Numerical analysis of buried steel pipelines under earthquake excitations

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ABSTRACT
The performance of buried pipes is affected by seismic wave propagation and its incidence due to out-of phase induction motion. In this study, three dimensional finite element models have been employed to evaluate the effect of bend angle and soil mechanical properties on seismic response of buried pipe in bent area. In these models, beam and nonlinear spring elements were used to simulate pipe and soil-pipe interaction, respectively. Furthermore, a suitable boundary condition has been used to simulate far field effect more closely. The travelling of seismic waves was assumed to be parallel to a pipe leg, causing time lag in vibration of different points of model. The influences of geometrical parameters such as diameter-to-thickness ratio and embedment ratio on elbow strains were also considered. Results indicated that a direct relationship exists between soil stiffness and axial strains due to smaller slippage. Diameter-to-thickness is a definitive ratio for axial strain of bend while effect of the embedment ratio is small.

RÉSUMÉ
Emission des tremblant ondes ont dues d'imposer des movements d'hors de la phase qu'affecter sur les inhumé pipelines performances. Dans cette recherche, effet d'angle des courbes tubes et les mécaniques propriétés du sol a été. sur la frémissment réponse des inhumé tubes utilisation d'éxecution modèles de limitées en trois dimensions étudiées performances. Dans la susmentionné modèles pour la portraitiste de tube et interaction du sol- pipe ont appliquée les traits élements et les resorts elements, en ordre. Aussi pour la précise modélisation d'effet de loin terme est utilizé aux équivalentes limites conditions. Emission d,onde est supposé parallèlement à l'une des courbes branches en ce qu, est créée latence de la phase dans la vibration des différentes parties de modèle.L'impact des géométrique parameters comme le diameter au grosseur de tube et l'inhumé profondeur sur les courbettes de tuyau region sont examines d'autres cas dans cette etude. L'Analyse des résultats indiques qu'en raison de plus bas glisser dans les sols qu'a une plus dureté, la réponse des tubes sont plus dans ce sol. Aussi plus effet de diameter au grosseur de tube comparé avec l'inhumé profondeur sur les courbette valeurs, autres résultats que sont considérés.

1 INTRODUCTION

Pipelines are used in different areas like natural gas transportation, sewage systems, water supply, petroleum transport and industrial sectors. With the improvement of economy and urbanization, the damage of pipeline systems severely affected life and manufacture; hence more extensive attention is required with regards to pipeline systems. Permanent ground movements and transient ground deformations are major seismic hazards which affect the behaviour of buried pipes. Transient ground deformations are generated through the wave propagation in soil. The effect of this phenomenon on the response of buried pipes (especially in bent areas due to stress concentration and larger strains) was studied in this paper.

Over the last three decades various investigators have studied the seismic performance of pipelines and have proposed several analytical and numerical methods to quantify the pipe response under wave propagation. The oldest and simplest analytical method was based on the assumption that the maximum axial strain of buried straight pipeline was equal to the maximum strain of the surrounding soil (Newmark 1967). In relation to Newmark's assumption, another closed form solution was developed, indicating that effects of inertia forces on dynamic response of straight pipes are negligible (Takahashi and Sakurai 1969). The study on straight buried pipes was advanced (Shinozuka and Koike 1979; O'Rourke and El Hamdi 1988) in order to simulate the interaction of soil and pipe more accurately where soil is modeled as linear elastic or elasto-plastic spring.

The behavior of buried pipes with elbow has also attracted attention by several researchers. According to Shah and Chu (1979), Shinozuka and Koike (1979) and Goodling (1983) various closed form solutions for evaluations of pipes' responses in their bent areas were developed using beam on elastic foundation theory. Also, referring to Kouretzis et al. (2006) another analytical formulation to investigate the buried pipelines under incident shear waves has been developed. In parallel, numerical methods have been also employed to analyze the straight buried pipelines and different results were extracted (Takada and Tanabe 1987; Takada and Katagiri 1995; Halabian et al. 2008; Vazouras et al. 2010). Evaluations of strains in bent regions (Ogawa and Koike 2001) and a quasi static research on embedded pipes with right angle elbows (O'Rourke and Mclaughlin 2003, 2009) are instances of numerical investigations on buried bent pipelines. According to the literature, most of research has been focused on pseudo-static analyses and less attention has been paid to numerical time history studies on behavior of buried elbow pipes. In the present research, the effect of bend angle, burial depth, and diameter to thickness ratio (*D/t*) on the pipe's deformations and induced strains were examined for assumed pipe models buried in different soils.

