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Article

The Effect of Three-Dimensional Earthquake P-Wave Propagational Speed on Buried Continues Straight Steel Pipelines

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Abstract. The analysis and design of gas and oil pipelines is of importance given the fact that they are long and go through lands. They are laid besides the faults and sometimes cross the faults. Various studies have already investigated the design process and the damages imposed on the pipelines crossing the faults. The aim of this research is studying the effect of longitudinal wave propagation method on the amount of nonlinear strains of pipeline. In addition, it investigates the effect of wave propagation speed as well as the simplified hypothesis of the same effect of the wave on the pipeline. Many researchers study on modal analyses or two-dimensional analyses. In this paper used three-dimensional modeling with propagational P-wave. It should be mentioned that analyses carried out on both clayey and sandy soil with different propagational speed in each of them. The accuracy of the proposed analyses is validated by the comparison of the proposed solution results with some existing solutions. According to the analyses, it became obvious that in dense soil the amounts of strain are less than soft soil. This amounts to 71 per cent in a sinusoidal wave. The average of the values of the reduced strain in different type of soil could reduce the amount of strain to be considered equal to 0.592 for clayey soils, and equal to 0.61 for sandy soil.

Keywords: Steel pipeline, time history analyses, asynchronous analyses, vibration frequency, and longitudinal wave propagation.

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1. Introduction

The buried oil and gas pipeline is one of the most vulnerable infrastructures. The previous earthquake experiences proved that the transmission pipeline affected by the earthquake in different ways. Perhaps one of the most important effects of an earthquake is on pipelines crossing the faults. Many researchers have investigated the effect of the fault on the pipelines and also investigated the damages resulted from the movement of the faults [1–3]. Datta et al. examined prior research on the impact of the earthquake on the pipeline [3]. They found that although much research did on the effects of faults on pipelines, the impact of random vibration and earthquake on pipelines less studied [3]. Various studies have examined the impact of normal faults [4–6]. Karamitros et al. analytical and numerical abundance of research conducted on the pipeline. They found that the regulation values of strain and stress at the intersection of faults with numerical and analytical values are a good match [5, 6]. Kouretzis et al examined the effect of P waves on the tunnels. They discovered hoop stress is higher in S-Wave in comparison with P-Wave [7, 8]. Sedarat et al. also found similar results [9]. In all the above cases one type of Soil used and the effect of changes in soil type were not studied [9]. The effect of reverse faults have also been studied [10, 11]. Rahim-Zadeh et al. examined the effect of reverse faults on the seismic behaviour of the pipeline's [12]. It found that although the values developed in pipelines in the different locations is acceptably similar to ALA relations, lifting bending forces is over ALA [30]. Then it expanded to include the analytical equations for different lengths of pipe, fault and the impact angle of pipe [6, 13]. Until this time not any buried pipelines which crossing the faults have suffered huge damages [9–16]. Saberi et al. examined the effect of wave propagation on curved pipes [14, 15]. It found that the highest levels of axial strain caused by the angle of 135 degrees in the pipeline and the axial strain values at 90 degrees was less than the angle of 135 degrees [14]. Kouretzis et al. studied the effect of two-dimensional Rayleigh waves [16]. It revealed that Rayleigh wave cause more axial strain and reduce hoop strain in comparison with S wave [16]. Kouretzis et al. studied the effect of wave propagation stemming from the explosion [17]. Moreover, different methods of modelling wave propagation in structures also investigated [18–24]. One of these methods was the use of springs to model the soil around the pipe [18, 19]. Asynchronous analysis performed to evaluate the effect of wave propagation in the pipe network of nuclear power plants (which often have different boundary conditions at the ends of the pipes) [20]. Yazdi et al. studied the effect of absorbing boundary condition on wave propagation [22]. For modelling pipe-soil interaction nonlinear spring used [14, 15, 24]. Regarding the issue of wave propagation in modelling, we should model the length of the pipe to mitigate the effect of the end of the pipe on analysis results. Hosseini et al. have calculated the minimum length of pipes based on the soil type around the pipe [25]. It supposed that structures located in areas 2 or 5 times more than the focal depth affect by the body waves. Structures located in areas beyond 5 times more than the focal depth dominate by surface waves.

O'Rourke et al. have presented graphs for changes in Rayleigh wave speed in layered soil profile [26]. Among the surface waves only Rayleigh waves studied for evaluating the effect of wave propagation on the buried pipes. Love waves lead to the bending strain in pipes which is low importance for usual diameters. Whereas longitudinal component of Rayleigh waves is parallel to the propagating direction, which leads to axial strain in the pipe parallel to the wave propagation. The speed of Rayleigh wave is slightly less than that of shear wave. But in normal soil layers in which the soil stiffness increases along with depth, the Rayleigh wave propagational speed depends on the changes in shear wave speed in depth as well as the frequency. Since the bending strain is not important when it comes to the propagation of axial-seismic waves in straight pipelines, only axial strains in the pipe important and affected by this. The aim of this research is the investigation of the effect of P-waves on the amounts of strain in the pipes.

It is seen that in previous studies by Roudsari et al. and other researchers only the modal analyses performed and focused on modal analyses and relationship [33]. In this research the effect of deference in frequency content investigated in two different ways. First, with sinusoidal wave, and second, with the time-history analyses. Many researchers try to avoid using time-history analyses with three-dimensional modelling of pipeline because of time consuming procedure. The main purpose of this paper is to investigate the effect of three-dimensional earthquake P-wave propagation on buried continues straight steel pipes and to determine the effect of propagational speed.

