Effect of Wave Impeding Barrier Depth on Buried Pipeline

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Abstract: Pipelines are one of most important component of lifeline engineering. For instance, the Southern Caucasus- Eastern Turkey energy corridors are formed by several key pipelines carrying crude oil and natural gas from Azerbaijan, via Georgia, to world markets through Mediterranean Sea. Many project accomplished recently and construction of new corridors are still going on. They should be protected from earthquake disaster especially when they pass through high seismicity zones. The wave impeding barrier (WIB) based on the cut-off frequency of a soil layer over bedrock can be used to reduce the earthquake excitation of this vulnerable the infrastructures. In this paper, efficiency of WIB with the application of various depths underneath of pipeline is investigated. The proposed model is analyzed as numerical simulation using 2D finite element analysis. A parametric study carried out for various depths of embankment of WIB. The soil is defined as semi-infinite medium by using absorbent boundaries and Mohr-Coulomb material model is chosen in the analysis. Results showed that artificial bedrock can be very promising as an isolator to protect pipelines when they buried for a certain depth.

Key words: Wave impeding barrier, Dynamic FE analysis, infrastructures, earthquake motion, passive isolation, absorbent boundaries

Introduction

Excessive dynamic loading during strong ground motion causes in enormous stress and deformation on underground structures in active tectonic regions. Last decade, shallowly buried pipelines are utilized for a wide range of key applications, such as natural gas/oil transmission, telecommunication and water supply. Damages to small pipelines were observed in some earthquakes such as 1964 Niigata and Alaska earthquakes however fewer damages were generally reported to large underground structures compared to surface structures. On the other hand, real performance of recent project of new energy corridors such as Southern Caucasus- Eastern Turkey natural gas pipelines still unknown under strong ground motion. These vital underground structures will affect the environment extensively and the countries that depend on them. Sustainability, durability and security of these pipelines are very critical for all earth habitants. Thus, recently, earthquake induced damages followed by severe earthquakes and earthquake corresponding resistance design have received considerable attention by the authors (Hall and O'Rourke, 1991, Liu and Song, 2005) in many countries.

There can be two way for reducing the response of pipeline as: I) by modifying the wave dissipation characteristics of the soil deposit underneath of pipeline, and b) by partially interrupting the spreading of waves into the understructure or by providing the structure more damping by means of installation certain devices such as additional base isolation systems which can be very costly. It is also possible to modify the dynamic transmitting behavior of local sub-soil through a complex mechanism of wave reflection and mode alteration around the vibration source by constructing a suitable wave barrier at the bottom of pipeline (Göktepe et al., 2010). Various numerical techniques for analyzing the influences of soil heterogeneity and layering on the vibration screening by means of trench and wave impeding barriers are investigated by the authors (Beskos et al., 1986, Leung et al., 1991, Klein et al., 1997, Takemiya, 1998a,b, Chouw and Schmid, 1999, Adam and Chouw, 2001, Pflanz et al., 2002, Adam and Estorff, 2005, Çelebi et al., 2006, Çelebi and Göktepe, 2012) to compare with the few experimental studies which are carried out full scale tests on site and laboratory model investigations only for particular cases (Woods, 1968, Haupt, 1981, Ahmad and Al-Hussaini, 1991, Forchap and Verbic, 1994).

In this paper a WIB, which behaves as artificial bedrock (concrete in this study), is tested as an isolator to reduce responses of buried pipelines under earthquake strong ground motion. 2D numerical finite element method is used for investigations. It is buried horizontally underneath of trench below the pipelines to be protected in various depths as seen in Fig. 1. A parametric study carried out for optimum depth.

