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Study on Soil Parameters Effect on Seismic Performance of Buried Pipelines

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ABSTRACT

Life line system, and its equipment's, provides essential services today, so seismic performance analysis in modern industrial area is exigent. We analyze and compare the performance analysis of gas bored pipes in various soil compactions with finite element method. We create a finite element model with three soil types and compare them. Finally, the soil with best performance is presented.

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INTRODUCTION

Today, vital arteries play an important role in urban modern industrial areas. This vital arteries system includes buried oil and gas pipes, underground electricity transfer cable, underground water distribution systems, etc. vital arteries system and the related equipments provide essential services in today lives. However, function necessity of its types is determined in modern industrial areas. Not only destruction of vital arteries has severe economical consequences, but also might have reverse effect on environment and quality of life after an earthquake. Examining past earthquakes and severe damages incurred to vital arteries in these quakes indicates the importance of studying vital arteries behavior under earthquake.

Earthquake can damage buried pipes in two ways. One group of these damages is due to the earthquake wave propagation phenomena and the other group is related to the permanent ground deformation, which in the follow is called PGD. Faulting, landslide, lateral spreading, as well as settlement are among the events categorized in permanent ground deformation [6]. One of the uncertainties about design and implementation of buries pipes is that after pipe placement in the ground depth whether material or the soil density filling the trenches has any effect on this pipeline performance. To this end, interaction between soil and pipe under different situations is investigated. So, finite element method and Plaxis software were used. Studied models have a same input stimulation and various soils such that soil parameters effect on seismic performance of pipe will be determined.

Numeric Modeling Method for Buries Pipelines vs. Earthquake:

Finite element method (FEM) might be used to analysis and design any pipeline in any loading situations including explosive charge and is applied for many cases of designing pipeline. Figure 1 shows an example of modeling by FEM method. Pipe can be modeled by linear element of beam (or pressure pipe). Near the loaded zone boundary, length of beam/pipe elements should not be more than pipe diameter. The model must conform to pipe material as well as non-linear geometry states (major deformations). In one case with more generality, axial symmetric and sell elements might be used to study the appropriate connections and other factors. Soil is modeled by lateral and axial springs which can provide non-linear behavior of force-displacement.

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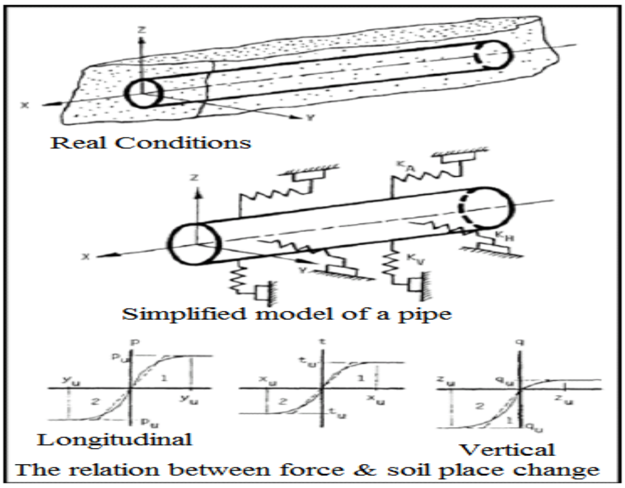

Fig. 1: Finite element (beam type) of buried pipe with soil and supports.

Analysis for Earth Quake Risk:

Earth shake causes random movements. This results in pipe deformation along with soil. Buried pipes in areas subject to seismic waves move together with soil which is against the local movements of earth like liquefaction, landslide, and fault deviation. Maximum strain in soil is estimated as follows [3]:

$$\varepsilon_{soil} = \frac{PGV}{c} \quad (1)$$

Where;
PGV= maximum earth speed in pipe place
C= speed of seismic wave in soil at pipe place. Wave propagation speed can be considered 13000 f/s, unless otherwise be justified.

A) *Continuum pipe:*

A continuum pipe has joints connected to the pipe body with significant toughness and perseverance (they are typically called restrained joints). An example of these pipes is steel pipe with weld (single pass lab shear weld, two pass lap shear weld and butt welding).

Force of pipe body design and joints is the minimum of F1 or F2 that F1 is a force assuming pipe is dependant completely on soil (that is, pipe does not slide in soil) and F2 is the final force which soil can transfer to the pipe.

Suppose that earth strain is transferred to pipe without slide, so

$$\varepsilon_{pipe} = \varepsilon_{soil} = \frac{PGV}{c} \quad (1)$$

$$F_1 = AE\varepsilon_{pipe} \quad (2)$$

$$F_2 = \frac{t_u \lambda}{4} \quad (3)$$

Where
A= pipe cross section
E= pipe Young`s module
t_u final friction force that is applied to pipe body in axial direction (force in length unit)
λ seismic wave length in soil in pipe place. Wave length can be considered 6500 foot unless otherwise is justified.