1.1. The Design Strain

The amount of axial strain investigated in various researches [25–30]. Diverse equations proposed for the amount of strain. Power et al. [27] have proposed Eq. (1).

$$\varepsilon_\alpha = \frac{V_{RP}}{C_p} \tag{1}$$

In which V_{RP} the maximum speed of land movement when P-wave emerges which equals to $0.681*V_{max,v}$ and C_p equals to the maximum speed of P-wave movement in the soil and $V_{max,v}$ is the maximum speed of land movement in horizontal direction. When the impact angle is different, Eq. (2) can be used.

$$\varepsilon_\alpha = \frac{V_{RP}}{C_p} cos^2\varphi + r\frac{a_p}{C_p^2} sin\varphi cos^2\varphi \tag{2}$$

$$\varepsilon_\alpha = \frac{V_{RP}}{C_P} \quad OR \quad \varepsilon_\alpha = \frac{V_{RS}}{C_R} \tag{3}$$

φ is the wave impact angle and a_p is the maximum velocity caused by land movement and r is the radius of the pipeline. Also, the amount of design strain equals to Eq. (3) according to the researches[28, 29] in which V_{RS} and V_{RP} are the maximum speed of vertical shear wave SV equalling to $1.0*V_{maxv}$ and the maximum speed of P-wave respectively and C_R equals to the maximum amount of the S-wave movement in the soil.

$$\varepsilon_\alpha = \frac{V_g}{\alpha \times C_a} \tag{4}$$

According to the guideline ASCE-ALA 2005 [30], the seismic design of the buried pipelines based on the maximum amount of the axial strain and approximate amounts calculated based on the Eq.(4) in which V_g is to the maximum speed of land movement equaling to V_{maxv} and C_a equals to 2000 meters per second irrespective of the type of soil and employed as the wave propagational speed in the soil [25].

Also the parameter α used for Rayleigh waves and pressure P-waves equal to 1 and for S-waves equal to 2. As a result, the maximum amounts of strains based on V_g produced by various ranges of earthquakes as shown in Table 1. Gas and oil pipelines go through areas with diverse soils, considering the long length of pipelines. Furthermore, all the analyses carried out in four types of soil given the fact that in most guidelines, including uniform building code 94 (UBC94) soils classified into four groups [35]. It should be mentioned that Eq. (1)–(4) based on the impact angle which leads to the maximum axial-pressure force. Figure 1 demonstrates the wave impacts the pipe and its angles with the pipe. D is the domain of wave propagation. Also the figure shows the amounts of sinusoidal wave which consisted of the wave parallel to the pipe and the wave vertically parallel to the pipe [29].

The amounts gave in the equations in Table 1 based on normalized earthquake spectra. In all cases, the amounts of axial strains calculated by ALA are less than the other equations (since the wave propagation speed is supposed to be 2000 m/s).

Based on laboratory reports presented by Newmark et al. the first sign of local buckling shown in the Eq. (5) in which R is the pipe radius and t is the wall thickness of the pipe [31, 32].

$$0.15\frac{t}{R} < \varepsilon < 0.2\frac{t}{R} \tag{5}$$

Based on researches expanded by Hosseini and Roudsari [33], a new equation introduced to investigate the first point of local buckling for sandy soil (Eq. (6) and (7)). Equation (6) depicts dense sandy soil and Eq. (7) depicts non-dense sandy soil [33].

$$0.17\frac{t}{R^{1.5}} < \varepsilon < 0.26\frac{t}{R^{1.5}} \tag{6}$$

$$0.15\frac{t}{R^{1.1}} < \varepsilon < 0.34\frac{t}{R^{1.1}} \tag{7}$$

Regarding the pipe diameter equaling to 1 meter and its thickness equaling to 1 centimeter, the minimum amounts of the strain to control local buckling is 0.003. Since the aim of this research is to investigate the effect of P-wave propagation on the seismic behavior of steel pipelines, we embarked on investigating impact wave with the impact angle of zero degree.

Table 1 The amounts of the maximum longitudinal strain permitted in design for different waves.

	SOIL TYPE	Loma Prieta	kobe	Imperial Valley	Northridge	Manjil
V_g		1.21	0.8	1.00	0.92	0.34
$\varepsilon_\alpha \times 10^{-3}$ (ASCE-ALA)	I-IV	0.06	0.40	0.50	0.46	0.17
$\varepsilon_\alpha \times 10^{-3}$ (HASHASH)	I	1.20	0.80	1.00	0.90	0.34
$\varepsilon_\alpha \times 10^{-3}$ (HASHASH)	II	1.50	1.00	1.25	1.15	0.42
$\varepsilon_\alpha \times 10^{-3}$ (HASHASH)	III	2.70	1.80	2.20	2.00	0.76
$\varepsilon_\alpha \times 10^{-3}$ (HASHASH)	IV	4.90	3.20	4.00	3.70	1.40

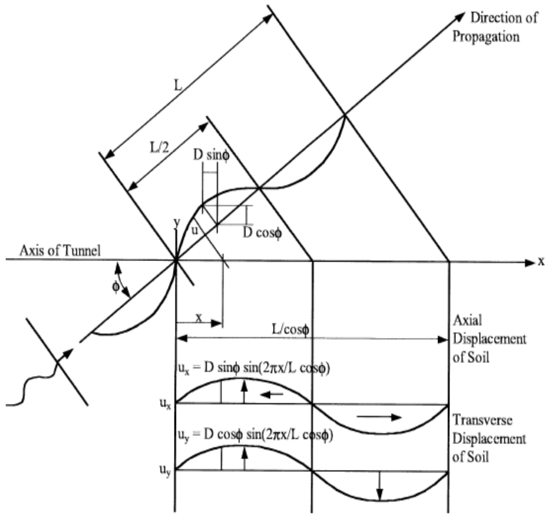

Fig. 1. Waves propagate method and impact with the pipe and the way a longitudinal wave expands in the pipe [2].

