Design Charts for Pipelinesunder Longitudinal Soil Loading

Selcuk Toprak, Volkan Helva, A. Cem Koc

***Abstract* – Buried pipelines are important part of the infrastructure systems. These pipelines extent long distance and cover wide areas where they may be exposed to several hazards. This study presents design graphs for the pipelines under longitudinal soil loading, such as lateral spreading due to liquefaction after an earthquake or landslides. Performance of buried pipelines during this type of loading is affected by many factors related to geotechnical properties of the surrounding soil and physical properties of pipe itself and its coating. Also the extent of moving ground and the magnitude of ground movement are important. Design charts(abaques) are expected to help engineers design straight continuous pipelines or analyze pipeline performance for expected longitudinal ground movements without performing finite element analysis or using analytical models.**

***Keywords* –Buried Pipeline, Design,Earthquake, Permanent Ground Deformation**

1. INTRODUCTION

Buried pipelines can be damaged significantly by moving ground which may result from lateral spreading due to liquefaction after an earthquake and land sliding. In general, pipelines are placed into the soil close to the ground surface, e.g. 1 m. Because of the deeper ground water table and/or soil type, the pipeline is mostly in non-liquefiable soil layer. However, if the underlying soil is liquefiable then lateral spreading can still be expected. This paper deals with pipeline performance under such condition and especially for the case of longitudinal ground movement. In other words, pipeline orientation is in the same direction with the ground movement.

There are different methods to analyze pipelines under longitudinal soil loading. For example, reference [1] proposed an analytical model based on the sliding block model. References [2]and [3] used and verified this model with the pipelines and soil

Prof. Dr S Teprak Pamukkale University, Denizli, Turkey (phone: +90-258-2963352; fax: +90-258-2963460; e-mail: stoprak@pau.edu.tr).
Graduate Student Volkan Haelva is with Pamukkale University, Civil Engineering, Denizli, Turkey (e-mail: vhelva09@posta.pau.edu.tr).
Ass.Prof. Dr.A.Cem Koc is with Pamukkale University, Denizli, Turkey(e-mail: a_c_koc@pau.edu.tr).

information from the Balboa Blvd. and the 1994 Northridge earthquake case study. Another common approach to analyze pipelines under longitudinal soil loading is the finite element method. Reference [4] presented their finite element analysis results for the same case study from the Balboa Blvd. and the 1994 Northridge earthquake. They used DIANA finite element program for theanalysis of four continuous pipelines, two of which failed and two of them were not damaged.

Performance of buried pipelines during this type of loading is affected by many factors related to geotechnical properties of the surrounding soil and physical properties of pipe itself and its coating [5]. Also the extent of moving ground and the magnitude of ground movement are important. In this study, design charts(nomograms, abaques) were produced to help engineers design pipelines or analyze pipeline performance for expected longitudinal ground movements without performing finite element analysis or using analytical models. Buckingham Pi Theoremwas used to find the appropriate dimensionless parameterfor the correlations.

2.SOIL-PIPE INTERACTION

The load transfer during the soil movement occurs as result of the frictional forces between soil and pipeline. Depending on the extent of moving ground and the magnitude of ground displacement, zero shear transfer conditions in the zone can be developed. The frictional force per unit length, f_m at the pipe-soil interface and L_e is the effective length over which f_m acts. The frictional force can be expressed by:

$$f_m = (c + \mu \times \bar{\gamma} \times H) \times \pi \times D (1)$$

where c is the soil cohesion, μ is the coefficient of friction at the soil-pipe interface, γ is the effective unit weight of soil, H is the depth to centerline of the pipeline, and D is the outside diameter of pipe.Using a Ramberg-Osgood model for the pipe material, the pipe strain, ε_{max} , can be expressed as follows:

$$\varepsilon_{max} = \frac{\beta_p L_e}{2\,E} \times \left\{1 + \frac{n}{1+r}\left(\frac{\beta_p L_e}{2\,\sigma_y}\right)^r\right\} (2)$$