2 3D FEM NUMERICAL MODELING

In order to get insight into the non-linear behavior of buried pipelines in the elbow areas and to examine the affecting parameters such as the pipe dimensions and elbow geometry, some three dimensional (3D) finite element models (FEM) were developed. In these 3D FE models, the pipe was modeled using beam elements, while Winkler theory was adopted to take soil-pipe interactions into account. The burial depth (H) and elbow radius were assumed 1.5m from the ground surface to the pipeline center and 3*d*, respectively; in which *d* is the pipe's diameter. The mechanical properties for the pipe taken from API-5L (American Petroleum Institute 2000) are summarized in Table 1.

Table 1. Mechanical properties of pipe.

Pipe type	**Diameter (mm)**	**Thickness (mm)**	**Mass density (Kg/m^3)**
Steel- API-X65	400	9.5	7850
Elasticity modulus E(GPa)	**Poisson ratio (υ)**	**Yield Stress σ_y (MPa)**	**Ultimate Stress σ_u (MPa)**
210	0.3	465.4	517.7

In this study, sandy and clayey soils with different strength properties were assumed as burial domain for pipes elbows. Tables 2 and 3, show the characteristics of sandy and clayey soils used in FE modeling.

It can be expected that soil-pipe interaction have a fundamental influence on pipe response against incident waves. Adopting Winkler theory, the surrounding soil has been simulated by a number of nonlinear spring elements around the pipe in three perpendicular directions. ALA (American Lifeline Alliance 2001, 2005) standard was employed to express the load–displacement relations for nonlinear springs.

The axial, transverse horizontal and transverse vertical soil bilinear force-displacement relationship (t-x, p-y, and q-z curves) are shown in Figure 1, in which t_u, p_u and q_u are the maximum soil forces in soil-pipe interface and x_u, y_u and z_u are the corresponding displacements. The soil-pipe slip as well as soil hardening in cyclic loadings can be simulated by nonlinear springs employed in this paper.

Since nonlinear springs act only in compression, therefore, to take the soil-pipe interaction into account properly, the springs were imposed to the model in both sides of the pipeline (Figure 2).

Table 2. Material properties of sandy soils.

	Soil type		
	Loose sand	**Medium sand**	**Dense sand**
Unit weight (KN/m3)	14	18	22
Internal friction angle φ (degree)	28	35	45
Friction angle between pipe and soil (degree)	17	21	27
Average shear wave velocity V_S(m/s)	75	220	450

Table 3. Material properties of clayey soil.

	Soil type		
	Soft clay	**Medium clay**	**Stiff clay**
Unit weight (KN/m3)	16	18	21
Shear strength S_u (Kpa)	10	50	200
N'_{70}	0-2	6-10	20-30
Average shear wave velocity V_S(m/s)	75	220	450

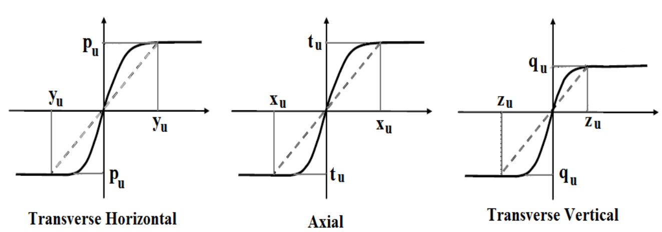

Figure1. The force-displacement behaviour of soil springs.

2.1 Modeling of Far Field and Input Ground Motions

To reach an accurate simulation, the length of each elbow leg should be taken to be infinite. However, due to computational problems, the modeling of the pipeline