B) *Sectional pipe:*

A sectional pipe has joints connected to pipe body with low toughness and perseverance (they are typically called unrestrained joints). For example, a cast-iron or a PVC pipe has washer joints with compression gasket filler. It is supposed that earth strains are transferred to relative axial movements between pipes which should be considered in pipe joints. If relative movements of joint are higher than that in the joint, then pipe pieces in the connection point will be separated under tension or pieces resist against each other under pressure, probably result in merging two pieces together or local bending of pipe wall occurs. Axial movement (in both direction of axial shortening and axial length increase) that a joint must be conformed to it, is obtained by the following equation:

$$\Delta_{joint} = 7 L_p \varepsilon_{soil} \quad (4)$$

Where: LP= pipe length

Laboratory tests show that axial toughness and perseverance is different among joints. Therefore, weak joints relative to neighboring strong joints are subject to more relative movements. In 1990, O'Rourke [5] showed that for cast-iron pipe with sealed joints by lead, about one percent of joints were under movement 3 times more than average movements of joint, while 0.1 percent were under movement 5 times more than average movement of joint. To design purposes, it is recommended to use movements 7 times more than average movements. And it is expected that damages would not be more than one in ten thousand joint. For example, suppose that PGV is 50 cm/sec and piece length is 16 foot, then:

$$\Delta_{joint} = 7 L_p \frac{PGV}{c} = 7 \times 16 \times 12 \times \frac{50}{13000 \times 12 \times 2.54} = 0.17(in) \quad (5)$$

Transaction between soil and pipe:

Buried pipes influenced by ground movements or incurred major charges to pipes like great temperature changes might be under high bending tensions or tensile loads. Cause of ground movement can result in different subsidence. The resulted deformations due to the earth subsidence are generally monotonic and do not have any effects on fatigue life and weariness of pipe. Usually, transaction between soil and pipe in buried pipeline during earthquake or explosion is a complicated matter; during earthquake or explosion, non-linear behavior of soil components make it more complicated. Most of this complication is due to soil features. In major pipeline analysis, using complete finite element model that shows the system non-linear behavior in the best way is recommended. Normally, various models are used to show transaction of soil and pipe which include:

A) Continuum model, in which a complex mathematical formula is developed for flexible pipes with finite length that are in a semi-finite soil medium.

B) Soil finite element grid model, which in this non-linearity of system complexity becomes model.

C) Winkler`s beam on foundation model (BNMF), in which soil is considered by the independent springs on certain point of the pipe.

Practically, among the above-mentioned models, BNMF model is used extensively due to simplicity of mathematical facilities and the capability of applying non-linear behavior. Following this topic, the method of modeling in BNMF for continuum and discontinuous pipelines will be provided.

As said before, an exact method for analyzing and designing buried pipes is considering non-plastic behavior for transaction between soil and pipe. ALA agenda [1] has provided the following method for analyzing and designing transaction between soil and pipe. In this method, non-linear tension-strain relations for steel pipes are considered. This model needs definition of the following parameters:

- Bending and axial resistance of pipe
- Longitudinal and transverse resistance of soil regarding internal friction and soil cohesion ratio

In this method, soil resistance is modeled normally as a complete elastic-plastic behavior with spring. The applied load on the pipe is modeled by a series of springs with non-linear behavior, as below Figure.

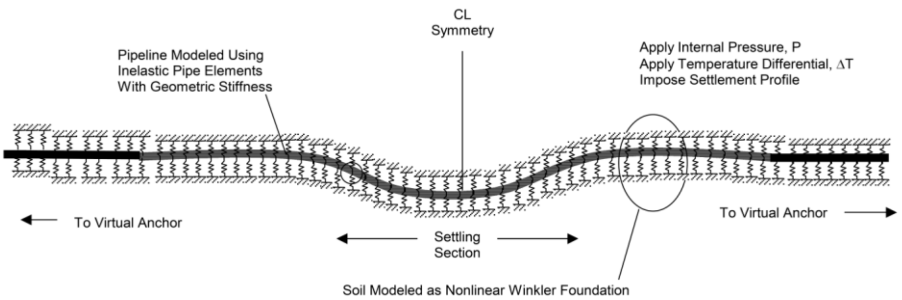

Fig. 2: Modeled soil with Winkler non-linear springs [1].

Soil modeling:

For some states of soil movements applied on the pipeline (like earthquake and explosion), it is expected that the pipe slide in the soil. So, load curves of soil deformation should be non-linear. In the next part, formulation extracted from America`s regulations [2] for soil springs are provided.

