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ANALYSIS OF BURIED PIPES UNDER TRAFFIC LOADING ACCOUNTING FOR SOIL-STRUCTURE INTERACTION

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***Abstract**: Concerning the buried pipes of water, sewage or gas networks, it is so important to develop design methods based upon soil-structure interaction that consider static and dynamic loads. Establishing appropriate design methods requires good recognition of soil-pipe interaction, combined soil-pipe system behavior and the effective factors regarding the applied loads. Such knowledge can be obtained through suitable numerical analysis of physical model of the pipes under dynamic loads of which is the traffic loading. Since finite element method is a successful method for studying many of geo-mechanic problems, in this paper ABAQUS 6.8-1 which is a 3D finite element software is used for numerical analysis of soil-structure system. In this work, C3D20R continuous 20-node element with reduced integration is adopted. In order to lessen the computing efforts, half trench is modeled only, considering the symmetric property. Such method has many advantages for presenting stress distribution and relative deformations in soil and in the structure and releases much information about soil-structure interaction properties. In this paper, useful information has been resulted concerning the arcing phenomena and optimum burial depth of the pipes.*

***Keywords**: buried pipes; soil-structure interaction; traffic loading; arcing phenomena.*

INTRODUCTION

Designing ductile buried pipes is one of the important engineering problems. For a correct design, it is necessary to have a good insight of soil-pipe interaction process. Such process has two useful effects which increase the load bearing capacity of the pipe; 1) decreasing the stress at the top of the pipe, 2) limiting the strain along the horizontal diameter.

Although the true nature of the action involved not yet fully understood, but that certainly depends on several factors such as burial depth, applied load intensity, the relative position of the pipe placement and loading plane and trench wall, and the relative density of materials. Dynamic analysis of buried pipelines during recent decades has been paid attention by many researchers. In the oldest and simplest method, it is assumed that the maximum axial strain of the buried pipe is

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equal to the maximum strain of the soil around the pipe, (Newmark, 1967). In such method, the soil around the pipe has been modeled as elastic or elastoplastic springs together with dampers. It is obvious that for soil, the pseudo static analysis and simple models with springs do not properly account for perfect effects of nonlinear behavior and properties. On the other hand, the finite element method as a direct numerical analysis method for soil environment can provide much information.

In this article, using the finite element method, a two-dimensional model of the buried pipe is analyzed by defining and implementing the model parameters.

EXPERIMENTAL MODEL; FINITE ELEMENT MODEL

Since the aim of this paper is numerical analysis of the pipe buried in the soil, a finite element model is generalized comparing the experimental model results and the results of the finite element model. At the end several numerical examples are considered.

Describing the Experimental Model

The laboratory model includes a rigid metal box with dimensions of 20*80*80 cm (test tank) which contains the modeled soil and pipe. Loading system consists of an air cylinder, a compressor for producing compressed air for applying static load and cyclic vertical load with maximum frequency of one Hz, a 60-channel system information recording having 0.1 second speed, three pressure cells to determine the compressive and shear stresses at the border of the trench, a special radial gauge to determine radial deformation of pipes in 8 point on the pipe and the load cell to measure the exact value of the cyclic vertical load applying on the trench surface, (Hosseini, 2000, Hosseini, 2002).

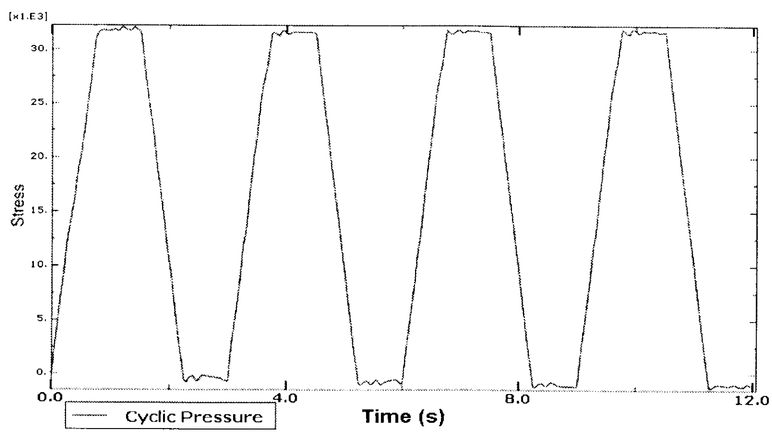

Fig. 1. History of applied cyclic load with frequency of 0.33 Hz.