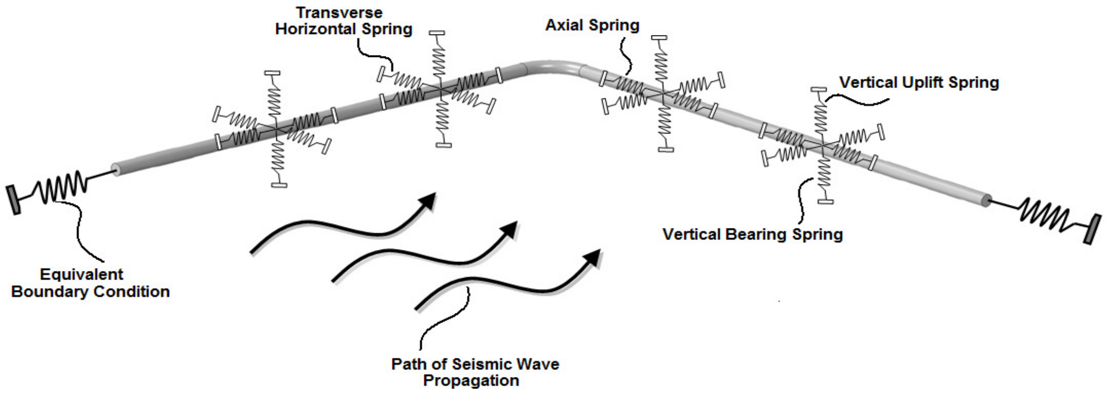

Figure 2. Schematic arrangement of the soil spring around the pipe and boundary condition.

with this assumption could be time consuming and therefore a different assumption for the far field should be considered. Accordingly, the part of the pipe, which is located on both sides of the elbow, assumed to have only axial elongation and can be modeled using beam elements supported by spring elements representing the pipe-soil interaction. The far ends of these parts of the pipeline are assumed to have fixed boundary, as in this region the pipe experiences very small axial strains.

To avoid the error analysis caused by the forced boundary (instead of using fixed boundary at the end of the beam segment of the pipeline) the equivalent boundary condition proposed by Takada et al. (2004) was adopted in this study. They assumed that the lateral deformations of pipe far from the elbow part do not affect the elbow part and only the longitudinal friction existed. The friction force along the straight part of the pipe stemming from axial force can be divided into two parts: (a) The static friction, (b) the slip friction. The static and sliding soil friction are expressed by Eqs. 1 and 2, respectively:

$$f = Ku \qquad [1]$$

Where, f is the static soil friction per unit length, u is the relative displacement between the soil and the pipe, and K is the stiffness of soil spring along axial direction.

$$f_s = 0.75\pi D H \gamma_s \mu = K u_0 \qquad [2]$$

In Eq. 2, f_s is the sliding soil friction per unit length, D is the pipe diameter, H is burial depth, γ_s is the weight density of surrounding soil, μ is the frictional coefficient, and u_0 is yield relative displacement between the soil and the pipe.

The total axial deformation of the buried pipe (ΔL) under axial force F is equivalent to a nonlinear elongated spring force. The relationship between axial force F and longitudinal extension ΔL is indicated by Eq. 3:

$$F(\Delta L) = \begin{cases} \sqrt{\dfrac{3EAf_s}{2} U_0^{-\frac{1}{6}} \Delta L^{\frac{2}{3}}} & 0 \le \Delta L \le U_0 \\ \sqrt{2EAf_s\left(\Delta L - \dfrac{1}{4}U_0\right)} & U_0 \le \Delta L \le \dfrac{\sigma_y^2 A}{2Ef_s} + \dfrac{U_0}{4} \end{cases} \qquad [3]$$

Where E is the soil modulus of elasticity, A is the pipe cross section area, and σ_y is the yield stress of the pipe material.

3D elbow pipeline models introduced in this study were subjected to different earthquake excitations to examine the effect of wave propagation on their behavior. The ground motions characteristics including the frequency content, the soil shear wave velocity, and the Peak Ground Acceleration were given in Table 4. In this study, to highlight the severity of the ground motions, the pipes assumed to be buried in soil with shear wave velocities, which corresponds to the selected ground motions sites. The records were also chosen in a way such that the frequency content of each individual record matches the pipeline-soil system's frequencies. A material damping ratio equal to 4% of critical damping has also been considered. It includes Rayleigh type damping with α and β coefficients for mass and stiffness proportional damping, respectively. Modal analysis was performed to discover the modes with important contributions. Therefore, the aforesaid coefficients have been computed through the results obtained from the analysis.

Table 4. Characteristics of input ground motion.