2. Numerical Modelling

The types of analyses employed based on time history analyses and the wave propagation method in pipes and soil. To carry out three-dimensional modelling, 1000 meters of pipeline used to increase the precision of the analyses. The modelling based on Beam theory on an elastic bed. The effect of changes in wave propagation speed without changing the frequency content of the wave investigated by two type of analyses. First, sinusoidal wave with the same frequency content with changes in the speed of wave transmission investigated. Second, five spectrum of earthquakes used to consider the effect of changes in frequency contents on seismic behaviour of pipelines. The aim is to calculate the effect of wave propagation on the amounts of longitudinal strains affected by P-wave. The load imposed in a way that the effects of P-wave propagation on the pipe investigated.

First, all spectra equalled to the acceleration of 1G to investigate the effect of changes in frequency content. Then the scaled spectra used by MATLAB according to boundary conditions and the meshing method. The boundary condition introduced for each pipe element depend on the coordination of the elements. The amounts of changes in displacement depending on the pipe length and over 1001 input file created by MATLAB. The investigation did for four type of soils in sandy and clayey soil. Eight analyses for each time history cases, and five case time-history analyses performed. Totally forty time-history analyses used for investigation with use of ABAQUS software [34].

Table 2. The properties of used sandy soil.

Soil type	ϕ	$\gamma(\frac{KN}{m^3})$	K	K_0	T_s	$V_s(m/s)$	$V_P(m/s)$	$\lambda(m)$
I	35	21	0.7	1.5	0.4	625	1000	250
II	33	20	0.65	1.2	0.5	500	800	250
III	31	19	0.55	0.8	0.7	275	450	192.5
IV	30	18	0.50	0.5	1.0	150	250	150

Table 3. The properties of used clayey soil.

Soil Type	$\gamma(\frac{KN}{m^3})$	$S_u(N/m^2)$	T_s	$V_s(m/s)$	$V_P(m/s)$	$\lambda(m)$
I	21	1.5	0.4	625	1000	250
II	20	1.2	0.5	500	800	250
III	19	0.8	0.7	275	450	192.5
IV	19	0.5	1.0	150	250	150

2.1. Pipe-Soil Interaction

There are various methods to model the soil. One of the acceptable methods in most worldwide guidelines is soil-spring equalization. In this method three springs with stiffness in three main directions employed. The amounts of spring stiffness as well as their movement calculated by ASCE-ALA guideline [30]. In this research the soil-spring equalization method used. Non-linear springs employed to take soil-structure interaction into account (Fig. 2 and 3).

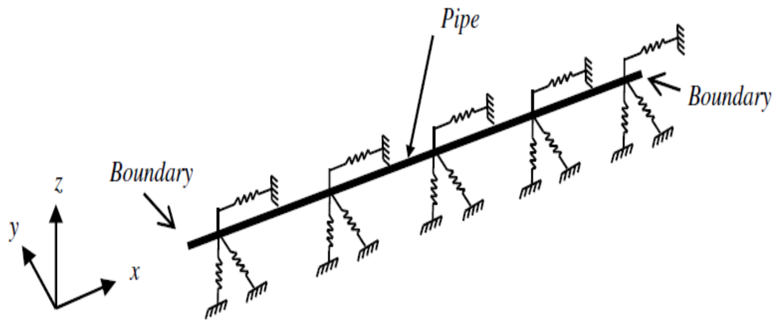

Fig. 2. Modelling of pipelines together with spring in different directions.

To model the soil, two types of soil employed; i.e. clayey and sandy soil, and each type of soil classified into four groups based on the density and the wave propagation speed. Properties of the soil used in analyses shown in Tables 2 and 3 [20, 28, 30]. In Table 2, the properties of sandy soil and in Table 3, the properties of clayey soil observed. In this Table, ϕ is sand internal friction coefficient, k is friction reduction coefficient between pipe and soil, K_o lateral resistance coefficient, S_u is undrained shear resistance of confined soil per N/m2, T is soil dynamic period per second, Vs is the shear wave speed in soil per m/s and λ is the wave length per meter [33].

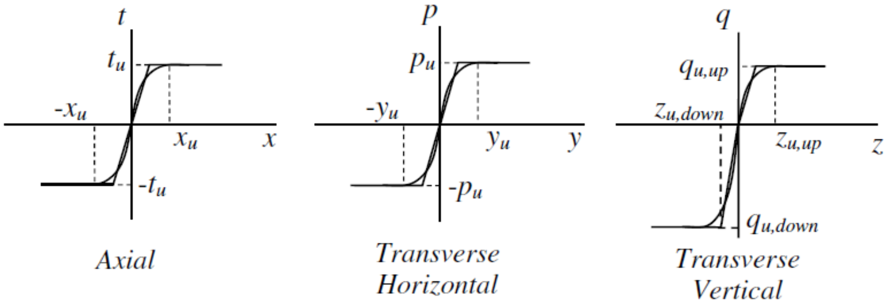

Fig. 3. The characteristics of modelled springs in three different directions of axial, transverse horizontal and transverse vertical.

