Impact of spatial variability of earthquake ground motion on seismic demand to natural gas transmission pipelines

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Abstract

In the past decades, a number of major earthquakes caused serious damage to natural gas pipeline networks. In most cases, the devastating effects were caused by permanent ground displacement. However, there exist at least two well documented cases (Mexico City and Northridge Earthquakes) where damage were due to seismic wave propagation. Response of buried pipelines is significantly different from that of above-ground structures. However, similarly to bridges or dams, pipelines are also prone to the effects of spatial variability of earthquake ground motion due to their length, which, in some cases, extends beyond national borders.

This paper focuses on the effects of asynchronous excitation on the seismic response demand of natural gas pipelines belonging to transmission networks. Parameters examined include time delay due to finite wave propagation velocity and loss of coherency along the pipelines' length, a parameter known to contribute to seismic strains. Impact of local site effects on pipeline response is examined through the use of bedrock-soil surface slope that forms a basin, with impedance ratios varying with depth. Finite element analysis and lumped springs are used to model the interacting soil-pipeline system while excitation input motions are generated through 2D site response analyses. The paper summarizes the effects of various parameters on seismic demand to pipelines.

The results indicate that ignoring the wave passage effect, the stress state in the pipeline is roughly symmetric, with the axial strains of the pipeline to be increased over the inclined sides of the basin and to be almost null in the middle. When the wave passage effect is incorporated in the analysis the stress state is no longer symmetric and the location of the maximum strains in the pipeline moves towards the central region of the basin but near to the inclined edge from which the seismic waves are coming. The comparison of the computed axial strains with the respective strains used in conventional design processes showed that in the case of irregular subsurface topographies the conventional may result in unconservative design.

Keywords: buried pipelines; asynchronous excitation; basin effects; 2d-site response analysis

1. Introduction

During the last decades, special attention has been paid to the structural safety of Natural Gas Pipeline Networks, mainly due to the increasing need for energy supplies all over the world. These complex infrastructure systems consist of various components, each one of them being responsible for a specific task during the gas transmission process [1]. Buried pipelines are the basic and at the same time weakest components in terms of seismic safety; their response is significantly different from that of above-ground structures due to their design being based on the estimation of ground strains and their inertial forces being negligible. In addition, as it also is the case with bridges or dams, pipelines are prone to the effects of spatial variability of earthquake ground motion due to their length, which, in some cases, extends beyond national borders. Therefore, their potential failure or loss of serviceability can have a disproportional direct or indirect socio-economic impact on the affected area.

Historically, a number of major catastrophic earthquakes have caused serious damage on lifeline networks and particularly on Natural Gas pipelines [2], [3]. In most cases, the devastating effects on buried pipelines were caused by permanent ground displacements due to the failure of the surrounding soil (fault movements, landslides or liquefaction), and therefore the observed damage were localized. However, there are also some well documented cases where seismic damage was attributed to the wave propagation hazard (Michoacan 1985, Northridge 1994) [4], [5]. In these cases, a combination of parameters related to the spatial variability of earthquake ground motion such as the peak ground acceleration (PGA), the peak ground velocity (PGV), the non-uniformity of the ground as well as the structural characteristics were the causes for the damage found at several locations along the pipelines' length [4], [6], [7]. Past experience has also proved that areas with variable subsurface conditions are more susceptible to damage on pipelines since the field of wave propagation velocity at those areas is more complex than in the case of uniform soil layering [8]–[10].

The literature has proposed a lot of methods for the seismic response analysis of buried pipelines. Each method adopts a different level of simplifications in order to overcome the complexity and computational cost of the analysis on the integral dynamic system (pipeline & surrounding soil). These simplifications are related to the relative displacements between the pipeline and the soil, the inertial forces, the soil-pipe interaction and the seismic waves. Ignoring the inertial forces of the pipelines and considering that they conform to the ground displacements, Newmark (1967) calculated the ground strains parallel to a pipeline's axis due to the wave passage effect (P & S-waves). The minor importance of inertial soil pipe interaction was also confirmed by the analytical study of Sakurai & Takahashi [11] who examined the effects of longitudinally propagating waves on straight pipelines, ignoring, however, the potential slippage at the soil-pipe interface. The latter was investigated by Shinozuka and Koike [12], O' Rourke & El Hmadi [13] and Ogawa & Koike [14]. The pioneering work of Newmark was extended by Kuesel [15] and Yeh [16] who examined different angles of wave propagation in relation to the orientation of the structure. Yeh [16] examined the effects of surface waves as well. O' Rourke & El Hmadi [13] pointed out that the strains due to Rayleigh waves can be larger than those due to body waves, and proposed the design strain to be the frictional strain which matches to soil strains derived from R-waves propagation.