In which n and r areRamberg-Osgood parameters, E is the modulus of elasticity of pipe steel, σ_y is the effective yield stress, β_p is the pipe burial parameter. For granular soil (c = 0), the pipe burial parameter β_p can be computed by:

$$\beta_p = \frac{\mu\,\bar{\gamma}\,H}{t} (3)$$

in which the frictional coefficient,$\mu = k\ \tan\varphi$, φ is the soil friction angle, and k is a coefficient related to the conditions at the soil pipe interface. Representativevalues of k for various types of external pipe coatings are as follows[6]:Concrete (1.0); Coal Tar (0.9); Rough Steel (0.8); Smooth Steel (0.7); Fusion Bonded Epoxy (0.6); Polyethylene (0.6). Yield strength performance must be well defined for use in analytical method. For this identification most widely used model is Ramberg and Osgood model [7]. The Ramberg-Osgood parameters defined in Equation 2 for various common grades of steel are listed in Table 1.

Table 1. Yield Strengths and Ramberg-Osgood Parameters for Mild Steel and X-Grade Steels[8]

	Grade B	**X-42**	**X-52**	**X-60**	**X-70**
Yield Strength (MPa)	227	310	358	413	517
n	10	15	9	10	5.5
r	100	32	10	12	16.6

3. ANALYSIS

Design chartshave been produced herein for use by engineerswithout applying finite element or analytical analysis. Users can find the strain practically by using these design charts if the ground motions isparallel to the pipe axis (Figure 1). Design chartsconsist of dimensionless parameters. In this study,Buckingham Pi-Theorem was used to get dimensionless parameters[9]. The Pi-theorem can be stated as follows. Let some dimension physical quantities a depend on n dimensional parameters $a_1 . a_2 \cdots a_n$, where k of them have an independent dimension. Then the functional equation for the quantities a;

$$a = f(a_1 . a_2 \cdots a_k, a_{k+1} \cdots a_n) \quad (4)$$

can be reorganized n - k dimensionless equation

$$\pi = \varphi(\pi_1 . \pi_2 \cdots \pi_{n-k}) \quad (5)$$

That contain n – k dimensional variables. The latter are expressed as;

$$\pi_1 = \frac{a_1}{a_1^{x_1^1} a_1^{x_2^1} \cdots a_k^{x_k^1}}, \pi_2 = \frac{a_2}{a_1^{x_1^n} a_1^{x_2^n} \cdots a_k^{x_k^n}} \cdots \pi_{n-k} = \frac{a_k}{a_1^{x_1^{n-k}} a_1^{x_2^{n-k}} \cdots a_k^{x_k^{n-k}}} \quad (6)$$

Dimensional analysis is performed to parameters affecting shape variations. Unitsbased on FLT (Force-Length-Time) system of parameters are given in Table 2.

Table 2. Physical Parameters used in Dimensional Analysis

Symbol	Meaning	Unit	The Dimension of FLT system
D	Pipe outside diameter	mm	L
H	Depth to center-line of pipeline	mm	L
$\bar{\gamma}$	Effective unit weight of soil	N/mm^3	F/L^3
t	Wall thickness of pipe	mm	L
σ	Yield strength	N/mm^2	F/L^2
L	Length of PGD	mm	L
E	Modulus of elasticity	N/mm^2	F/L^2
δ	Permanent displacement of ground	mm	L
L_B	The length of pipeline system	mm	L

Dimensionless π terms was found by using Dimensional Analysis Technique and Buckingham π Theorem;

$$\pi_1 = \frac{H}{D} \qquad \pi_2 = \frac{D \times \bar{\gamma}}{\sigma} \qquad \pi_3 = \frac{t}{D} \qquad \pi_4 = \frac{E}{\sigma}$$

$$\pi_5 = \frac{L}{D} \qquad \pi_6 = \frac{L_B}{D} \qquad \pi_7 = \frac{\delta}{D}$$

πterms can be used to have another dimensionless parameters. Different operations were tried to get such a parameter, S_P. This parameter is defined as

$$S_P = \frac{L\,H\,\bar{\gamma}}{t\,\sigma} \tag{8}$$

Parameter works for steel pipes up to 1000 millimeter diameter and for cohesionless ground. Calculations were made for ground displacements (δ) between 0,25 to 4 meters. Results show that strain is smaller under 0,25m ground displacement therefore it was not included in production of the graphs. In essence, the design charts provides conservative value for the ground displacements less than 0,25 m.