2.2. Pipeline Modelling and Specifications

The pipe used in this research made of steel X60 range which is one of the most common gas and oil transmission pipelines in the world.

$$\varepsilon = \frac{\sigma}{E}\left[1 + \frac{n}{1+r}\left(\frac{\sigma}{\sigma_y}\right)^r\right] \tag{8}$$

Ramberg-Osgood equation employed to achieve the amounts of strain [32]; in which in terms of X60 pipe, the amounts of n, r, σ_y are 10, 12, 413E10^6 N/m2 respectively [32].

2.3. Minimum Required Length of the Pipe Segment for Modelling

The length of the pipe used in the modelling should be in a way that the boundary condition at the end of the pipe does not affect the amounts of strain or the tension in middle element of the pipe. According to the researches [33], it became obvious that the minimum length of the required pipe in clayey soil should equal to 2λ and in sandy soil should equal to 4λ [33]. 1000 meters' pipeline length used for both types of soil, regarding the fact that the maximum amounts of wave length equaled to 250 meters. Since modelling with pipe limited components of 1000 meters long with shell elements and three-dimensional soil model is really time-consuming, PIPE elements employed to model the pipe which is a kind of beam element. Therefore, the only way to control local buckling in a pipe is to control the maximum amounts of strains.

For studying the effect of pipe length while taking modal analysis of pipelines in soil into account in order to calculate the minimum required length of the pipeline. The effect of pipeline length on higher modes investigated by Hosseini et al. [33]. It became obvious that if the length of pipe considered infinite, the amounts of the limit state of angular frequency obtained using Eq. (9).

$$\lim_{l\to\infty} \bar{\omega}_i = \sqrt{\frac{k_u}{m}} \tag{9}$$

It also became evident that if the length of pipe is not infinite, the amounts of $\bar{\omega}_i$ contain the percentage difference equaling β [33].

$$\begin{aligned} \bar{\omega}_i &= (1+\beta)\sqrt{\frac{k_u}{m}} \\ \beta &= \frac{m}{2k_u}\omega_i^2 \end{aligned} \tag{10}$$

In case the length of the pipe tends to the infinite, β tends to become zero. Otherwise, Eq. (11) used to obtain the minimum required length of the pipe in order to obtain β acceptable percentage error [33].

$$l = \sqrt[4]{\frac{EI\alpha_i^2}{2\beta K_u}} \tag{11}$$

$$l = \sqrt[4]{\frac{\pi\alpha_i^2\xi}{8\beta}\frac{Et}{\gamma}\frac{R^2}{N_{qh}}\left(1+\frac{R}{H}\right)} \tag{12}$$

$$l = \sqrt[4]{\frac{\pi\alpha_i^2\xi}{8\beta}\frac{Et}{S_u}\frac{R^2}{N_{ch}}\left(H+R\right)} \tag{13}$$

Hosseini et al. proposed equations for the minimum length of pipeline in sandy and clayey soils using ASCE as well as Eq. (11) (Eq. (12) and (13)) in which H is the depth of burial, N_{qh} is dimensionless coefficient and ζ is dimensionless coefficient which is about 0.02 for dense sand and about 0.1 for loose sand and is approximately 0.3 for stiff clay and is about 0.05 for loose clay.

2.4. The Verification of Modelling

The amounts of frequency belonging to this research's model compared with those of Hosseini et al. [33] so as to verify the modelling results. When it comes to models belonging to Hosseini et al. [33], the results of modal analysis of the first hundred modes observed in Fig. 4. The diagram for clayey soil (type I) as well as the results of modal analysis of Hosseini et al. [33]. Three models with the length of 200, 400 and 1000 meters created to carry out verification and the amounts of frequency obtained while taking 100 modes into consideration. It became obvious that in sample with the pipe length of 200 meters, the results depict the percentage difference of 7.9. when it comes to samples with the pipe length of 400 meters, this difference reached to 5.86 %, and when it comes to sample with the pipe length of 1000 meters, this difference comes to 2.22%. As it observed, when it comes to long pipes, the amount of difference is of little and can be overlooked. That's why pipes with the length of 1000 meters employed in analyses.