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Axial spring of soil:

Regarding to the soil embankment material used for trench of pipeline, soil axial spring features are estimated. Though this is appropriate only when pipeline movement response relative to neighboring embankment is not significantly affected by trench outside soil, in the below Figure ideal behavioral curve of axial soil spring is shown.

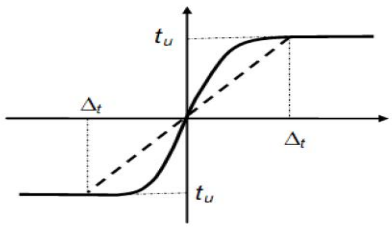

Fig. 3: Ideal behavioral curve of axial soil spring.

Maximum transferred axial force to the pipe in length unit is:

$$T_U = \pi D\alpha c + \pi DH\gamma \frac{1+K_0}{2}\tan\delta \tag{6}$$

$$\alpha = 0.608 - 0.123c - \frac{0.274}{c^2+1} + \frac{0.695}{c^3+1} \quad \text{(c is in KPa/100)} \tag{7}$$

$$\delta = f\phi \tag{8}$$

And in the above equations parameters are as follows:
Pipe external diameter D
Soil coherence inside channel c
Pipe axis depth from ground surface H
Specific weight of soil ϒ
Coefficient of soil pressure at rest K_0
Coherence ratio σ
Friction angle between pipe and soil δ
Soil internal friction angle φ
Coating dependant factor resulting from f
Soil internal friction angle and friction angle
Between pipe and soil
The following table is used to determine the coating dependant factor for different materials:

Table1: Coating dependant factor.

Material	f
Concrete	1
Coal tar	0.9
Hardened steel	0.8
Mild steel	0.7
Epoxy	0.6
Polyethylene	0.6

Also, displacement in axial force point transferred to pipe T_U is estimated by the below table:

Table 2: Estimation of displacement at transferred axial force point.

Soil type	deformation in millimeter
Dense sand	3
Loose sand	5
Hard clay	8
Soft clay	10

Soil lateral spring:

Regarding to the soil type available, soil lateral spring features are accounted. Next table shows ideal behavioral curve for soil spring.

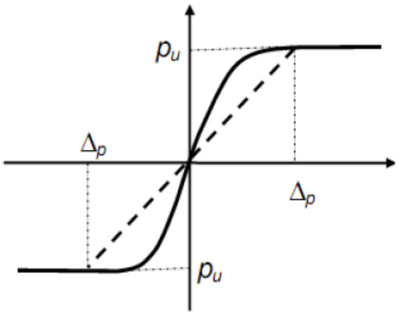

Fig. 4:. Ideal curve for lateral soil.

Maximum lateral force transferred to the pipe in length unit is:

$$P_u = N_{ch} cD + N_{qh} \gamma HD \quad (9)$$

$$N_{ch} = a + bx + \frac{c}{(x+1)^2} + \frac{d}{(x+1)^3} \le 9 \quad (10)$$

$$N_{qh} = a + b(x) + c(x^2) + d(x^3) + e(x^4) \quad (11)$$

Horizontal bearing capacity factor for clay (for soil Without coherence it is zero) N_{ch}

Horizontal bearing capacity factor (for soil without Internal friction angle it is zero) N_{qh}

Provided equations and the below table for N_{ch} and N_{qh} value determination are obtained by experimental results.

Table 3: N_{ch} and N_{qh} value determination.

Factor	ϕ	x	a	b	c	d	e
N_{ch}	0°	H/D	6.752	0.065	-11.063	7.119	--
N_{qh}	20°	H/D	2.399	0.439	-0.03	$1.059(10)^{-3}$	$-1.754(10)^{-5}$
N_{qh}	25°	H/D	3.332	0.839	-0.090	$5.606(10)^{-3}$	$-1.319(10)^{-4}$
N_{qh}	30°	H/D	4.565	1.234	-0.089	$4.275(10)^{-3}$	$-9.159(10)^{-5}$
N_{qh}	35°	H/D	6.816	2.019	-0.146	$7.651(10)^{-3}$	$-1.683(10)^{-4}$
N_{qh}	40°	H/D	10.959	1.783	0.045	$-5.425(10)^{-3}$	$-1.153(10)^{-4}$
N_{qh}	45°	H/D	17.658	3.309	0.048	$-6.443(10)^{-3}$	$-1.299(10)^{-4}$

N_{qh} value for soil with internal friction angle different from above table value can be calculated by interpolation.

In addition, displacement in lateral force point transferred to pipe P_u is obtained by the following equation:

$$\Delta_P = 0.04\left(H + \frac{D}{2}\right) \le 0.1D - 0.15D \quad (12)$$

Soil vertical spring:

Soil spring features for states of uplift or bearing are different. Probably, available soil features will be used, while for soil spring in uplifting state embankment features will be considered. The following Figure shows the ideal behavioral curve for soil vertical spring.