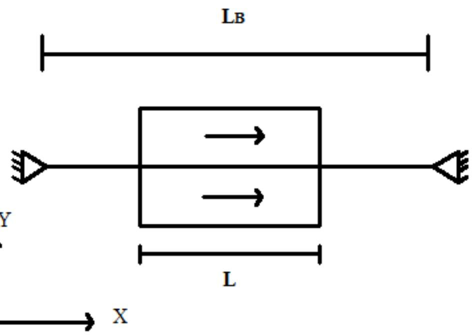

Fig. 1. Ground motion parallel to the pipe axis

S_p parameter is correlated with strain calculated from Equation 2 for steel pipe which has 227 MPa yield strength. Also finite element analyses were performed. Many different combinations of different burial depth, wall thickness, ground conditions, length and size of the ground motion were used to develop the correlations shown in Fig 2.The horizontal axis indicates strains whereas the vertical axis indicates S_p values. It was noted that strains increases as the frictional coefficient $k\ \tan\varphi$increases. Dots (a pair of S_p and strain)in Fig. 2 correspond to different frictional coefficients. The lines were obtained from the data points by using 6^{th} degree polynomial equation. Values corresponding to intermediate frictional coefficients can be found by interpolation.

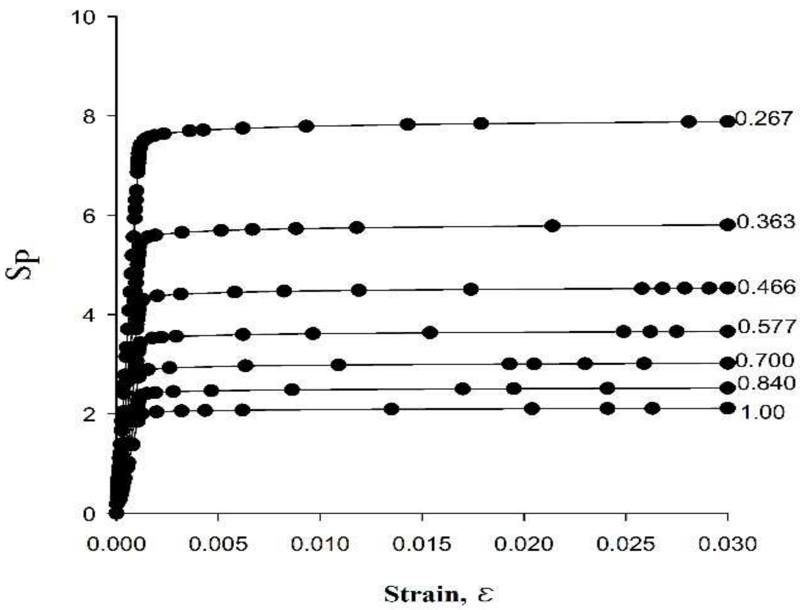

Fig 2. Design charts for steel pipe withσ_y= 227 MPa

4. RESULTS AND CONCLUSIONS

Thousands of analyses were performed to prepare design charts for steel pipes with different yield strengths. Figure 3 and 4 provides the charts for yield strengths of 310, 358, 413 and 517 MPa. An example is presented below on how to use these correlations in pipeline design.