Methodologies which considered pipelines as beams on elastic foundation have been also presented. Hindy & Novak [17] studied the buried pipeline seismic response using a lumped mass model and taking into account the dynamic soil-pipe interaction through a spring dashpot system. They concluded that there are cases (when a pipeline crosses different mediums) for which the neglect of SSI effects can result in unconservative design. Following a similar process, Mavridis & Pitilakis [18] highlighted the significant effects of soil-pipe interaction for the axial analysis. Apart from the deterministic approach, Hindy & Novak [19] examined the buried pipelines' response under random and partial correlated motions, described by specific power and cross power spectral densities, using a distributed mass model. Their study was extended by Datta & Mashaly [20] using a lumped mass model and solving the problem in the frequency domain. John & Zahrah [21] presented mathematical expressions for the calculation of forces that are applied to stiff pipelines in relation to the surrounding soil under transverse horizontal and vertical shear waves. The axial and transverse response of continuous pipelines under random earthquake motion was also investigated by Zerva et al. [22] who pointed out the significance of partially correlated motions on the pipelines mode excitation.

Models based on shell theory have also been developed in order to describe phenomena related to the cross section of pipes, such as local buckling and ovalization. Usually, pipelines are modeled as cylinder shells embedded in an elastic, homogeneous and isotropic medium. Following this process, Muleski & Ariman [23] investigated the effect of a set of parameters on pipelines' response, taking into account the attenuation effect of the motion. Wong, Datta & Shah [24], [25] studied the three dimensional motion of long continuous pipelines under body and Rayleigh waves, while Liu et al. [26] investigated the potential effect of the backfill on the dynamic response of a pipeline due to P and SV waves. More recently, using the 3D shell theory and ignoring the potential soil-pipe interaction, Kouretzis et al. [27] calculated the axial, hoop and shear strains over the entire cross-section of a pipe embedded in either uniform ground or in soft soil over bedrock under shear wave excitation. This method was extended for Rayleigh wave propagation too [28].

More sophisticated methods have been also proposed in the literature [29]. Some of them are based on the Boundary Element Method and the Finite Element Method in order for the three dimensional soil-pipe interaction problem to be solved in the time domain [30]. Zhang et al. [31] used a combination of BEM and FEM in order to calculate the ground response across the surface of a valley. Using the FEM Nishio et al. [32] and Ando et al. [33] examined the amplification response due to the soil-rock interface inclination, while Liu & O 'Rourke [34] verified through FEM their simplified method for the estimation of ground strains in such regions. It is almost evident that this complicated field of strains can affect the response of buried pipelines crossing such areas. Similar results were found for pipelines on submarine slopes [35].

Methods for the simulation of seismic ground strains that are applied at buried pipelines have been also used. Zerva [36] investigated the contribution of spatial incoherence to seismic strains comparing strain time histories simulated through the frequency-wavenumber spectral representation method [37] with velocity time histories divided by the apparent propagation velocity. Recognizing the significance of surface layer stochasticity on strain estimates, Zerva & Harada [38] proposed an approach for the considerations of spatial variation of the motion on buried pipelines response.

Although the seismic codes recognize the potential effects of wave propagation hazard on buried pipelines, they do not provide any guidelines for pipelines crossing a site with irregular subsurface topography. More specifically, in Annex B of EC8-part 4 two methodologies are provided; (a) different wave trains, with characteristics that correspond to the region of interest, are constructed, and they are applied as input motion on the pipelines, which are connected to the soil through radial and longitudinal springs, ignoring any dynamic effect, and (b) the Newmark's method (1967) which is based on the apparent propagation velocity of the waves. The latter methodology is also the only one provided by the American Lifeline Alliance [39] for the estimation of axial strains on a pipeline under wave passage effect.

The objective of this paper is to study the effects of asynchronous excitation on the seismic response of natural gas pipelines belonging to a transmission network. The impact of local site effects on pipeline response is examined through the use of a bedrock-soil surface slope that forms a basin, with impedance ratios varying with depth. Finite element analysis and lumped springs are used to model the interacting soil-pipeline system while the excitation input motion is generated through a two dimensional site response analysis. The paper summarizes the effects of this irregular topography on seismic demand on the basis of axial strains.

2. Description of the examined case

The differences in amplitude, phase and frequency content among the ground motions recorded along a pipeline are almost self-evident and physically justified. The differences are due to [40]: (a) the wave passage effect, (b) the loss of coherency of seismic waves as a result of multiple reflections, refractions and superpositions within the soil medium, (c) the local site effects (d) the attenuation of seismic waves and (e) the relative flexibility of foundation–soil system [41]. Therefore, it is practically impossible to predict the input motion along an extended structure in a deterministic manner or to generate uniform scenarios triggering the same features of structural response under multi-support excitation [42]–[44].

Plenty of methods based on the stochastic process theory have been presented for the simulation of spatially varying ground motions ([45]–[48] among else). However, in the case of non-uniform sites and especially in those with irregular surface or subsurface topography, for which the 1D wave propagation assumption is not valid, questions are raised about the appropriate simulation of the motion with respect to the amplitude, the apparent propagation velocity (which cannot be considered constant) and the loss of coherency model (site conditions, isotropic/anisotropic random field).