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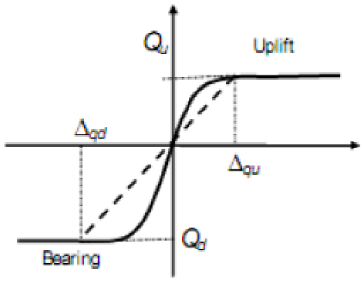

Fig. 5: Ideal curve for soil vertical springs.

A) Uplift:

The provided equation in this section to determine vertical force of springs to the soil is based on test results in small-scale and analysis models. This equation is applicable for surface and pipe`s being on surface or depth is based on ratio.

$$Q_u = N_{CV} cD + N_{qV} \gamma HD \quad (13)$$

Upward vertical force ratio (for the soil without coherence is zero) N_{ch}
Upward vertical force for sand (for the soil without internal friction angle is zero) N_{qh}

$$\left(\frac{H}{D}\right) \leq 10$$

Where

$$N_{CV} = 2\left(\frac{H}{D}\right) \leq 10$$

$$N_{qV} = \left(\frac{\phi H}{44D}\right) \leq N_q$$

$$N_q = \exp(\pi \tan\phi)\tan^2\left(45 + \frac{\phi}{2}\right) \quad (14)$$

Displacement in the place of vertical force transferred to the pipe Q_u is equal to:

For dense sand to the loose sand Δ_{qu} value is equal to:

$$0.01H - 0.02H \leq 0.1D$$

For hard clay to soft clay Δ_{qu} value is equal to:

$$0.1H - 0.2H \leq 0.2D$$

B) Vertical bearing

$$Q_d = N_c cD + N_q \gamma HD + N_\gamma \gamma \frac{D^2}{2} \quad (15)$$

N_c and N_q and N_Υ are bearing capacity ratios.

$$N_c = \left[\cot(\phi + 0.001)\right]\left\{\exp\left[\pi \tan(\phi + 0.001)\right]\tan^2\left(45 + \frac{\phi + 0.001}{2}\right)\right\} \quad (16)$$

$$N_\gamma = e^{(0.18\phi - 2.5)} \quad (17)$$

N_q is calculated based on the equation in the last section.

Displacement in the place of vertical force transferred to pipe Q_d is equal to:

Table4: Displacement estimation in place of vertical force transferred.

Soil type	deformation
Grained soil	0.1D
Cohesive soil	0.2D

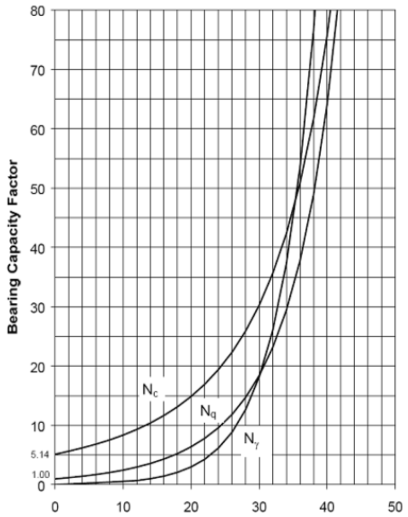

Fig. 6: Cohesive soil resistance rations for various values of soil friction.

Modeling buried pipe in Plaxis software:

Plaxis is software used for analyzing deformations and stability in geotechnical engineering projects. Usually, in major geotechnical issues, there is a need for an advanced behavioral model for modeling non-linear and time-dependant behavior of soils relative to desired purpose. By this software, one can model excavation and embankment with various loading and boundary conditions using 6 and 15 nodal triangle elements. First edition of this software was commissioned by water resource management of Netherlands in Delft Industrial University in 1987 to analysis earth dams constructed on soft soil in low level areas of this country. Then in 1993 it was extended and confirmed and supported by Center for Civil Engineering Research and Codes institution. In this software, behavioral models of Moher-Colomb, hardening hyperbolic model, softening model (Cam-Clay) and soft soil creep model are applicable. Also, developing and excavation process is done with this software by enabling and disenabling elements in calculation steps. One example of this application is layer analyzing in slope, dam and tunnel stability.

In the present research model 15 nodal triangle elements are used. Regarding that pipe length is more than its cross section, for convenience 2D model is used under plane strain 16. In addition, to achieve element relation between soil and pipe interface element 17 is used. On the other hand, to raise modeling accuracy elements surrounding pipe are considered finer. Furthermore, tunnel element with elasto-plastic behavior for pipe modeling is applied.