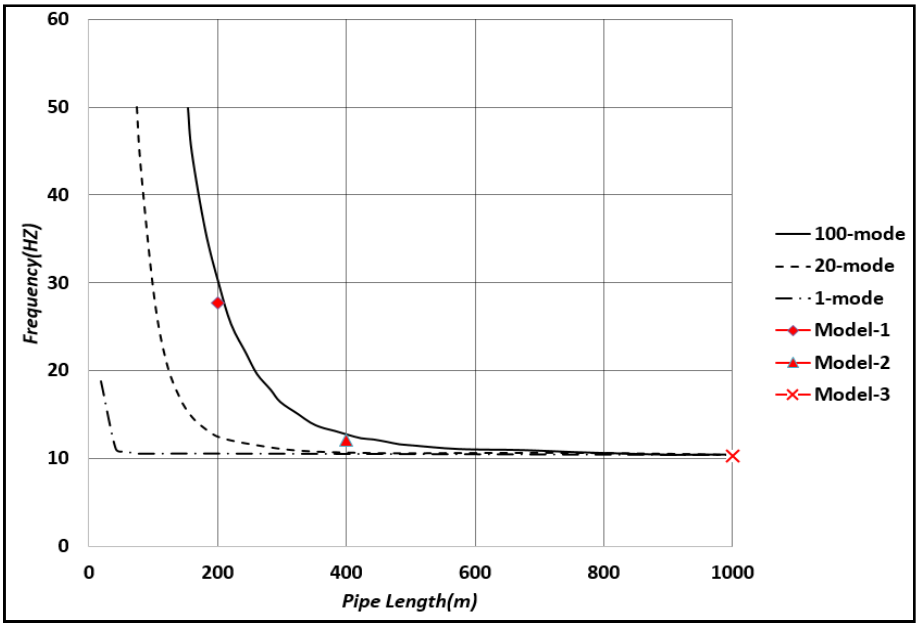

Fig. 4. Depicts the comparison between the obtained results of verification and the modelling belonging to Hosseini et al.[33].

3. The Analyses Cases

The analyses have two steps. In the first phase sinusoidal wave propagation effect on the pipelines will be discussed. To investigate the effect of different vibration frequencies of sinusoidal waves with different frequencies used. The analyses performed in different soils and with different wave propagational speed. After that time history analyses performed for different soils and under five earthquake spectra.

3.1. The Effect of Sinusoidal P-Wave Propagation

First the effect of wave propagation speed on sinusoidal wave investigated. As observed in Table 4, the amounts of axial strain in pipe's middle elements in four different types of soil and in various frequencies investigated. Also, the wave propagational speed in each type of soil modeled with respect to the P-wave propagational speed in soil. In this modelling, one type of sinusoidal wave with an equaled acceleration of 1G used and the only difference between analyses is the different amounts of vibration frequency belonging to each wave. Fig. 5 shows the form of input wave.

Table 4. The amounts of axial strain obtained for the middle elements under the influence of sinuous wave with different frequencies.

Soil Type	$V_P\left(m/s\right)$	$V_{particle}\left(m/s\right)$	Frequency	ε_a
I	1000	0.62	2.5	0.00015
II	800	0.62	2.5	0.00018
III	450	0.62	2.5	0.00022
IV	250	0.62	2.5	0.00011
I	1000	0.78	2	0.00012
II	800	0.78	2	0.00015
III	450	0.78	2	0.00021
IV	250	0.78	2	0.00011
I	1000	1.00	1.56	0.00009
II	800	1.00	1.56	0.00012
III	450	1.00	1.56	0.00017
IV	250	1.00	1.56	0.00017
I	1000	1.56	1	0.00006
II	800	1.56	1	0.00008
III	450	1.56	1	0.00014
IV	250	1.56	1	0.00017
I	1000	3.12	0.5	0.00003
II	800	3.12	0.5	0.00004
III	450	3.12	0.5	0.00007
IV	250	3.12	0.5	0.00011

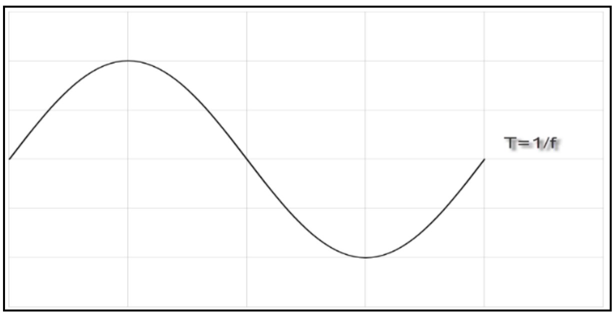

Fig. 5. The imposed sinusoidal wave on pipelines in various soils.

Considering Table 4, it became clear that the amounts of strain in stiff soils (types I and II) are less than those of looser soils and as the wave propagational speed increases, the amounts of strain decrease. Furthermore, the effect of wave frequency content on the propagational speed should not be underestimated. Waves with different frequency contents had various effects on the amounts of strain. As the amount of vibration frequency decreases, the amounts of strain in low speeds will be in a crisis. When the amount of frequency increases, the most amount of strain happens in terms of wave propagation speed of 450 m/s instead of 250m/s. The amounts of strains in each frequency observed in Table 4. To investigate more, the amounts of strains in four samples equaled with respect to the most amount of strain and equaled trends for the five different frequencies depicted in Fig. 6.

It obvious that the maximum amounts of strain produced in the wave speed of 450 m/s and soil type III in terms of 2 and 2.5 hertz frequencies. In other samples with 1.56, 1.0, 0.5 hertz frequencies the most amounts of strain found in soil type IV. As a result, it can be concluded that wave propagation speed has a significant effect on the amounts of responses and in soil types of III and IV (in which the wave motion speed is less), the amounts of strain are more than those of soil types I and II. In other words, the stiffer the soil, the less the amounts of strain. Also, it became obvious that as the frequency of imposed wave increases, the amounts of axial strain increases simultaneously. For instance, in soil type I, the change in wave frequency from 2.5 hertz to 0.5 hertz will lead to strains ranging from 0.00015 to 0.0003 which indicates the amount of reduction in strain equals to %20.