Therefore, in the present paper the variability of input motion along a pipeline that crosses a multi-layered soil basin is examined with the development of a finite element model under 2D plane-strain conditions, which incorporates all the lateral geotechnical heterogeneities. It is important to mention that this study is restricted to the examination of SH-wave propagation. Subsequently, having estimated the input excitation motion at the pipelines' depth, the effect of asynchronous excitation is investigated through the use of a beam element model that accounts for the interaction with the surrounding soil through appropriate springs. Two different cases are examined. In the first case, the spatial variability of ground motion is considered to be due to the incoherency and the local soil condition effects (CASE A), while in the second case, the wave passage effect is also examined (CASE B). In the latter case, the time delay of the motion is applied at the beam element model considering a Vapp=500m/sec.

The cross section of the pipeline under consideration, its burial depth, as well as the 2D cross section of the basin that the pipeline crosses are illustrated in Fig.1. More specifically, a steel continuous pipeline with a diameter of 1.00 m and thickness equal to 0.03m is considered to be buried at a depth of 1.50 m to pipe centerline. The valley is considered to be symmetric, with a width of 180m length and a maximum depth of 57 m. The inclination angle of the soil-bedrock interface at its two edges is equal to 60°. Four soil layers of different thicknesses overlie the bedrock. The shear wave velocity profile is increased with depth, resulting in different impedance ratios between the consecutive layers.

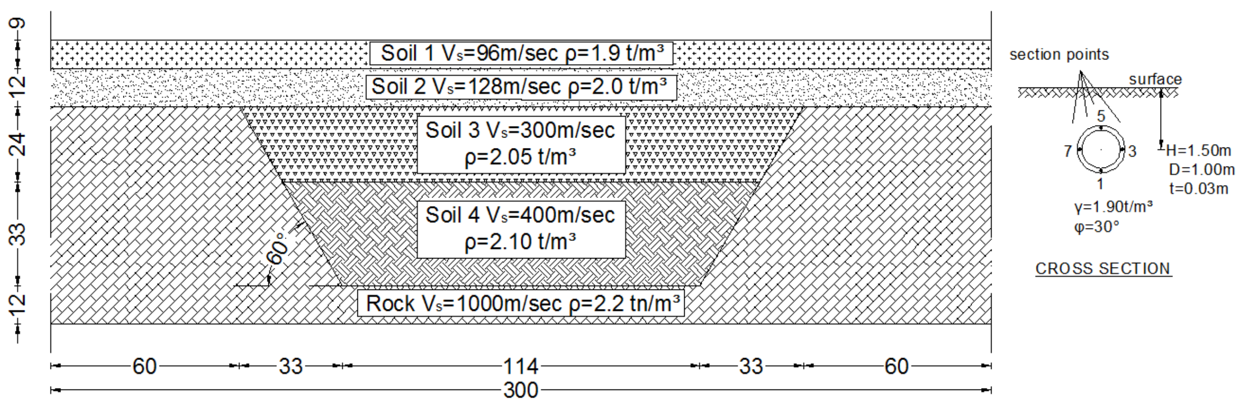

Fig. 1 – 2D cross section of the considered (hypothetical) basin that is crossed by the examined buried pipeline

3. Development of the Finite element model

A two-dimensional finite element model of the irregular topography site of Fig.1 was developed in ABAQUS 6.10. The simulated soil domain is 300 m long and 90 m deep. The model considers 7358 elements, 7090 nodes and 14180 degrees of freedom. The model (Fig.2) is used for the calculation of the input motions that excite a pipeline which is buried 1.00m deep (1.50m deep to its centerline) along its longitudinal and vertical direction.

3.1. Soil

The soil along with the lateral geotechnical heterogeneities was simulated assuming plane strain conditions. The whole domain was discretized using four-node, bi-linear plane strain elements, considering the soil to be linear elastic. The material properties assigned to each layer are in accordance with its shear wave velocity and density that correspond to low-strain values, all presented in Fig.1. It is important to mention that in the present study any potential difference of the backfilled material properties with the in-situ soil was neglected. Special attention was paid to maximum element dimensions; bearing in mind that at least 8 nodes are needed for the accurate description of a wavelength, the maximum element size was selected with respect to the shear wave velocity of each layer, in order for the propagation of shear waves up to 8 Hz to be described accurately.

3.2. Boundary conditions & input excitation

Since the simulated computational domain is only part of ground half-space, boundary conditions along its base and lateral sides are crucial for the avoidance of spurious reflections of outgoing waves. Therefore, all nodes along these boundaries (base & lateral sides) are connected with specific horizontal and vertical Lysmer-Kuhlemeyer dashpots [49]. The first ones absorb the shear and compressive outgoing waves at the base and the lateral edges respectively, while the latter have the exact same function inversed. The dashpot coefficient values (per unit area) depend on the properties (ρ, V_s and V_p) of the material outside the computational domain, as illustrated in Fig.3. Earthquake excitation is applied as equivalent force (per unit area) at each base node using earthquake's velocity time history.

Considering that the shear wave propagation is vertical, the assumption of one-dimensional wave propagation is expected to be valid in a long distance away from the basin. Therefore, in order for the continuity of displacements at the lateral edges of the model to be satisfied, velocity time histories corresponding to the free field region are applied to each free node of the horizontal dampers at the lateral edges (Fig. 3). These time histories are calculated through a 1D site response analysis; an auxiliary finite element model, with the same discretization along the depth as the one in the main model is used. In this model, the nodes at each depth are constrained to be subjected to the same transverse and vertical displacements (Fig. 3).