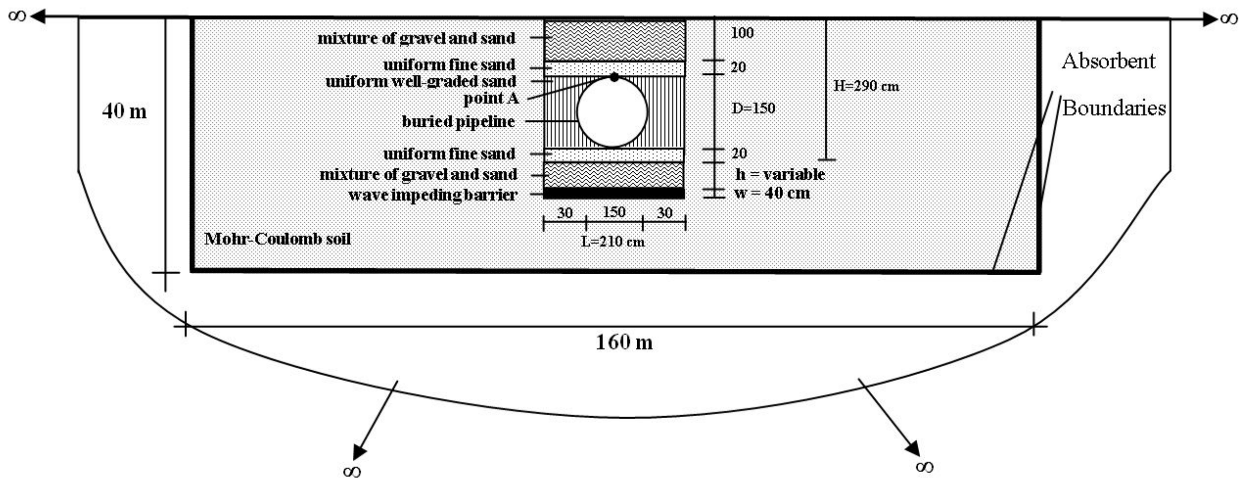

Figure 1: Schematic diagram of the considered soil-structure model with wave impeding barrier

Numerical Model

Soil-structure interaction, wave propagation, defining realistic material properties of the local soil condition and adequate software for the numerical analysis have fundamental influence on soil related finite element analysis.

In order to analyze the wave propagation of surface vibrations in the soil, and to predict the mitigation of buried pipelines responses produced by an earthquake excitation the proposed model and its computational work as numerical simulation with wave propagation in the soil are performed using finite element analysis by the computer program (Brinkgreve et al., 2002).

Special boundary conditions named as absorbent boundaries, which can absorb the energy waves, were specified to both the vertical and horizontal model boundaries to avoid spurious reflection of waves back into the soil medium. The mechanical behavior of the underlying soil medium considered in the model is simulated by an elasto-plastic Mohr Coulomb model under plane-strain conditions. 1990 Upland Earthquake acceleration record is considered as input motion.

Wave-impeding barrier buried in various depth are considered as reduction measure to reveal the optimal geometrical properties. The FE discretization of the soil-structure system with a WIB is shown in Fig. 1. The observation point (A) chosen for investigation is on the top of the buried pipeline as shown in the same figure. The essential material parameters considered in FE model for the underlying and filling soil together with steel pipeline are summarized in Tables 1-3.

Table 1: Properties of soil for undrained FE Mohr-Coulomb model (Gamber, 2004)

Parameter	Symbol	Unit	Magnitude
Total unit weight	γ	(kN/m^3)	16.67
Mass density	ρ	(Mg/m^3)	1.70
Young's modulus	E	(kPa)	34500.00
Shear modulus	G	(kPa)	13270.00
Poisson's ratio	ν	-	0.30
Constrained modulus	M	(kPa)	46440.00
Compression wave velocity	V_p	m/s	165.200
Shear wave velocity	V_s	m/s	88.300
Rayleigh damping with alpha coefficient	α	-	0.001
Rayleigh damping with beta coefficient	β	-	0.01
Void ratio	e	-	0.50
Cohesion	c	(kPa)	0.00
Friction angle	ø	(º)	33.00
Dilatancy angle	ψ	(º)	3.00
Interface strength reduction factor	R_{inter}	-	0.67

Table 2: Properties of filling soil of buried pipeline for undrained FE Mohr-Coulomb model (Zaneta, 2006)

Soil type	Mixture of gravel and sand	Uniform fine sand	Uniform well-graded sand
Mass Density (Mg/m^3)	2.00	1.60	1.80
Young's Modulus(kPa)	15000	15000	20000
Poisson's Ratio (-)	0.25	0.25	0.25
Friction Angle (º)	38.00	32.00	33.00
Cohesion (kPa)	3.00	0.00	0.00

Table 3: Properties of steel pipeline for FE elastic plate-element

Parameter	Symbol	Unit	Magnitude
Total unit weight	γ	(kN/m^3)	77.00
Mass density	ρ	(Mg/m^3)	7.85
Young's modulus	E	(kPa)	$2x10^8$
Damping factors	α, β	-	0.05
Poisson's ratio	ν	-	0.30

Results

In order to obtain the influence of a wave impeding block as an isolator when constructed underneath of pipeline in various depths, a parametric investigation has been performed for reducing adverse effects of earthquake vibrations. Göktepe et al. (2011) proposed a WIB, investigated various thicknesses from 10 cm to 100 cm and a 40 cm thickness was chosen for given best performance. In the current study depths of embankment 20, 40, 80, 160 and 200 cm are examined. Selected material properties of the concrete block are given in Table 4.