Earthquake	Station	Shear wave velocity, Vs (m/s)	Peak Ground Acceleration (g)
Chichi	CHY041	Vs<180	0.639
Chichi	CHY028	180 <Vs< 360	0.821
Chichi	CHY080	360 <Vs< 750	0.968

Northridge	Montebello-Bluff Rd	Vs<180	0.179
Northridge	LA-Centinela St	180 <Vs< 360	0.465
Northridge	Santa Monica City Hall	360 <Vs< 750	0.883

3 NUMERICAL RESULTS OF PARAMETRIC STUDY

There is no consensus on the minimum required modeled length of pipe legs _in far distance with the elbow_ to analyzing the bend. Thus, in order to evaluate the influence of the boundary condition on the pipeline's response, a number of models with various lengths with far field boundary conditions have been analyzed. The length of straight part of the pipeline was evaluated using some preliminary analyses and the results showed if the end boundary condition is assumed to be fixed, 800*D* is a sufficient length for accurate evaluation of the elbow's response. The preliminary analyses also stated the 400*D* is the case when the axial spring is used as the end boundary condition. In this study to optimize the cost of computations, the length of 400*D* for the straight parts of the models along with equivalent boundary was employed.

In the current paper, a number of numerical models of buried elbow pipes with different geometries were developed to assess the magnitude of strains induced in the elbow region as well as the pipe-soil slippage. The effect of geometrical properties such as bend angel, the diameter to thickness ratio (*D/t*) and the embedment ratio (*H/D*) were investigated throughout a comprehensive study. The travelling of seismic waves was assumed to be parallel to one of the pipe's legs (Figure 2). This assumption causes time lag in vibration of different points of the model. It is noteworthy that all the parameter variations, determined in the following sections, were evaluated using the mentioned characteristics of the pipe model in Section 2.1 as the base model. The axial strain values were normalized by the yield strength (ε_y) of the pipe material which is assumed to be 0.002.

3.1 Effect of Bend Angle

In this section the effect of elbow angle on elbow's axial strain, which have different soil types, were investigated. The results were presented in Figure 3. The variations of elbow angle were assumed to be 90° to 180° in the present study. As it can be seen from Figure 3, the values of axial strain induced in the elbow areas tend to

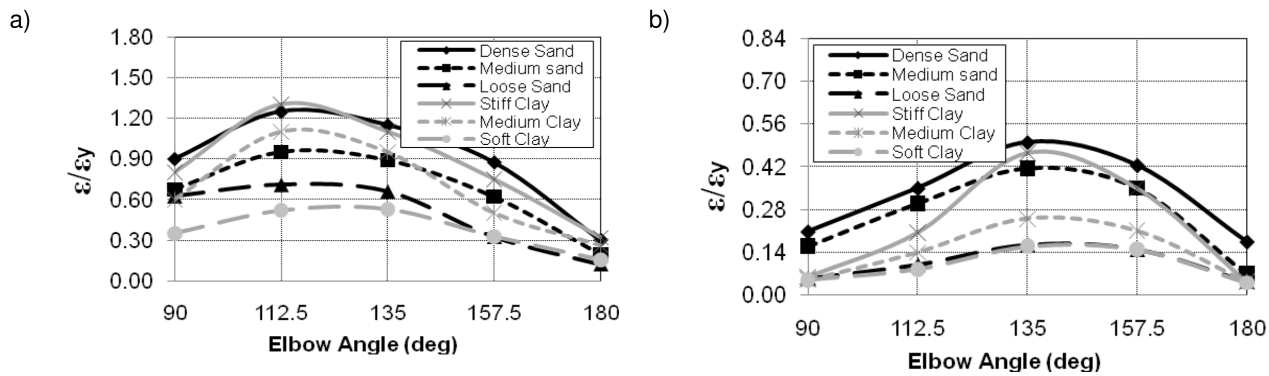

Figure 3. Effect of elbow angle on maximum axial strain in bend for various surroundings soil (H=1.5m, D=0.4m, t=0.0095m); (a) Chichi earthquake, (b) Northridge earthquake.