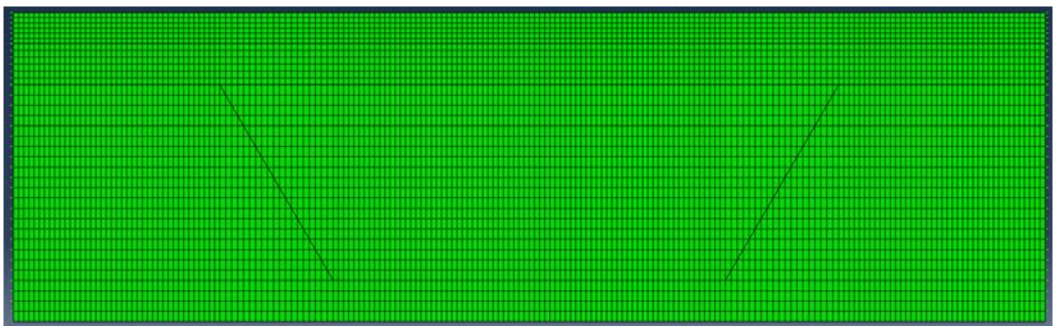

Fig. 2. The finite element model of the basin

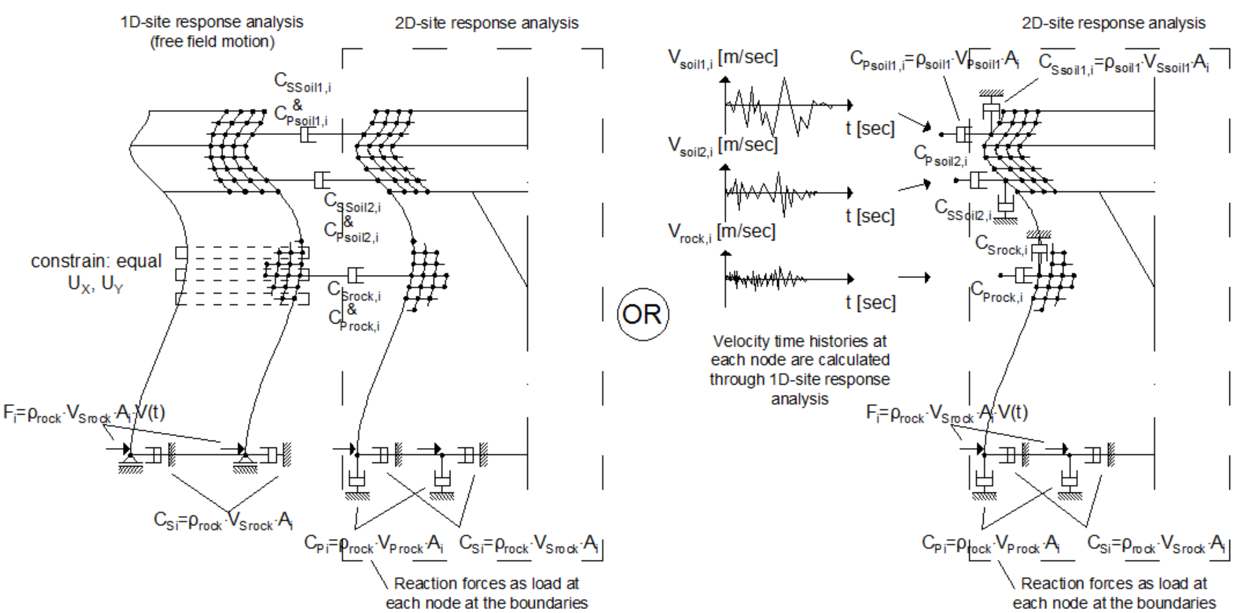

Fig. 3 – Two alternative ways for the simulation of the boundary conditions at the soil computational domain in order to conduct a two-dimensional site response analysis

3.3. Verification of the process

In order to verify the soundness of the results, a simple case of a uniform damped soil on elastic rock is used as a test-bed. It is obvious that the ground motion on the surface, calculated through a 2D site response analysis in the time domain, should be the same with the one obtained by a 1D site response analysis in either the time or the frequency domain [50]. Therefore, a single layered soil is considered with V_s=500 m/sec and a density equal to 1.9t/m^3 while the bedrock properties are the same as in the main model (Fig.1). The Friuli (foreshock) ground motion (06/06/1976, Ms=4.5, station: Tolmezzo-Diga Ambiesta, epicentral distance: 23 km, fault distance: 6 km, local geology rock) was selected as the incident earthquake motion at the model base (Fig.4). Comparison of the three analyses in terms of the horizontal accelerations at the surface is illustrated in Fig.4 and it is concluded that all the time histories match.