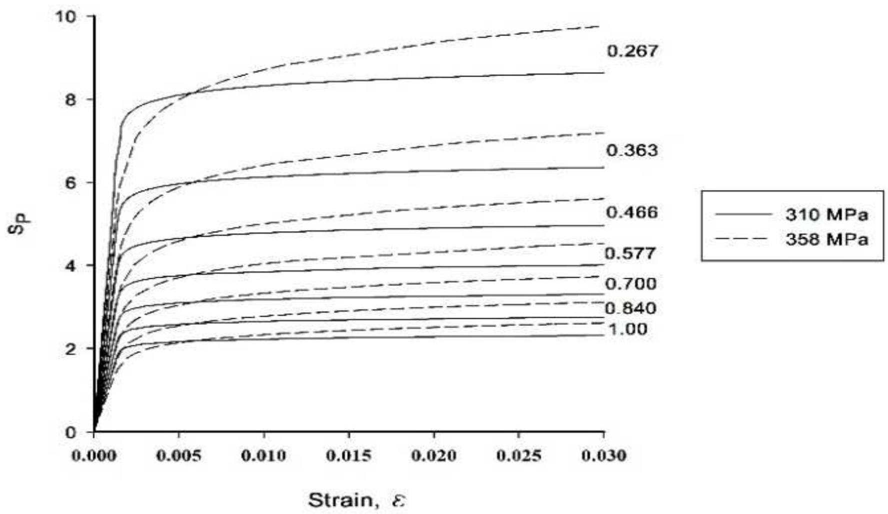

Fig. 3. Design charts for steel pipe with σ_y= 310 and 358 MPa

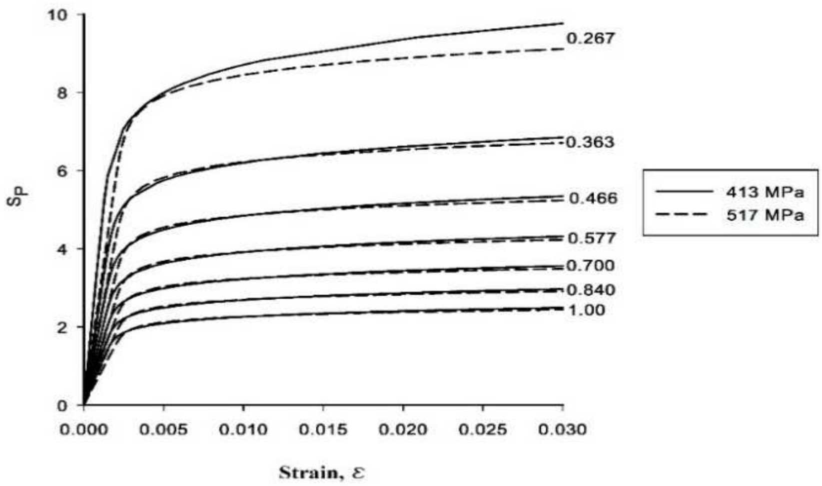

Fig. 4. Design charts for steel pipe with σ_y=413 and 517 MPa

Example

The conditions for the planned pipeline and soil conditions are as follows: diameter of pipe, D = 406 mm, wall thickness of pipe, t = 7.9 mm, yield strength,σ_y = 358 MPa, Ramberg-Osgood parameters, n = 9, r = 10, length of pipeline system,500 m, $\bar{\gamma}$ = 19,65kN/m^3, soil friction angle,φ = 35°, burial depth H = 1.5 mand coating material of pipe is concrete,k= 1. The expected displacement (δ)of the moving ground where pipeline is located is: 0,4 m. The predicted length (L) of the moving ground is: 250 m and 350 m. The design question is: the strain in the pipeline is at acceptable levels to Eurocode 8 Part 4?

First step is the calculationof S_P parameter which requiresthe conversionof the units:L = 250 m, H = 1.5 m, $\bar{\gamma}$ = 19.65 kN/m^3, t = 0.0119 m, σ = 358000 kN/m^2. Then,$S_P = \frac{250\times1.5\times19.65}{0.0079\times358000}$= 2.605. $S_P = \frac{350\times1.5\times19.65}{0.0079\times358000}$= 3,65.The second step is to calculate friction factor to determine the appropriate curve: k = 1, f = 35°, $\mu = 1 \times \tan 35$, $\mu = 0.7$. The last step is to read the strain values from the graphs for the steel pipe withσ_y = 358 MPa as shown in Fig. 5. The result is '0.00217 = 0.217 %' and '0.0239 = 2.39 %'.

The limits from Eurocode 8 Part 4 are: tensile strain limit: 3%, compressive strain: limit {Min. 1%; 20t/D (%)}. Accordingly, the compressive strain limit is:$20 \times \frac{0.0079}{0.406}$ =0.39 %. The results show that the pipe is safe for 250 m ground displacement whereas not safe for 350 m ground displacements. Design parameters should be changed.