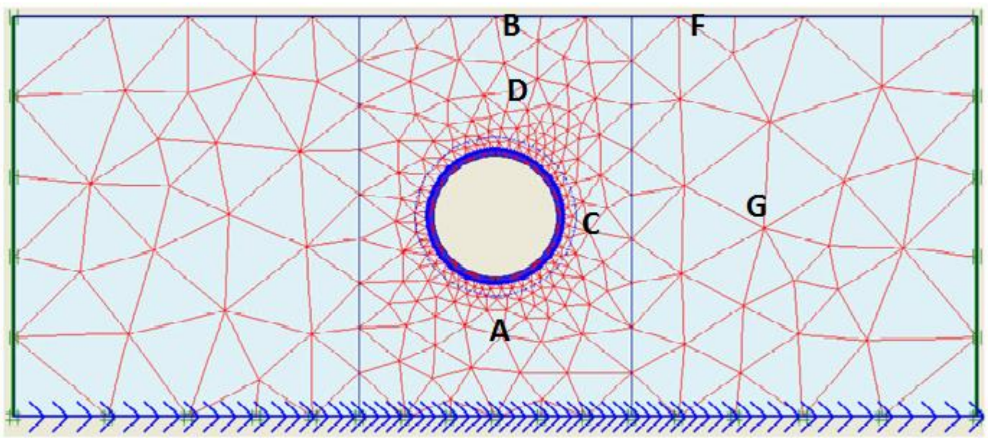

Fig. 7: Finite element model of buried pipe with 15 nodal element meshing.

Velocimetry applied for this model was harmonic which has various types with pga= 0.4g and 5Hz frequency, but all their time is 5 seconds.

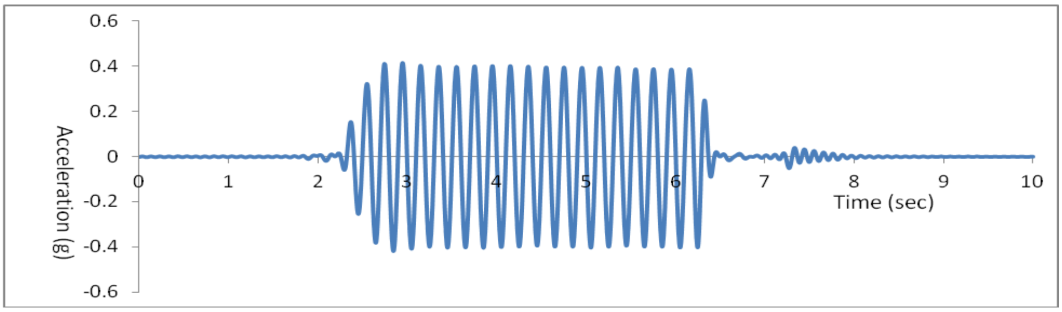

Fig. 8: Velocimetry applied for models.

Material:
Soil:

Used soil in this research is the combination of the following soils. In the present study, based on the hardening soil model three types of soil are used for modeling. Hardening soil model parameters are provided in the below Figure.

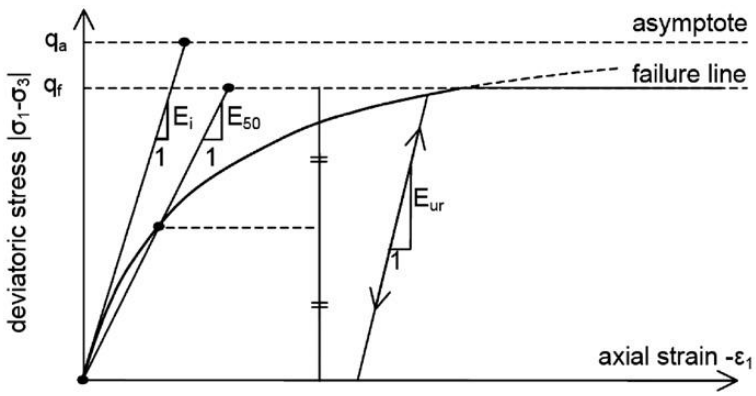

Fig. 9: Hardening soil model parameters.

1) Firoozkouh standard sand, 2) sand with 15 percent clay, and 3) construction sand

Firoozkouh 161 sand has density of dry grain 2/65Kg/cm^3. Also, sand with clay used in this study is the combination of Firoozkouh 161 sand and clay in the ratio of 1 to 0.15.

Soils parameters are obtained by triaxial tests in the state of undrained, as well as soil direct shear in Soil & Foundation Laboratory of Tehran University. Additionally, σ and ß Rayliegh parameters related to damping are obtained by trial and error.

Table 5: Soils parametric features.