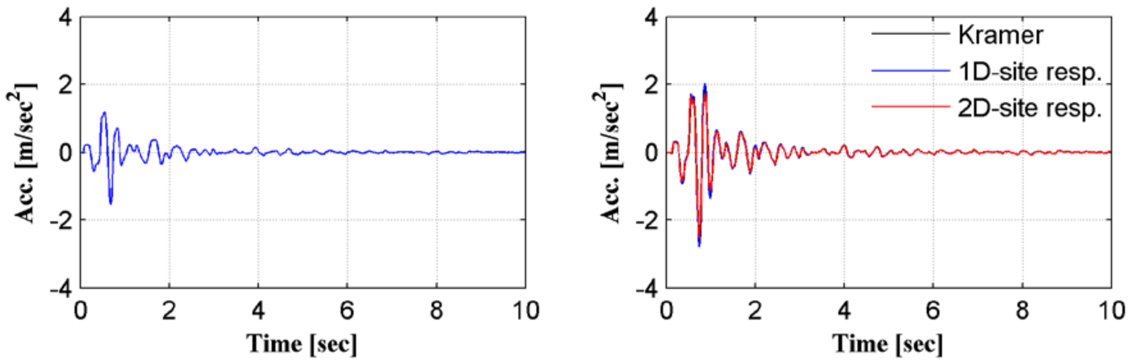

Fig. 4 –Left: The Friuli (foreshock) ground motion (06/06/1976, Ms=4.5). Right: Time histories on the ground surface computed through 2d site response analysis in time domain and through 1d site response analysis in time and frequency domain (Kramer)

4. Calculation of the input motion

The Friuli (foreshock) ground motion (06/06/1976, Ms=4.5, station: Tolmezzo-Diga Ambiesta, epicentral distance:23 km, fault distance:6 km, local geology rock) [51] was applied synchronously as an equivalent force (per unit area) at each node of the base in the finite element model of Fig.2. Therefore, the differences observed at the ground motion of the surface across the basin are solely due to the loss of coherency of the seismic waves.

The horizontal acceleration time histories computed for vertical incidence of the SH waves at each node of the surface across the basin are depicted in Fig. 5. An amplification of the SH-waves window of the motion is generally observed, especially in the center of the basin, due to the impedance ratios between the consecutive soil layers. Apart from this amplification, generation of laterally propagating surface waves due to the irregular subsurface topography is also detected. These waves compose a complex wave field that elongates the duration of the motion especially in the center of the valley.

Two time histories, one at a distance of 20 m from the left edge of the model and another one in the middle of the basin, are compared in Fig.5. Apart from the amplification of the motion described above, a phase difference is also observed due to the propagation of the waves through two multi-layered soil columns with different shear wave velocities. Under the assumptions of ergodicity and stationarity, the lagged coherency of these records was also estimated (Fig. 5) from the smoothed (11-point Hamming window) cross spectrum of the time series between point 1 & 2, normalized with respect to the corresponding power spectra. It is important to mention that the motions are partially correlated throughout the frequency range, an observation that is in agreement with the results of other studies based on real records about the loss of coherency between stations located inside and outside of a valley.

The computed displacements at a depth of 1.50 m along the horizontal and vertical direction were used for the further examination of asynchronous excitation effects on a buried pipeline across the valley.