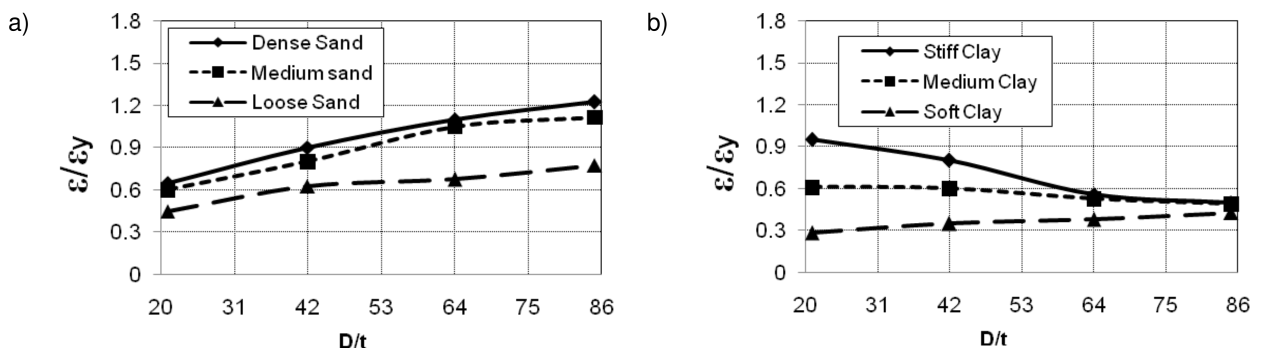

Figure 4. Effect of D/t ratio on maximum axial strain at elbow of buried pipe in different soil (H=1.5m); a) sand, Chichi earthquake, b) clay, Chichi earthquake, c) sand, Northridge earthquake, d) clay, Northridge earthquake. (to be continued)

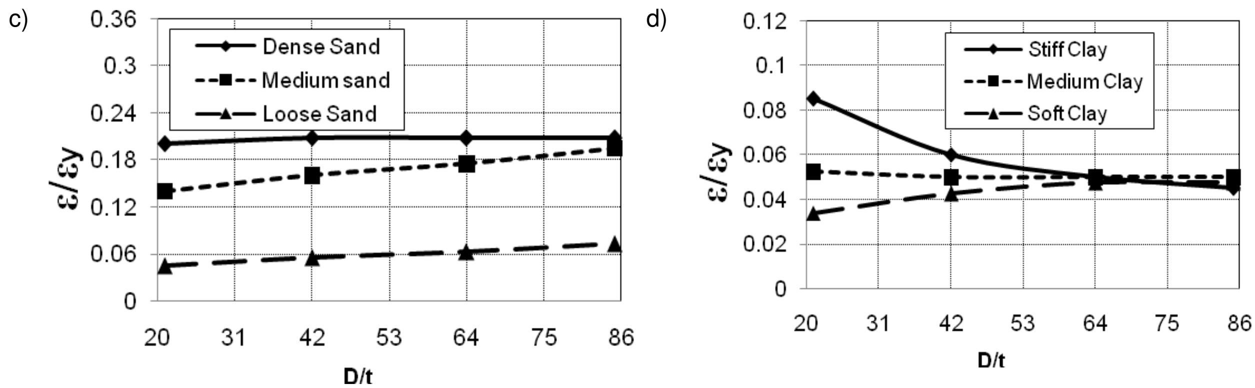

Figure 4. (Continue)

be increasing bend angles around 135° in most of cases studied here. Furthermore, the strain responses of buried steel pipe increased in stiffer soil in which the yielding occurred.

3.2 Effect of Aspect Ratio on Pipe's Strains

The effect of diameter-to-thickness ratio (*D/t*) on elbow's strain was also examined. A 90° elbow was selected to be studied in this section. In sandy soil, an increase of *D/t* ratio leads to a growth in induced axial strains in the pipe bend. Cohesion properties significantly affect the behavior of embedded piping system in cohesive soils. The discussions above are supported by Figure 4. As it can be seen the maximum induced strains in the elbow is inversely proportional to the *D/t* ratio for stiff clay and directly proportional for soft clay.

3.3 Effect of Embedment Ratio

In order to examine the effect of embedment ratio (buried depth (*H*) to pipe diameter (*D*)), on maximum axial strains in the elbow, a soil-pipe system with 90° bend was selected. Other characteristics of the pipeline system are according to Table 1. As indicated in Figure 5, the *H/D* ratio has a slight influence on the maximum