Material	Internal friction angle φ_{uu}(deg)	Dilation angle (deg) ψ	$E_{ur}\,(Mpa)$	value β	value e0	Undrained cohesion c_{uu}(kg/cm^2)
Firoozkouh standard sand	30	1.9	35.8	0.98	0.647	0.152
Clay sand	32.5	3.7	53.2	0.98	0.682	0.192
Construction sand	33	4.2	76	1	0.637	0.258

Modeled pipe features are as follows:

Table 6: Used pipe features.

Nominal diameter in	material	Internal diameter mm	thickness mm	Elastic module‹E GPa	Bending rigidity‹EI kN.m^2	Axial rigidity‹EA, kN
4	steel	101.6	5.1	200	485.5	340507.43

Model dimension is a rectangular with 1.5 m height and 2 m width. The dimensions are selected such as boundary effects are minimized.

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Transaction between soil and pipe:

In this section, transaction between soil and pipe and influential parameters on them are studied. Compared parameters are 1) pressure on the pipe, and 2) strains on the pipe.

The effect of relative density of soil around pipe on pipe relative deformation:

To study the effect of soil density on seismic behavior of pipe two models are used. This means that two same stimulations once in loose sand and once in dense sand were applied on the pipe. Soil features in loose and dense states are as follows.

Table7: Sandy soils with various densities

$E_{ur}(mpa)$	$\psi(Deg)$	$\varphi(Deg)$	B –value	e_0	Dr (%)	type
35.8	1.9	32.5	0.98	0.737	40	Loose sand
82.7	44	38.3	1	0.439	70	Dense sand

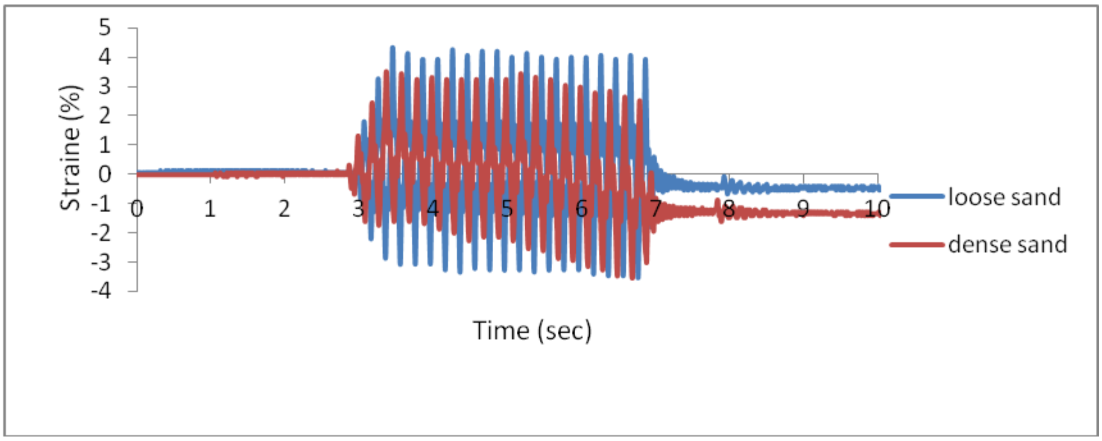


Fig. 10: Comparing strains on pipe in loose and dense sand.

To study relative density of soil around pipe on pipe relative deformation, diagram of c nodal strains in the right of pipe element was drawn and is shown in Figure 1.

As it can be seen in Figure 10 when soil is denser strain is more. Regarding this increase it can be said that when the soil is denser, pipe and soil coordination is more and transaction between soil and pipe is increased too. So, incurred force on pipe is higher.

The effect of relative density of soil around pipe on incurred force on pipe:

Incurred force in node C is considered to study the effect of relative density of soil around pipe on incurred force on pipe. So one can say that when the soil around pipe is denser transaction between soil and pipe is raised. This result is consistent with findings about strains in the last section.