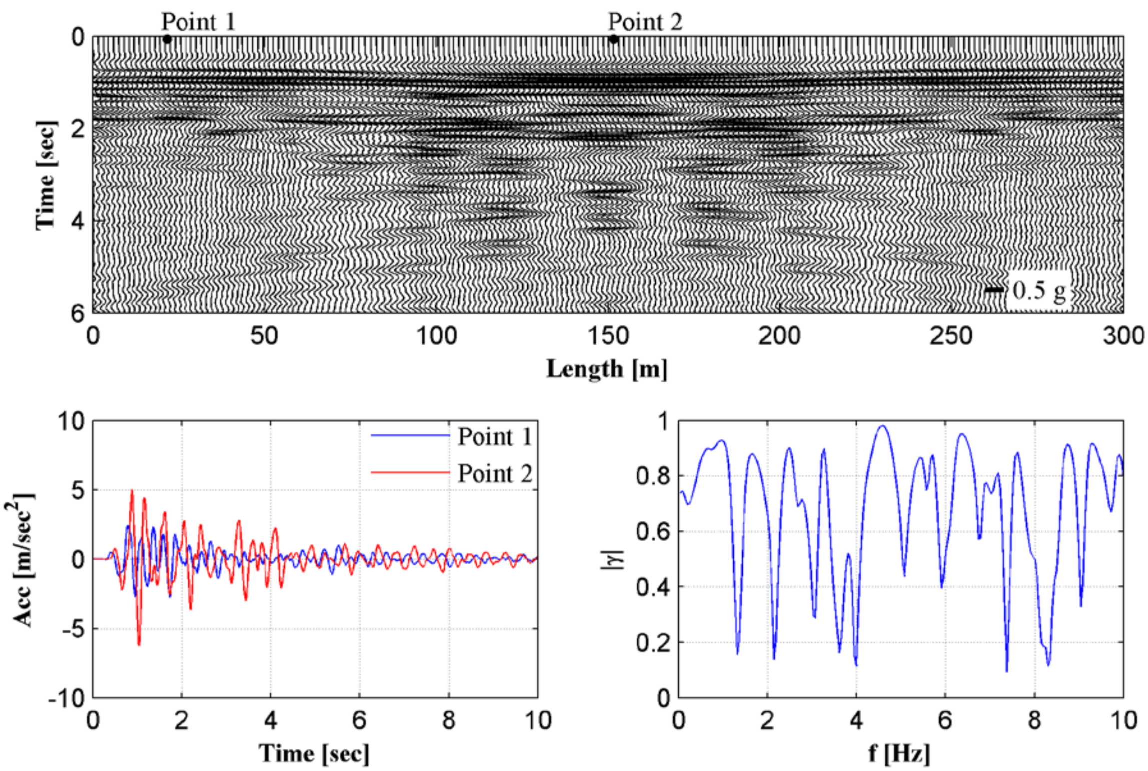

Fig. 5 – Top: The horizontal accelerograms that were computed at the surface of the basin. Left: The horizontal accelerograms computed at the points 1 & 2. Right: The estimated lagged coherency between the records at the points 1 & 2.

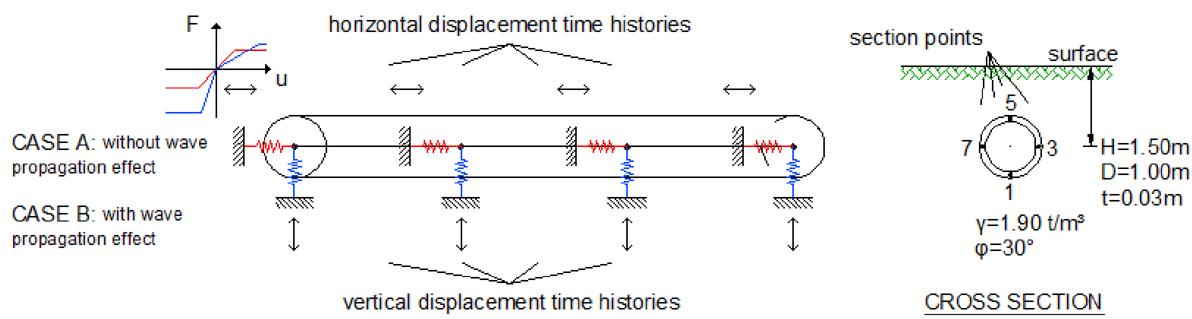

Fig. 6 – The beam element model used. The soil properties and the section points in the pipe's cross section are also illustrated

5. Analysis of buried pipeline

The impact of local site effects on the response of a buried pipeline is studied through a beam element model in which soil-pipe interaction is accounted for through discrete nonlinear springs. The finite element model was developed in ABAQUS using the PIPE31 element. Discretization was performed in such a way, so that the nodes along the pipeline correspond to those of the soil model used for the 2D site response analysis. Two nonlinear springs were used in each node, along the horizontal and vertical directions respectively, according to the Appendix B of ALA [39]. Since the excitation motions along the pipe derived above are along the horizontal and vertical directions, the analysis of the pipeline performed thereafter is restricted in the same plane. The pipeline model is illustrated in Fig.6.

The maximum soil spring forces and the associated relative displacements are computed according to the equations proposed by ALA. These relationships are valid for uniform soil conditions and consider constant soil forces after they reach their maximum values. In the case examined herein, the surrounding soil of the pipe is uniform, irrespectively of the irregular subsurface topography. Assuming that the backfill soil is loose sand, the relationship used for the spring coefficients' calculation along the axial directions is:

$$T_U = \pi D H \bar{\gamma} \frac{1+K_o}{2} tan\delta = \pi D H \bar{\gamma} \frac{1+K_o}{2} tan(f \cdot \varphi) \quad (1)$$

while along the vertical direction, the coefficients for vertical uplift and vertical bearing are calculated respectively through:

$$Q_u = N_{qv} \bar{\gamma} H D \quad (2)$$

$$Q_d = N_c c D + N_q \bar{\gamma} H D + N_\gamma \gamma \frac{D^2}{2} \quad (3)$$

where D is the pipe's diameter, H is the depth to the pipe centerline, γ *and* $\bar{\gamma}$ are the total and the effective unit weight of the soil respectively, K_o is the coefficient of pressure at rest, δ is the interface friction angle between the pipe and the soil that is equal to $f{\cdot}\varphi$, where f is a factor that depends on the material of the pipe, and N_c, N_{qv}, N_q, and N_γ are factors, the values of which can be found in ALA. The displacements needed for the above forces to be developed were calculated as 4 mm, 30 mm and 10 mm for the axial, vertical uplift and vertical bearing directions respectively. The bi-linear soil springs used are illustrated in Fig.7.