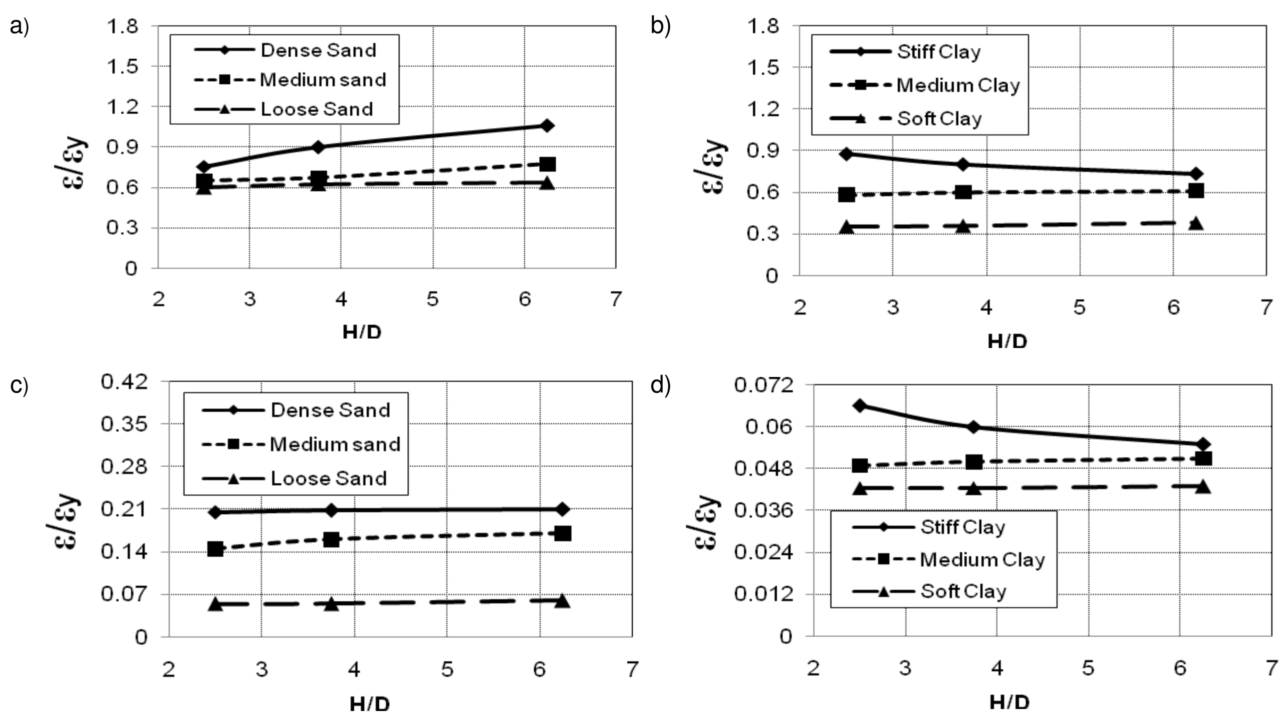

Figure 5. Effect of embedment ratio on maximum axial strain at elbow of buried pipe in different soil (D=0.4m, t=0.0095m); a) sand, Chichi earthquake, b) clay, Chichi earthquake, c) sand, Northridge earthquake, d) clay, Northridge earthquake.

strain response compared to the other mentioned parameters in the previous sections. However, further investigation into the results illustrated that there is a direct dependency between strain response in the bend and embedment ratio for buried pipelines in non-cohesive soils. The cohesion properties affect the behavior of the buried pipe in cohesive soils as it was stated earlier. For cohesive soils, again, a changing trend similar to the *D/t* effect on the elbow's strain is observed. In other words, raise in the embedment ratio results in a decrease in the elbow strains for buried pipes in stiff clay, while the results in soft clay are different.

3.4 Pipe-Soil Slippage

Figure 6, shows the maximum axial relative displacements of the pipeline system with various bend angles subjected to different earthquake ground motions. The effect of soil types on slippage of the pipe in soil was also considered. As observed from Figure 6, the bend angles corresponding to maximum axial strain (Section 3.1) generally lead to minimum slippage between pipe and soil. Furthermore, particular emphasis is placed on the pipe slippage in softer soils. As it was shown in the results, the soil with low stiffness experiences more slips compared to stiffer soil. In stiff soil, the displacements of pipe and ground are roughly equal, so the minimum slippage values are obtained in high stiffness soils. Accordingly in most cases, the maximum axial strain at elbow area occurred in stiff soils, as illustrated in previous sections. In addition, the values of slip in sandy soils are larger than clayey soils because the relative displacement between soil and pipe is nearly prevented by cohesion properties.