Table 4: Properties of concrete wave impeding block (WIB) for FE elastic model

Parameter	**Symbol**	**Unit**	**Magnitude**
Total unit weight	γ	(kN/m3)	22.00
Mass density	ρ	(Mg/m3)	2.24
Young's modulus	E	(kPa)	$3.7x10^{7}$
Damping factors	α, β	-	0.01
Poisson's ratio	ν	-	0.25

Mixture of gravel and sand filling soil is used for the depth of embankment. A dimensionless parameter which is obtained from the ratio of depth of embankment (h) to height of trench (H) is derived and proposed for the optimum thickness. The height of trench which is equal to 290 cm is assumed as summation of the radius of pipeline and filling upside down of the pipeline as 20 cm uniform fine sand and 100 cm mixture of gravel and sand is shown Fig. 1. Therefore h/H ratios for 20, 40, 80, 160 and 200 cm depth of embankment are 0.07, 0.14, 0.28, 0.55 and 0.69 respectively.

Vertical displacements recorded after dynamic analysis without WIB and for various h/H ratios are shown in Fig. 2. The ratio with 0.14 results in the best attenuation considering peak ground displacement (PGD). Any depth of embankment seems effective compared without WIB. It is seen that 40 cm is the most effective depth where 92% reduction is achieved on the pipeline.

On the other hand, there is no change at all on horizontal displacements. Displacements are plotted and showed as one centimeter shifted for better visualization (Fig. 3). About 5 cm total displacements are seen in each case which means, the WIB has no effect in horizontal displacement.

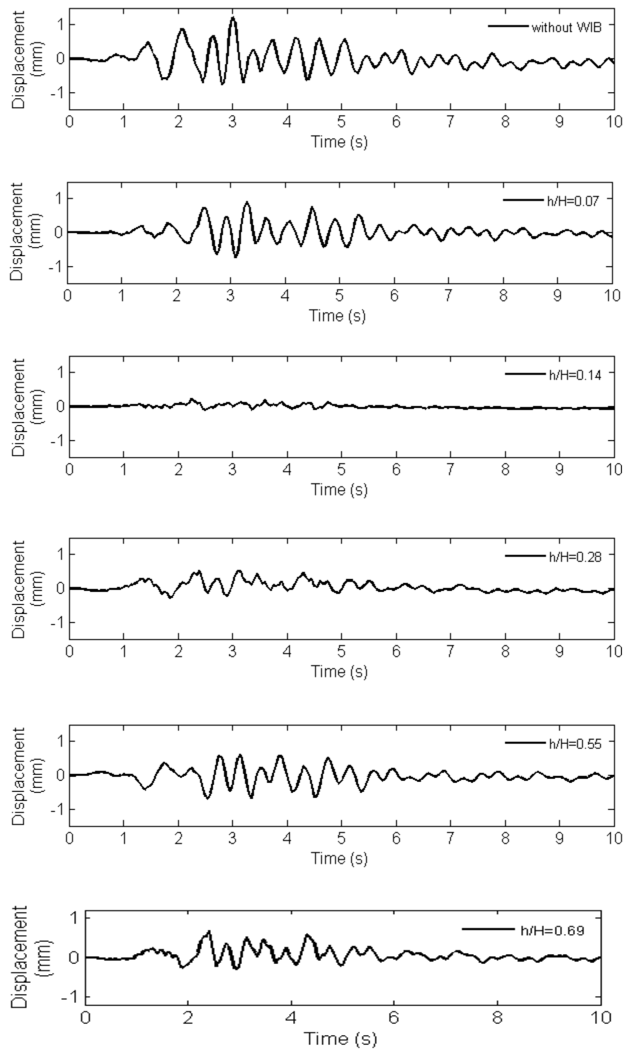

Figure 2: Records of vertical displacements depending on various h/H ratios at point A

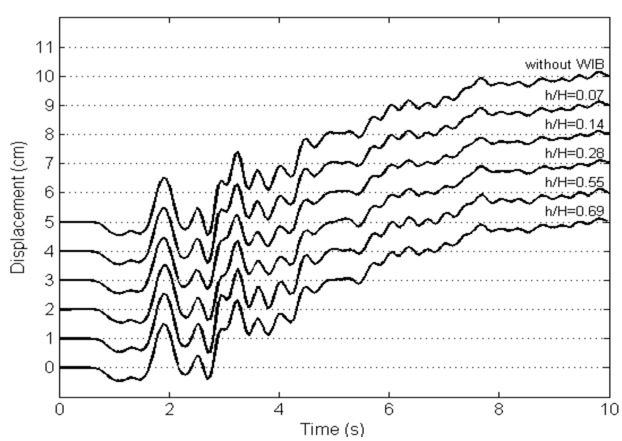

Figure 3: Records of horizontal displacements depending on various h/H ratios at point A (records are shifted 1 cm)

