Full and pressurized (p_i=5.89 Mpa)* condition, the figures 11.a and 12.a to 12.d illustrate the seismic response of the maximal transversal displacement of the soil-pipeline interaction model, at *28.8 and 35.68 sec*. respectively. The figures 12.a to 12.c shown the seismic response of the transversal displacements of the soil-pipeline interaction model at three points along of the pipe (*L_1=10cm, L_2=500cm, L_3=900cm*) respectively.

The figure 12.d illustrate the Von Mises stresses and it is observed that the maximal Von Mises stresses (σ_{VM} $=16.63Mpa$) are near to the both ends, ends when the pipe is horizontally excited in the perpendicular direction, causing a bending pattern mode (*strain and curvatures*) along of the pipe.

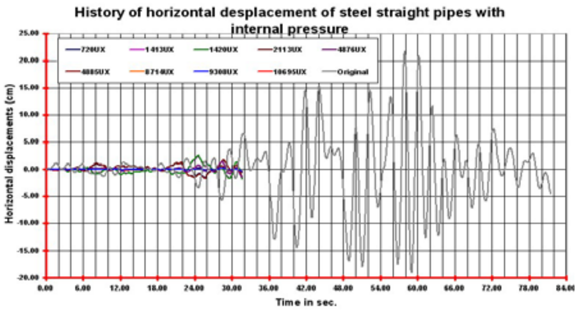


Figure 12.c. – History of the horizontal displacement of the steel pipes segment to L_3=990cm

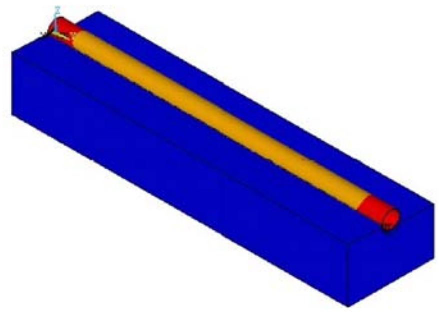


Figure 12.d. View 3D of the seismic response of the Von Mises stresses of the soil-pipeline interaction model, pressure p_i = 5.89 *Mpa*

Case b. *Full without pressure* condition, the figures 13.a to 13.d. report the seismic response, horizontal displacements history at different part of the long ($L_1=10cm$, $L_2=500cm$, $L_3=900cm$) of the steel pipe. Figure 13.e illustrates the Von Mises stresses and is observed in figure 13.f that the maximal Von Mises stresses (σ_{VM} $=26.00Mpa$), that appear along of the pipe and near to the both ends, the horizontal and perpendicular action produce a bending pattern mode (*strain and curvatures*) along of the pipe.

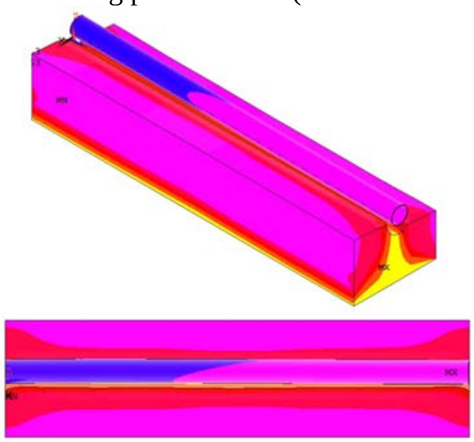


Figure 13.a - 3D and plane view of the seismic response of the transversal displacement

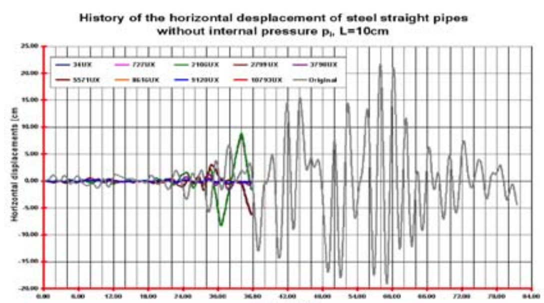


Figure 13.b. - History of the horizontal displacements of the steel pipes segment to L_1=10cm

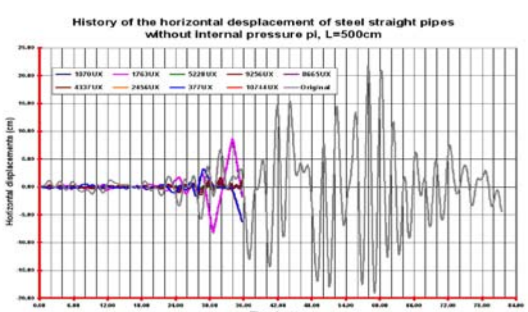


Figure 13.c. - History of the horizontal displacements of the steel pipes segment to L_2=500cm