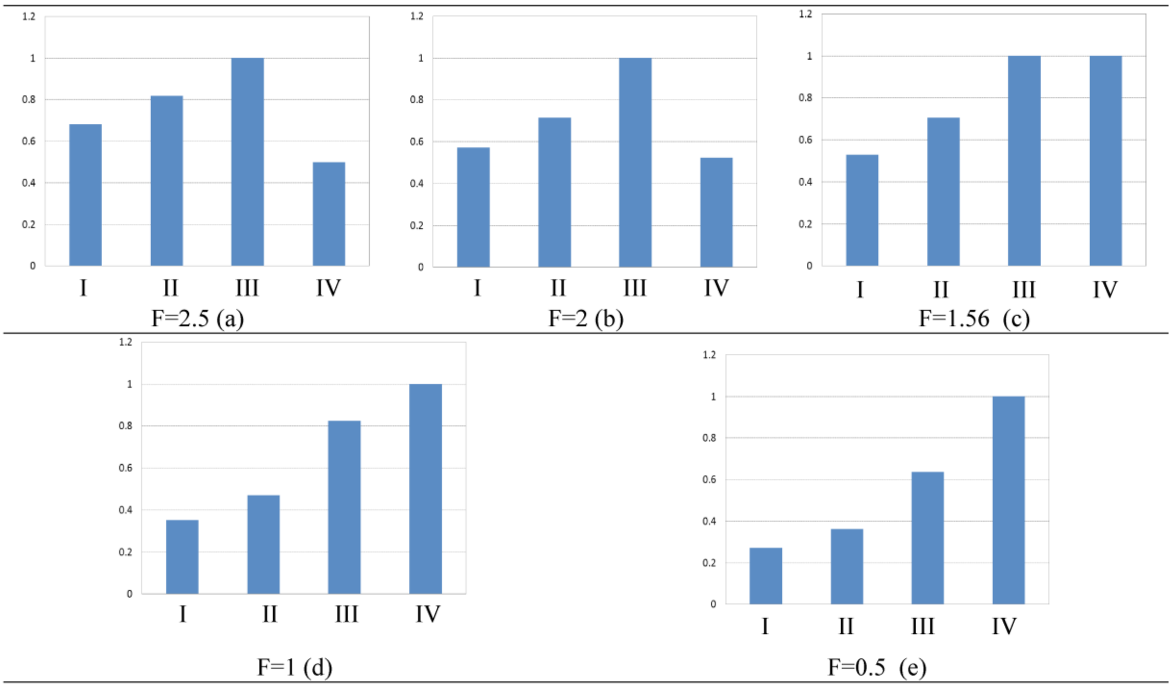

Fig. 6. The relative amounts of strain in different frequencies: a) 2.5, b) 2, c) 1.56, d) 1, e) 0.5 hertz. Horizontal axis indicates soil types and vertical axis indicates the ratio of strain to the maximum strain.

3.2. The Effect of Time History Analyses for Five Earthquake Spectra

To investigate the effect of different vibration frequencies of spectra with different frequency contents used. The analyses performed in different soils and with different wave propagation speed. After that time history analyses performed for different soils and under five earthquake spectrum.

Then, the research embarks on investigating the effect of wave propagation speed after installing five earthquake spectrum on the pipelines. The end results can be observed in Table 5. For comparing the axial strain in the pipe middle element the absolute value of strain for each spectrum analyzed. The graph of strain amounts versus time for some spectra depicted in Figs. 7 and 8. In these figures, the effect of Manjil earthquake investigated. Table 5 shows the results of the maximum amounts of strain produced during all five types of recorded earthquakes. It observed that although all earthquake records had the same acceleration, i.e. 1G. , in Loma-Prieta record (in which the maximum wave speed exceeded the other ones and the wave speed equaled to 1.21 m/s) the amounts of strain produced exceeded the other records and equaled to 0.0028. The Manjil record with the maximum speed of 0.34 m/s (while having the minimum speed among the records) had the minimum amount of axial strain, equaling to 0.00028. This indicates the enormous effect of frequency content on the amounts of response so much. The maximum amount of strain is ten times more than its minimum amount.

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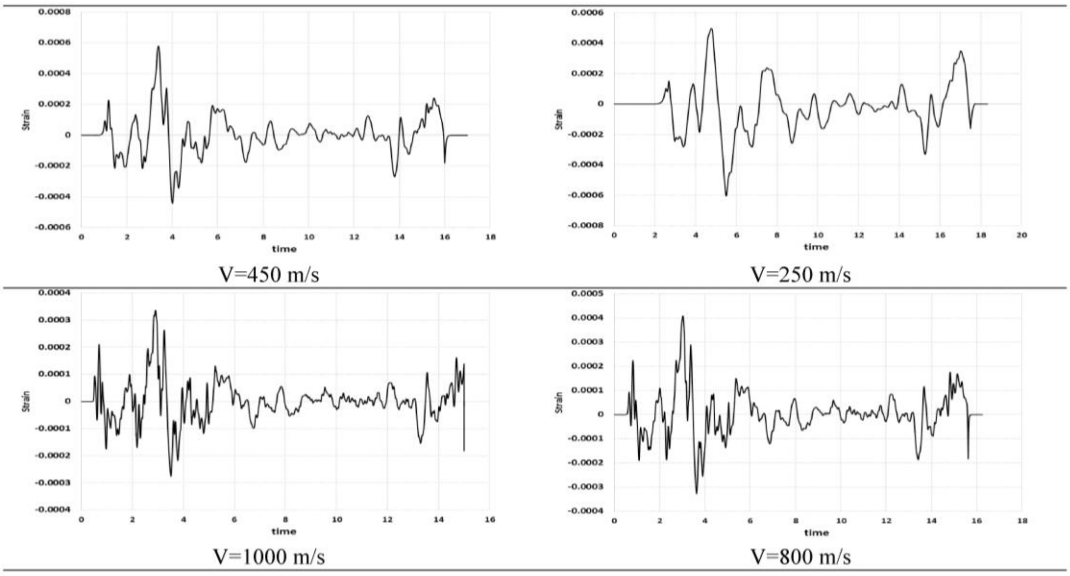

Fig. 7. The imposed spectrum on pipelines in various soils.