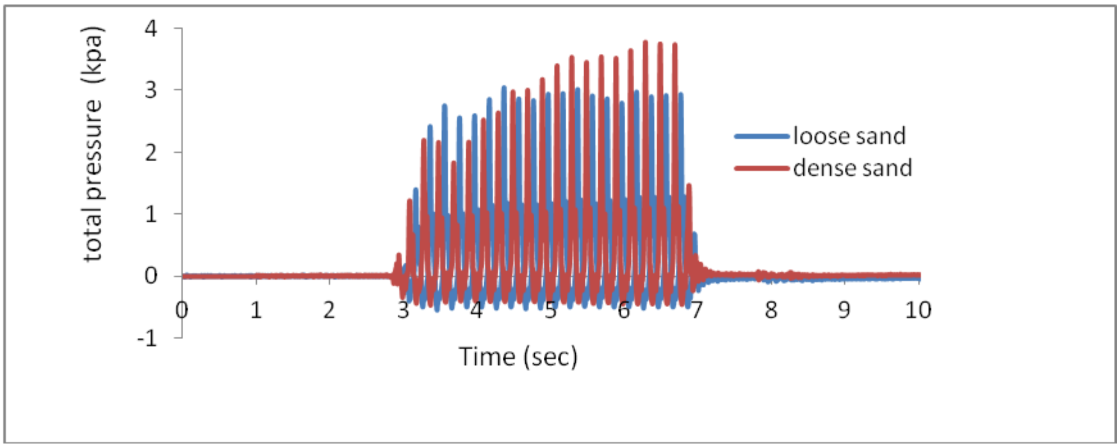


Fig. 11: Comparison of incurred force on pipe for loose and dense sand.

There are two views about density effect on transaction between soil and pipe. First view: when the soil around pipe is loose, then there is more resonance in soil; that is velocity resonance factor increases. In turn, this increase raises the velocity and therefore incurred force on pipe grows.

Second view: when the soil around pipe is dense. Soil density around pipe raises the coordination between pipe and soil. In addition, density increase makes lateral force on pipe more. Thus, in this way incurred force on pipe increases. According to the comparison of bearing and strain on the pipe in two cases of dense and loose soil it can be concluded that transaction between soil and pipe is higher when soil around pipe is denser. Therefore, effect of lateral bearing on pipe in the case of density is higher than effect of velocity increase in loose soil.

Effect of relative density on resonance ratio results:

Figure 12 is drawn to determine the relation between soil density around pipe and resonance phenomena. This diagram shows resonance ratio in different levels of soil for a model with 0.4 g velocity and 5Hz frequency in both loose and dense soil. As it can be seen, whether under pipe level in depth of 65 cm or higher levels in trench, there is no difference in resonance. It can be said that density has no effect on resonance factor.

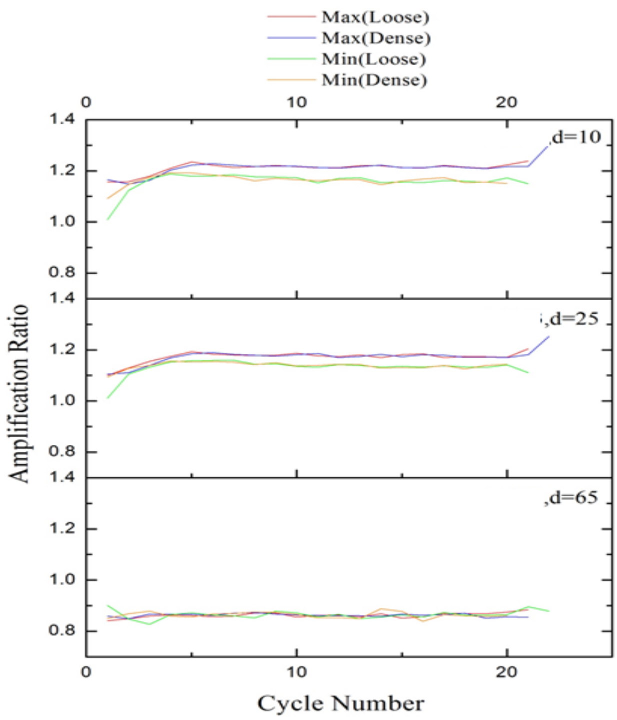
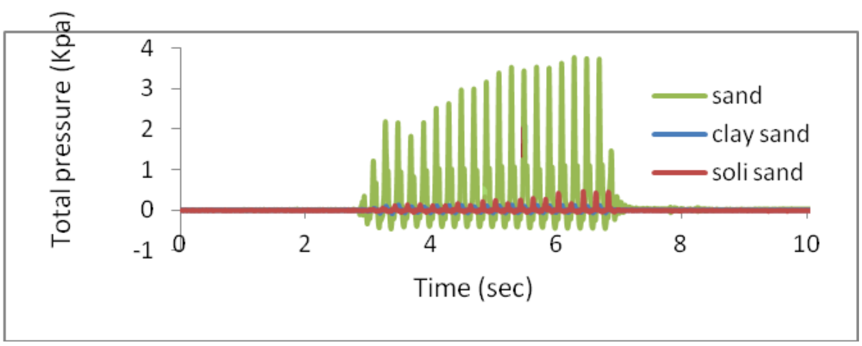


Fig. 12: Resonance factor based on cycle numbers.

Effect of soil type on incurred force on soil from pipe:

In developed models to study effect of soil type around pipe on incurred force on pipe, three types of soil, Firoozkouh 161 sandy soil, Firoozkouh clay sand, and construction sand under same conditions were used. Features of these soils are provided in table 2. According to Figure 13 it can be seen that Firoozkouh 161 sand has the most bearing on pipe. In addition, bearing amount, in the case of Firoozkouh clay sand, shows the least bearing.