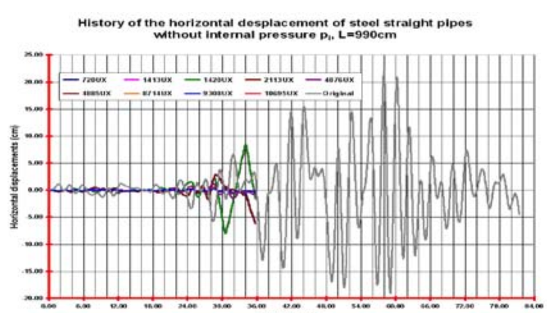


Figure 13.d. - History of the horizontal displacements of the steel pipes segment to L_3=500cm

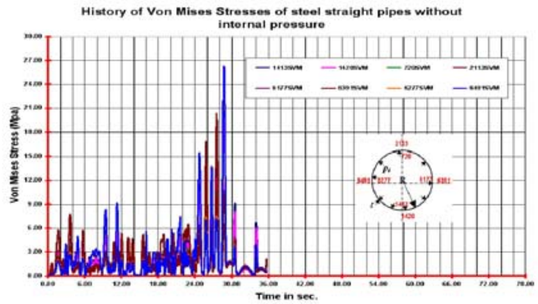


Figure 13.e. - History of the Von Mises stresses of the steel pipes without pressure

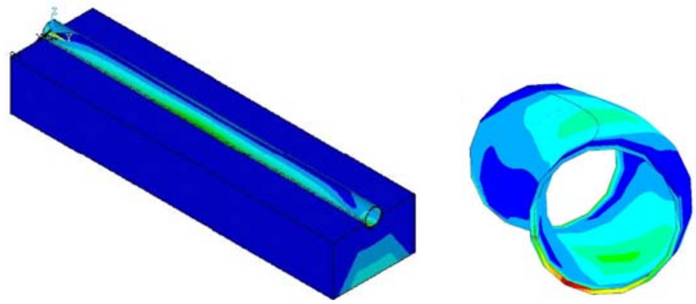


Figure 13.f. - View 3D of the seismic response of the Von Mises stresses of the soil-pipeline interaction model, without p_i

Case c. Horizontal seismic excitation in the direction *y* and *full without pressure* condition**. T**he figures 14.a to 14.c report the horizontal displacements history at different part of the long ($L_1=10cm$, $L_2=500cm$, $L_2=990cm$) of the steel pipe, and figure 14.d report Von Mises stresses history.

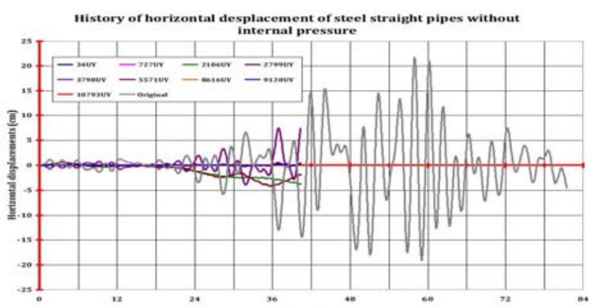


Figure 14.a History of the horizontal displacements of the steel pipes segment to L_1=10cm

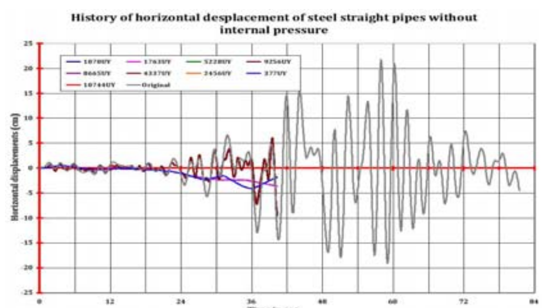


Figure 14.b. History of the horizontal displacements of the steel pipes segment to L_2=500cm