4 CONCLUSIONS

A parametric evaluation of buried pipeline with elbow subjected to earthquake excitation was performed by the time history analysis. The effects of soil properties, bend angles, pipe diameter to thickness ratio, and embedment ratio on response characteristics (e.g. the maximum axial strain in bend and pipe-soil relative displacement) were analyzed. Followings can be discussed as conclusions:

- Increasing the surrounding soil stiffness raises the strain response of pipe in bent region because of approximately similar deformations of soil and pipe.
- The majority of maximum axial strain values occurred in vicinity of 135˚ elbow angle.
- The elbow strains response of buried pipes are more sensitive to combination of *D/t* ratio and soil types.
- Increasing the embedment ratio up to practical limit would have no significant effect on the results.
- The bend angles corresponding to maximum axial strain generally lead to minimum slippage between

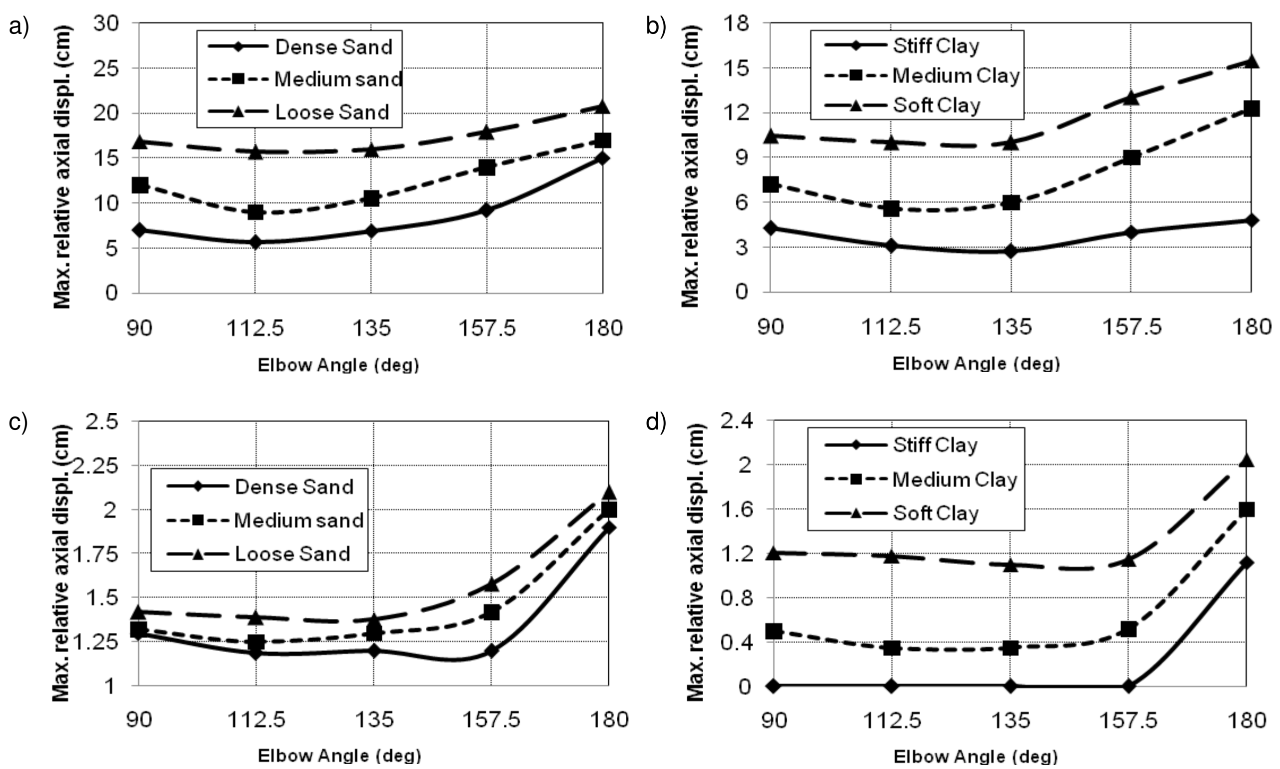

Figure 6. Effect of soil types and different elbow angles on maximum relative displacement between soil and pipe under earthquake loading (H=1.5m, D=0.4m, t=0.0095m); a) sand, Chichi earthquake, b) clay, Chichi earthquake, c) sand, Northridge earthquake, d) clay, Northridge earthquake.

pipe and soil. In addition, decreasing the surrounding soil stiffness raises the values of slippage between the soil and the pipe.

- The values of axial strains in buried pipes under wave propagation exceed the yield limit in some cases but do not reach the ultimate strength.

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