Also after investigating the amounts of strain in both soil types of clayey and sandy under a particular record, it became obvious that the amounts of strain in clayey soil are more than those in sandy soil. For example, in Loma-Prieta earthquake the ratio of strain produced in sandy soil to clayey soil in soil type II is 0.625. Furthermore, for Kobe, Imperial Valley, Northridge as well as Manjil spectrum were 0.627, 0.987, 0.829 and 0.92 respectively. The ratio of minimum to maximum strain values in the clayey soils in different soil type (type I to type IV) in Loma-Prieta ,Kobe, Imperial Valley, Northridge, and Manjil spectra equaled to 0.55 and 0.42 and 0.57, 0.81, 0.63 respectively. In sandy soil equaled to 0.63, 0.67, 0.58, 0.79, and 0.47 respectively. The average of the values of the reduced strain in different type of soil could reduce the amount of strain considered equal to 0.592 for clayey soils, and equal to 0.61 for sandy soil.

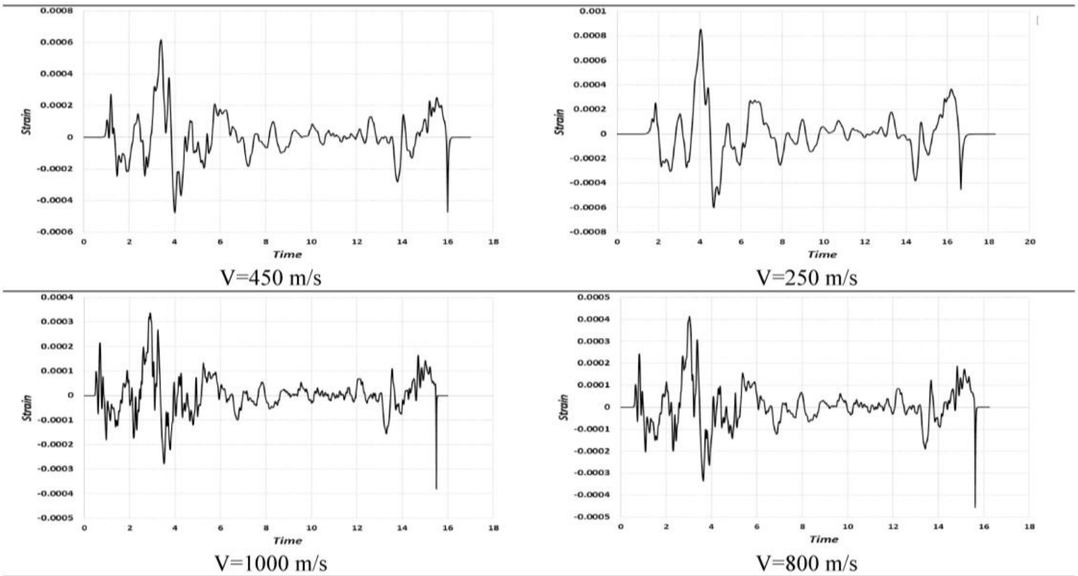

Fig. 8. The imposed spectrum on pipelines in various soils.

Table 5. The characteristics of the maximum amounts of strain obtained for soils in different spectra.

Name	Soil Type	$V_P\left(\frac{m}{s}\right)$	$\varepsilon_a - sandy\,soil$	$\varepsilon_a - clayey\,soil$
Loma Prieta	IV	250	0.00137	0.00200
	III	450	0.00200	0.00280
	II	800	0.00197	0.00275
	I	1000	0.00126	0.00176
kobe	IV	250	0.00088	0.00160
	III	450	0.00121	0.00193
	II	800	0.00100	0.00101
	I	1000	0.00081	0.00082
Imperial Valley	IV	250	0.00084	0.00133
	III	450	0.00143	0.00145
	II	800	0.00103	0.00103
	I	1000	0.00083	0.00083
Northbridge	IV	250	0.00032	0.00040
	III	450	0.00039	0.00047
	II	800	0.00037	0.00045
	I	1000	0.00031	0.00038
Manjil	IV	250	0.00060	0.00060
	III	450	0.00044	0.00048
	II	800	0.00033	0.00046
	I	1000	0.00028	0.00038

To investigate the effect of wave propagation speed on the amounts of strain more precisely, Table 5 equaled based on the maximum amount of strain (Fig. 9). This figure depicts the ratio of strains to the P-wave propagation speed in both soil types of sandy and clayey. In both sample types of soil, the maximum strain observed in soil types III and IV (which their longitudinal wave propagation speed equals to 250 m/s and 450 m/s). Also, the minimum amounts of strain belonged to soil type I with wave propagation speed of 1000 m/s.