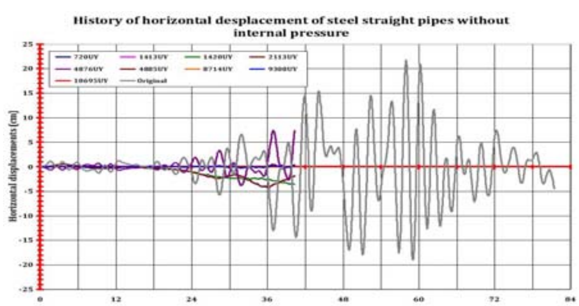


Figure 14.c. History of the horizontal displacements of the steel pipes segment to L_3=990cm

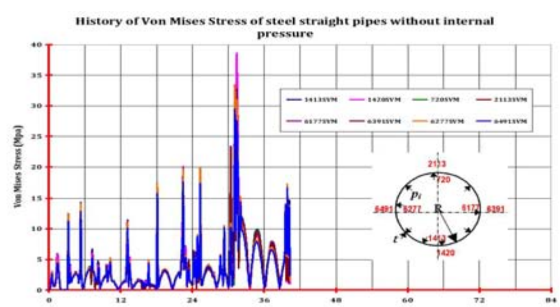


Figure 14.d. History of the Von Mises stresses of the steel pipes without pressure

Case d. Horizontal seismic excitation in the direction *y and full and pressurized (p_i=5.89 Mpa)* condition**. T**he figures 14.a to 14.c report the horizontal displacements history at different part of the long ($L_1=10cm$, $L_2=500cm$, $L_2=990cm$) of the steel pipe, and figure 14.d report Von Mises stresses history.

In brief, the history of the horizontal displacements and Von Mises stresses (*case a and b*) explain the mechanical behavior observed in the pipelines semi-buried making obvious that when the internal pressure intensity is important, the pipes are pre-stressed increasing its stiffness and consequently permit a low amplitude levels of the displacements, then for the case a, with internal pressure (p_i=*5.89 Mpa*) the maximal horizontal displacement was *1.87cm* at *31.68sec* while the case b, when the internal pressure is zero, the pipe allowed *8.14cm* at *34.14sec*, causing in both cases damage on the thin wall of the pipes such as, the plastic deformations or buckling (*see figure 13.f*) and uplift of the pipe.

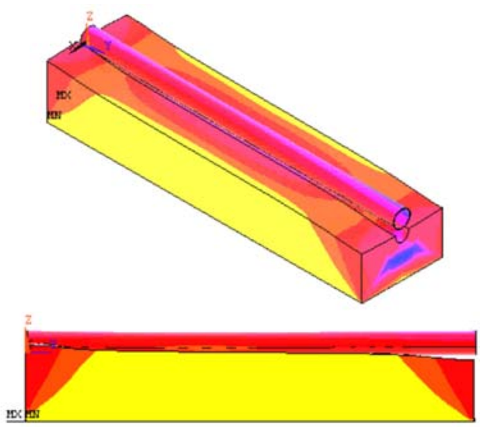


Figure 14.a **Case d**, 3D and elevation views of the seismic response of the longitudinal displacement

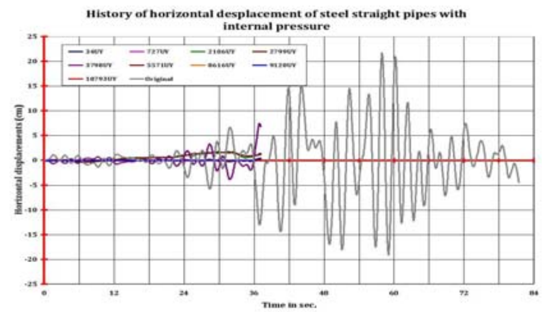


Figure 14.b. History of the horizontal displacements of the steel pipes segment to L_1=10cm

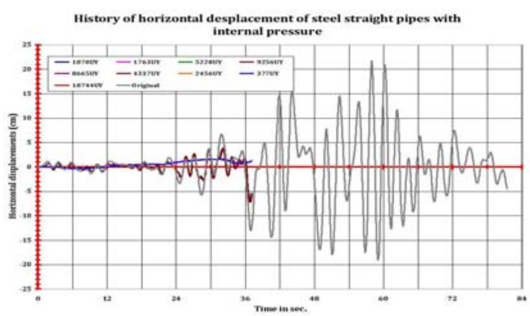


Figure 14.c. History of the horizontal displacements of the steel pipes segment to L_2=500cm