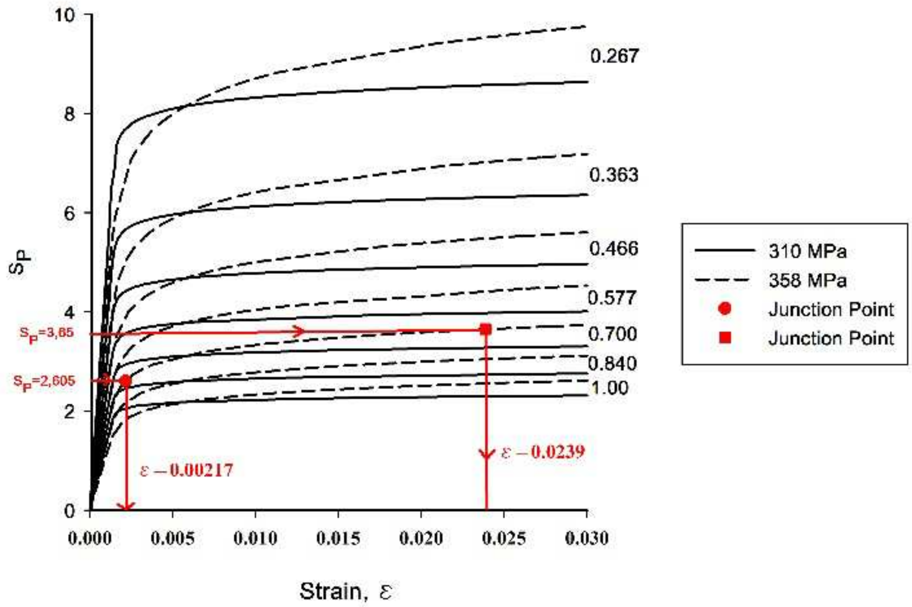

Fig. 5. Pipeline design example for steel with σ_y=358 MPa

The design charts presented herein applicable for the straight continuous steel pipelines under longitudinal soil loading. Other different cases such as network of pipelines as in water/gas distribution system of an urban area, segmented pipelines and other type of pipe materials are being studied and will be presented in future publications.

5. ACKNOWLEDGMENTS

The research reported in this paper was supported by Scientific and Technological Research Council of Turkey (TUBITAK) under Project No. 114M258. Partial grant provided by PAU BAP to attend the conference is acknowledged.

6. REFERENCES

[1] O'Rourke, M. J., Nordberg, C. (1992), Longitudinal Permanent Ground Deformation Effects on Buried Continuous Pipelines, NCEER-92-0014, NCEER, Buffalo, NY.
[2] Toprak, S. (1998), Earthquake Effects on Buried Lifeline Systems, PhD Thesis, Cornell University, Ithaca, NY.
[3] O'Rourke, T. D. and Toprak, S. (1995), Case History of Pipeline Response to Ground Deformation at Balboa Blvd., 1994 Northridge Earthquake., Proceedings, Sixth U.S. - Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems, Osaka, Japan, Pp: 3-20.

[4] Toprak, S., Nacaroğlu, E., Koç, A. C. 2015. Seismic Response of Underground LifelineSystems, Perspectives on European Earthquake Engineering and Seismology,Geotechnical, Geological and Earthquake Engineering 39, Edited by Atilla Ansal, Volume 2.
[5] Toprak, S.; Çetin, O. A.; Nacaroğlu, E.; Koç, A. C., (2010), "Pipeline Performance Under Longitudinal Permanent Ground Deformation", Paper No: 1407, 14th European Conference on Earthquake Engineering (14th ECEE 2010), Ohrid, Macedonia.
[6] American Lifelines Alliance (ALA). (2001). Seismic Fragility Formulations for Water Systems, Part 1- Guideline, [Online] at availablewww.americanlifelinesalliance.org.
[7] Ramberg, W. and Osgood, W., (1943), Description of Stress-Strain Curves by Three Parameters, Technical Note, No. 902, National Advisory Committee for Aeronautics, 28p.
[8] O'Rourke and Liu, Response of Buried Pipelines Subject to Earthquake Effects, Part 4, Page 60, 1999.
[9] L.P. Yarin, Applications to Fluid Mechanics and Heat and Mass Transfer, Part 2 Basic of the Dimensional Analysis 2012.
[10] European Standard(2006). Eurocode 8 - Design of structures for earthquake resistance -Part 4: Silos, tanks and pipelines