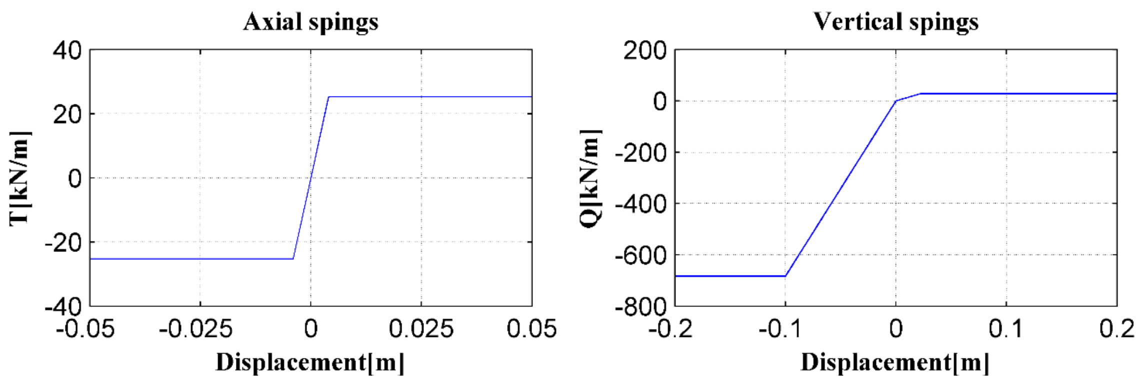

Fig. 7. The bi-linear soil springs that represent the soil-pipe interaction in the examined case.

6. Results

Fig.8 illustrates the envelopes of the axial strains developed along the pipeline for the two cases (without & with time delay) at the four section points of the cross section (Fig. 6). Although the values of the stains are small, there are some interesting observations. First of all, in the CASE A where the time delay of the motion is ignored, the axial strains of the pipeline are small at the two regions above the shallow soil, as well as in the middle of the basin's length, while strain concentrations are found on the pipe at the region over the inclined soil-bedrock interface. More specifically, the envelopes of the strains are roughly symmetric with the largest strains to be found at the distances of 75 m and 225 m from the left edge which correspond to the point where the interface between soil layers 3 & 4 meets the inclined subsurface. This is due to the reflections of the seismic waves on the inclined edges of the basin which result in laterally propagating waves trapped in the valley (Fig.10). For the same reason the axial section force in the middle of the pipe is zero (Fig.9); the antisymmetric trapped waves that propagate laterally are cancelled out at this point (Fig.10).

On the contrary, when the time delay (Vapp=500m/sec) is taken into account (CASE B), the symmetric stress state of the pipeline is no longer valid. As indicated by Fig.8., the main difference takes place in the middle of the pipeline where the axial strains are significantly increased resulting in a axial section force equal to 1MN (Fig.9). The maximum strains are no longer developed in the region of the inclined subsurface; with respect to the direction of wave propagation (left to right or vice versa), the maximum strains of the pipeline are located in the central region of the basin near to the inclined edge from which the seismic waves are coming. In contrast with the axial forces which are increased when time delay is taken into account, bending moments are slightly decreased over the whole length (Fig.10). It is important to mention that the axial forces and the bending moments illustrated in Fig.9 are the maximum values and do not occur simultaneously.

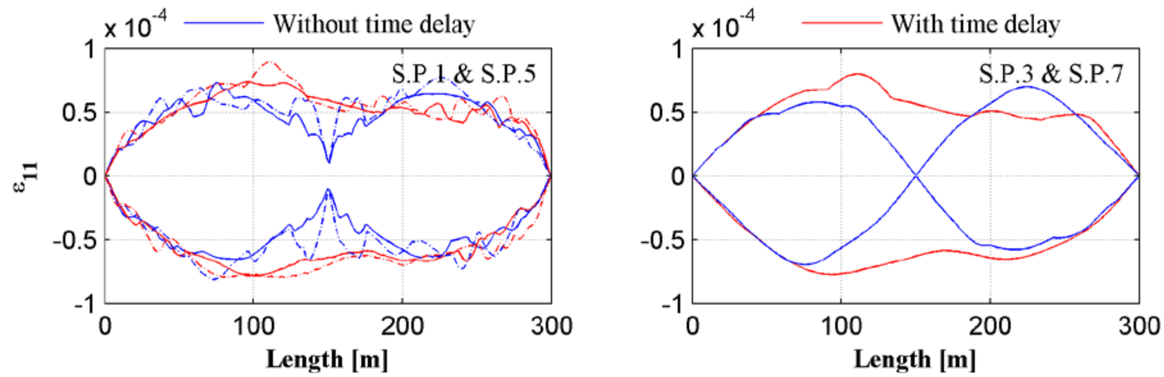

Fig. 8 – The envelopes of the computed axial strains at the four section points of the pipeline's cross section along its length (dashed lines correspond to S.P.5 and S.P.7, same color scheme is used for the two figures)