The horizontal acceleration records are plotted in Fig. 4a. Similar tendency is seen for all ratios. The vertical accelerations are also shown in Fig. 4b. Top waveform shows acceleration without WIB where the waveforms underneath demonstrates with different depth of embankment. According to peak ground acceleration (PGA), best result is acquired from the WIB for 0.14 of h/H ratio.

a

b

Figure 4: Records of horizontal acceleration (a) and of vertical acceleration (b) depending on various h/H ratios at point A (records are shifted 150 cm/s2 and 40 cm/s2 respectively)

We introduce a reduction factor which is defined with following equation;

$$RF_{Displacement} = \frac{PGD_t}{PGD_c}, \;\; RF_{Acceleration} = \frac{PGA_t}{PGA_c} \qquad (1)$$

where indexes t is for various h/H ratios and c is stands for without WIB. Relations of reduction factors (RF) with h/H ratios for acceleration and displacement results are shown in Fig. 5a,b.

Ratio of 0.14 gave the smallest RF for PGD and PGA in the analyses. For the former, a very promising reduction is achieved with 92% and the latter is succeeded 64% reduction in vertical acceleration. Interestingly, only h/H=0.55 is bigger than 1.00 in horizontal acceleration which means wave barrier is amplified around 1% for this depth of embankment as seen Fig. 5.

As for horizontal acceleration, 40 cm embankment made best isolation with 32%. Göktepe et al. (2011) previously found that 20 cm WIB is better than the 40 cm according to horizontal and vertical PGA (not in PGD). We showed that if the 40 cm WIB applied to 40 cm depth, the reduction is better compared with the performance of 20 cm WIB.

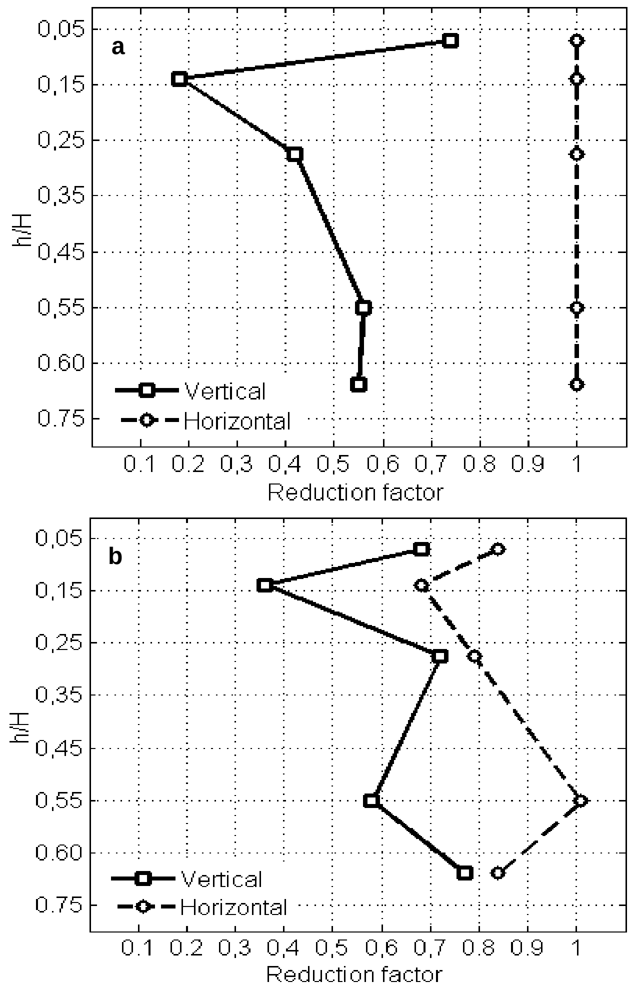

Figure 5: Reduction factors depending on various h/H ratios at the point A. Vertical and horizontal (a) displacements (b) acceleration (RF are dimensionless)

Analyzing the all cases, a general tendency is inferred that employment of wave impending barrier for buried pipelines is a very effective application to reduce the vibration. However a special care should be taken for amplification cases before application.

Conclusion

Earthquakes have caused colossal casualties and severe damages to engineering structures and especially leading to substantial economic loss to the underground structures and/or infrastructures. Security, sustainability, and durability of these pipelines are very vital for many reasons The response of lifeline engineering under earthquake excitation which present a risk for population and environment is influenced by deformability of the buried pipelines such as used in natural gas transmission, especially in case of very soft ground conditions. A parametric investigation has been executed to obtain the influence of a wave impeding block as an isolator when constructed below pipeline for reducing adverse effects of earthquake vibrations. Various depth of embankment for the artificial bedrock (concrete block) are investigated by using 2D finite element method. It is found that even 40 cm depth of embankment with 40 cm thickness of the block can reduce the peak ground acceleration and displacement. It is concluded that wave impending barrier can be used in practice in the field.

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