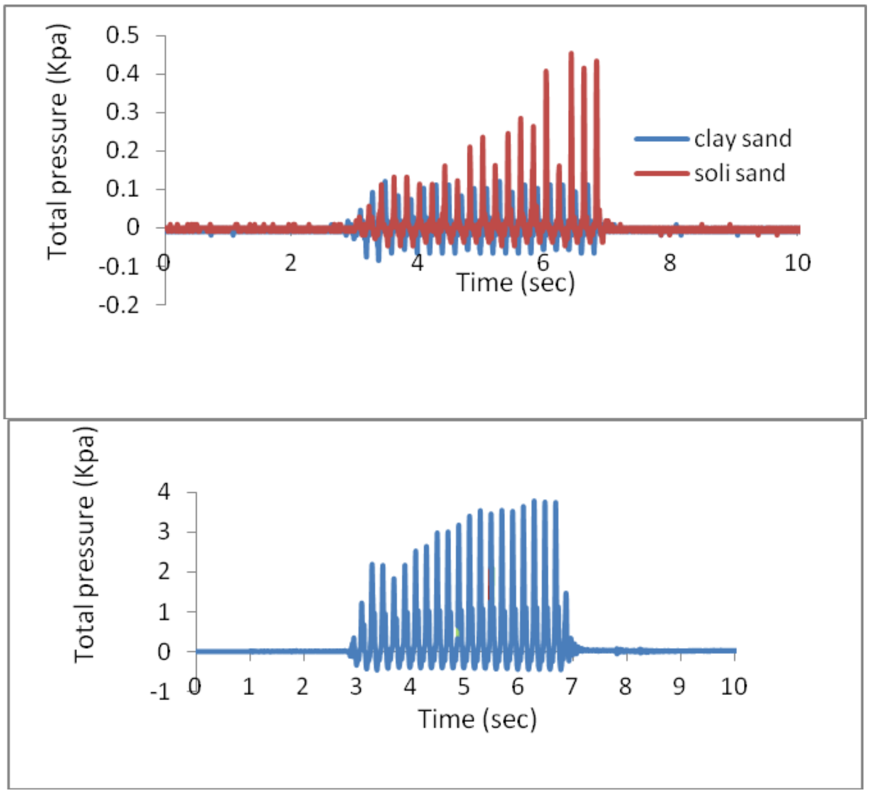


Fig. 13: Comparison of bearing on buried pipe for three types of soil.

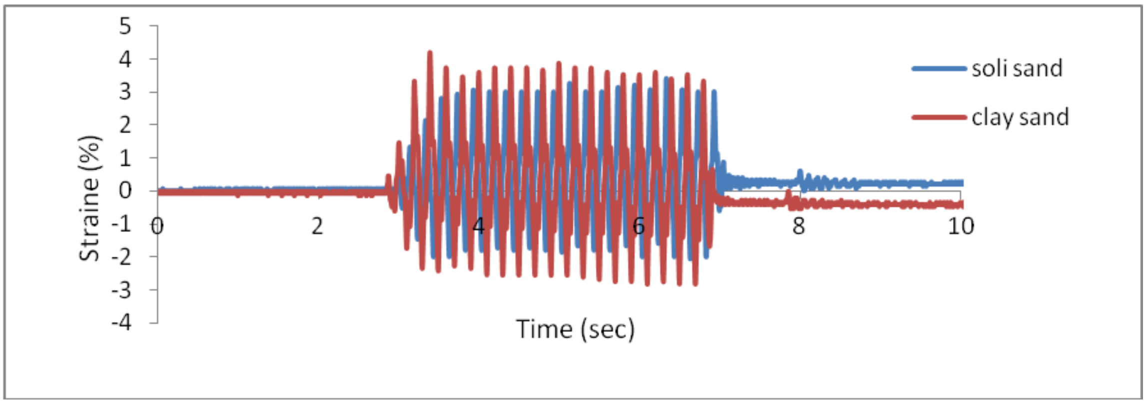


Fig. 15: Comparisons of pipe strains under cyclic charge in two types of construction and clay sand soils

As it is clear strains amount on pipe in cohesive soil is more than construction sand soil, and this implies that cohesion increase results in rising incurred force on soil from pipe.

Conclusion:

According to the obtained results from this research it can be said that first high density of soil makes incurred force on pipe more, and therefore results in more relative deformation of pipe. So it is recommended that soil used around pipe in trench should be screened and has low density. Also, it can be said that more the soil cohesion less the incurred bearing on pipe, and pipe will show better performance.

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