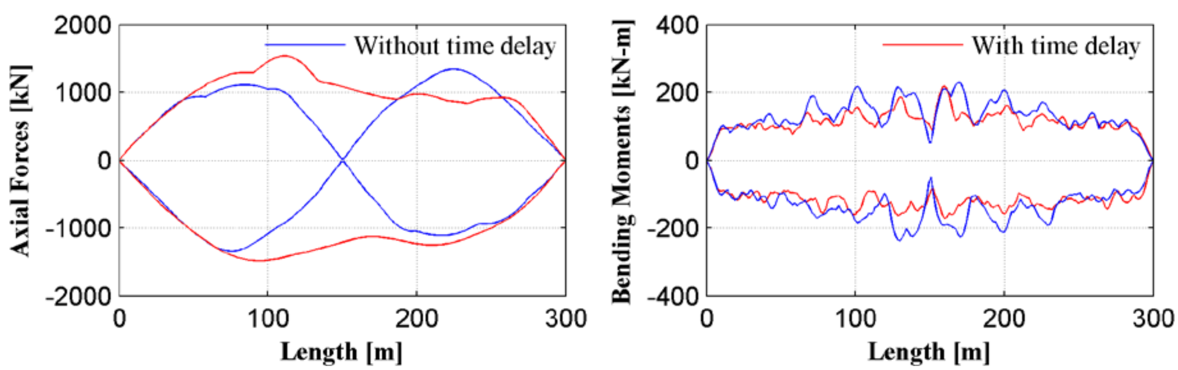

Fig. 9 - The envelopes of the computed axial forces and bending moments at the cross section of the pipeline along its length

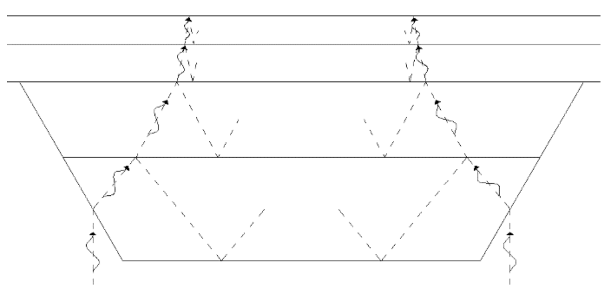

Fig. 10. – Generation of laterally propagating waves that are trapped in the basin

Additionally, in order for the impact of the irregular subsurface topography on the pipeline to be examined, the computed axial strains were compared with the strains that would have been used in a conventional design process. According to ALA, the axial strain on a pipe can be approximated by the following equation:

$$\varepsilon_{\alpha} = \frac{V}{a \cdot C_s}$$

where V is the peak ground velocity (PGV), α is a coefficient equal to 2 if the apparent propagation velocity ,C_s, is estimated with respect to the shear wave velocity while α is equal to 1 if C_s is conservatively assumed to be 2km/sec. Considering the PGV computed at the free field surface (it is equal to 0.166 m/sec) and the apparent propagation velocity that is proposed by ALA, the ratios of the computed over the approximated axial strains along the pipeline are illustrated in Fig.11. It is observed that in the central region of the basin near to the inclined edge from which the seismic waves are coming (at a distance of 110 m), conventional design underestimates the developed strains.

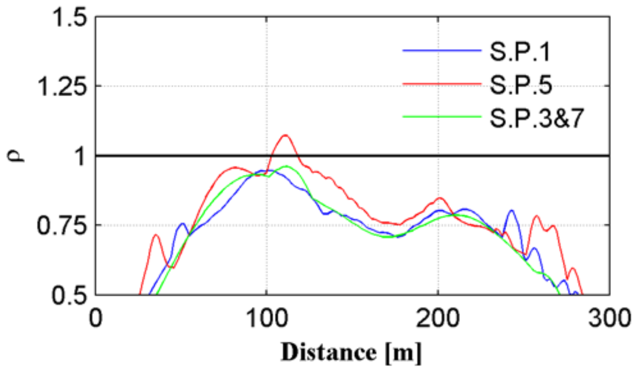

Fig. 11. – Ratio of computed over approximated (ALA) axial strains developed at the cross section of the pipeline along its length

7. Conclusions

In this paper, the potential effect of asynchronous excitation on the seismic response of natural gas pipelines is investigated. More specifically, the impact of local site effects on pipeline's response is examined considering a bedrock-soil surface slope that forms a basin with impedance ratios varying with depth. Assuming plane strain conditions, the ground response of this complex site was estimated through the development of a two dimensional finite element model. Lysmer-Kuhlemeyer dashpots were used at the boundaries in order for the spurious reflections to be avoided, while the earthquake excitation was applied at the base as an equivalent force (per unit area). Seismic displacements along the horizontal and vertical direction at a depth of 1.50 m were computed and used for the study of the impact of asynchronous excitation on a buried pipeline across the valley. Two cases were examined: (a) in the first case, the wave passage effect was ignored and only the effects of the loss of coherency were considered, and (b) in the second case, the effects of time delay and loss of coherency were simultaneously investigated.

The results indicate that when the wave passage effect is ignored, the stress state of the pipeline is roughly symmetric, with the axial strains of the pipeline to be increased over the inclined sides of the basin while being almost null in the middle. This can be attributed to the reflections of the seismic waves on the inclined edges of the basin which result in laterally propagating waves trapped in the valley. On the contrary, when the time delay parameter is also involved, the stress state is no longer symmetric and the location of the maximum strains on the pipeline moves towards the central region of the basin but near to the inclined edge from which the seismic waves are coming. Comparison between the computed axial strains with the respective strains used in conventional design processes showed that in the case of irregular subsurface topographies, conventional strains may lead to non-conservative design.

8. Acknowledgements

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