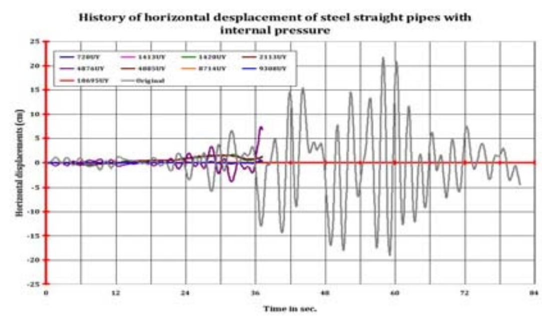


Figure 14.d. History of the Von Mises stresses of the steel pipes without pressure

CONCLUSIONS AND COMMENTARIES

The purpose of this work was evaluated the structural behavior and response of the segment steel pipelines semi-buried submitted to the seismic action. The numerical results obtained by different soil-pipelines models developed in this work have permitted to know and verified the seismic response and mechanical behavior of the steel straight semi-buried pipes, using in the national oil industry.

From the obtained results of the soil-pipelines interaction models with the selected seismic record for the boundary conditions considered, between the soil surrounding with the pipe and the influence of the internal pressure level; is observed that in the cases *a and b* studied when the structures are horizontally excited in the perpendicular direction, occurs a bending pattern mode causing deformations (*strain and curvatures*) along of the pipe, simultaneously with a maximal radial deformation on the thin walls at the middle of the long (*L=500cm*) and the maximal stresses appear at the ends of the pipeline due to the border boundary conditions. The mechanical behavior observed in the pipeline segments semi-buried studied make obvious that when the internal pressure intensity is important ($p_i = 5.89$ *Mpa*), the pipes are pre-stressed increasing its stiffness and consequently permit low amplitude levels of the horizontal displacement when is submitted a seismic actions causing damage on the thin wall of the pipes such as, the plastic deformations or buckling and uplift of the pipe. Respect to the longitudinal seismic action (*cases c* and *d*) the bending pattern mode is less manifest, but the deformations (*curvature)* is presented in vertical direction (*see figure 14.a*).

PERSPECTIVES

This approach of the seismic analysis on the semi-buried pipelines may well be used for the evaluation of the buried pipes considering a major deep of the soil with different mechanical characteristics.

NOMENCLATURE

t = thickness of pipe
R = outside radius
D = 2R
h = height of the model
B = Large of the model
L = pipeline long
E = Young modulus of the steel pipe
ν = Poisson ratio
E_s = Young modulus of soil
G_s = Young modulus of shear
ν_s = Poisson ratio of soil
p_i = internal pressure

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REFERENCES

ASME B31-4, (2002). Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids, Code for Pressure Piping, B31 an American National Standard.

API 5L, (2000). Specifications for Line Pipe, American Petroleum Institute, Forty-Second ed., January.

Calladine, C.R. (1988). Theory of shell structures, Ed. by Cambridge University Press, Cambridge, G.B., 763 p.

Flores, B.R. and Xiangyue, Li Liu (2003). Seismic Vulnerability of Buried Pipelines, *Geofisica Internacional*, **Vol. 42, Num. 2, pp. 237-246**.

Page, R. A., Boore, D.M., Joyner, W. B. and Coulter, H. W. (1972). Ground Motion Values for Use in the Seismic Design of the Trans-Alaska Pipeline System, *Geological Survey*, **Circular 672**.

Pineda-Porras, O. and Ordaz, M. (2003). A New Seismic Intensity Parameter to Estimate Damage in Buried Pipelines due to Seismic Wave Propagation, *ASCE*, **International Conference on Pipe Engineering, Baltimore, M.D.**

Sánchez-Sánchez, H. and Cortés, Salas C. (2006). Risers stability under external pressure, axial compression and bending moment considering the welded as geometrical imperfection, **Proceedings of the 25th International Conference** *OMAE*, Hamburg, Germany 4-9, June.

Sanchez-Sanchez, H., and Cortés, Salas C., (2005). Riser stability under external pressure and axial compression observing geometrical imperfections, **Proceedings of the 24th International Conference** *OMAE*, Halkidiki, Greece 12-17, June.

Sánchez-Sánchez, H., and Cortés, Salas C., (2003), Estabilidad de tuberías sometidas a presión externa considerando imperfecciones geométricas, **Proceedings of the Congreso Internacional de Ductos**, Puebla, Pue., 12 – 14 Noviembre.

Sánchez-Sánchez, H., Minchaca, M.E., and Avelino R.J., (2002). Pandeo de estructuras axisimétricas con imperfecciones geométricas iniciales, **Proceedings of the XIII Congreso Nacional de Ingeniería Estructural**, No. 159, Puebla, Pue.