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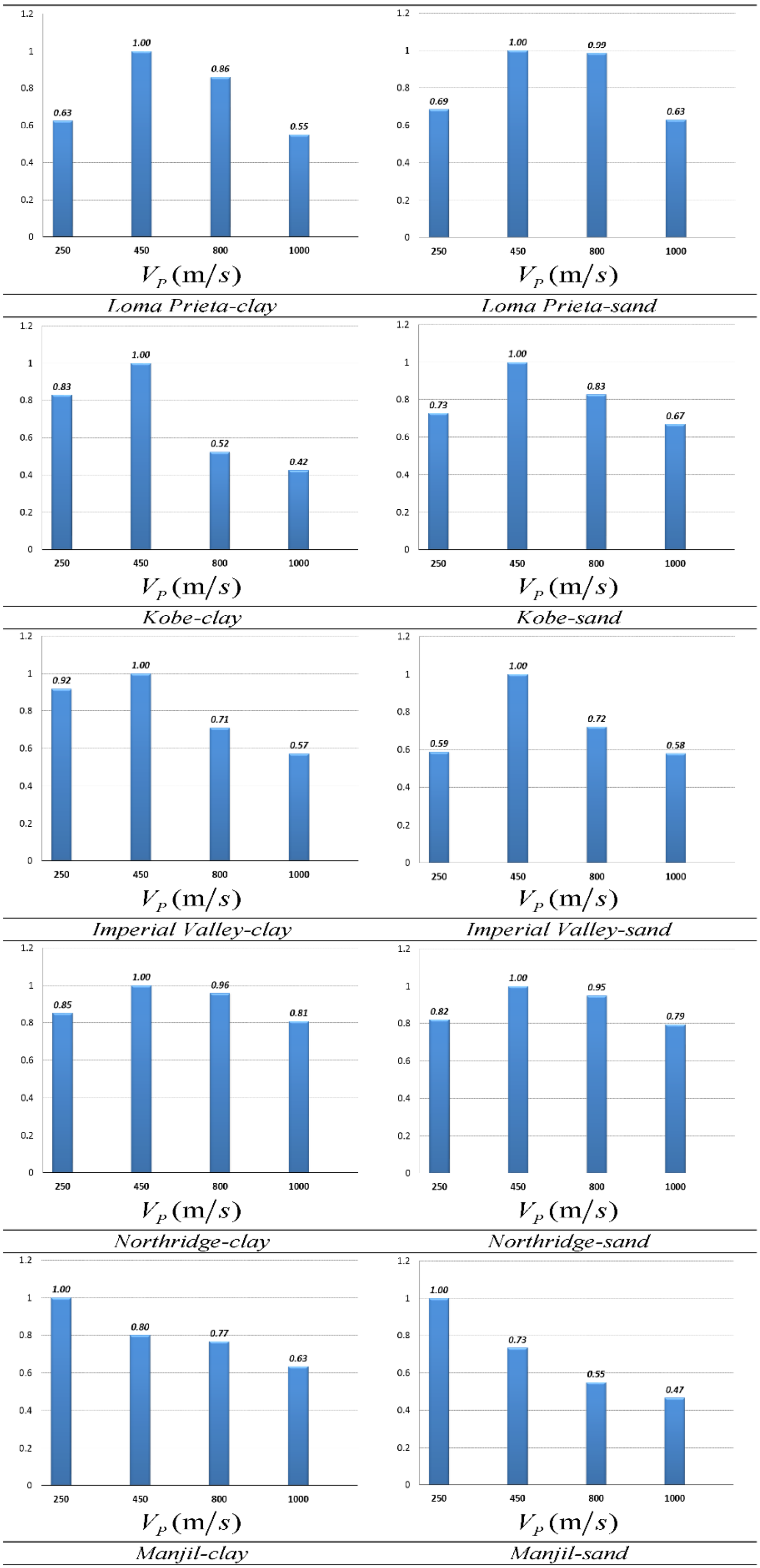

Fig. 9. The relative amounts of strain in various soils in terms of wave propagation speed.

4. Conclusions

After studying the imposition of sinusoidal wave with diverse frequencies, it became evident that as the frequency of the imposed wave increases, the amounts of axial strain increases as well. For instance, in soil type I, the changes in wave frequency from 2.5 hertz to 0.5 hertz led to the decrease in axial strain, equaling to 20%.

The speed of grains' movement in times of earthquake and the produced vibration frequency stemming from the earthquake has a huge effect on the response amounts. Five earthquake spectrum with the maximum speed of different grains' movement investigated and the following results obtained.

- Although all earthquake records had the same acceleration, in Loma-Prieta record the amounts of strains obtained were more than the other records and equaling to 0.0028. The maximum wave speed exceeds the other records and the wave speed equals to 1.21 m/s. Manjil record with the maximum speed of 0.34 m/s (having the minimum speed among the records) possessed the minimum amount of axial strain, equaling to 0.00028. This indicates the enormous effect of frequency content on the amounts of response so much so that the maximum amount of strain is ten times more than its minimum amount.
- After investigating the amounts of strain in both soil types of clayey and sandy under a particular record, it became obvious that the amounts of strain in clayey soil are more than those in sandy soil. For example, in Loma-Prieta earthquake the ratio of strain produced in sandy soil to clayey soil in soil type II is 0.625. This trend almost applies to all analyses, and the amounts of strain in sandy soil were not more than those of clayey soil in any of the cases.

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