The type of the materials used are sand with particle size between 0.38 and 1.04 mm and curvature coefficient between e=1.01 and e=0.68. Experiments have been done in the relative density of 85%. Test tubes are made of flat sheet of spring steel with thickness of 0.4 mm, width of 200 mm, Young's modulus of 210000 kg/cm^2 and Poisson coefficient of 0.3. Figure 1 indicates the history of cyclic stresses applied to the experimental and finite element models.

Finite Element Model and a brief description of the ABAQUS software and its features

For numerical analysis of soil-pipe, in ABAQUS software, a two-dimensional finite element mesh with length of 80 cm and height equal to at least 35 cm which are the same as length and height of the experimental model has been used. In this model the element B21 (two-dimensional beam element with the ability to withstand bending and axial force) and for soil the element CPE4R (four node element of plane strain type with reduced integration property) is used, (Tajaddini, 2009), (see Fig. 2).

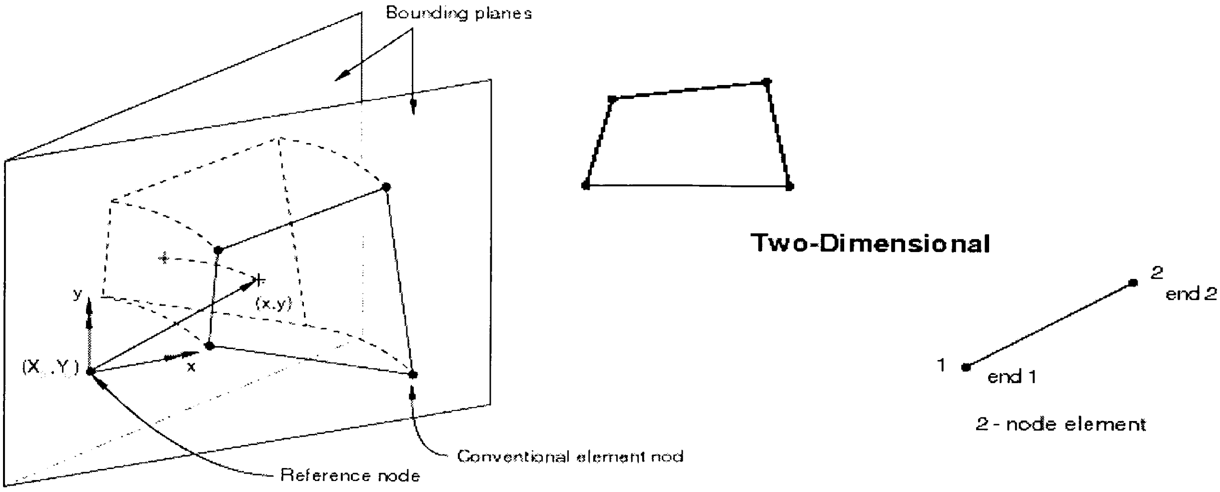

Fig. 2. Elements of B21 and CPE4R.

In 1999 the first graphic version of this software as ABAQUS / CAE has been released to the market. The main feature of this version is having models with advanced behavior for different materials such as metals, rubber, foam, visco-elastic materials, piezoelectric materials, concrete, soil, polymers, liquids, etc. Each modeling process in ABAQUS / CAE includes 9 stages that here, two stages are described briefly

Interaction of soil and pipe

In this section the interaction mechanical behavior (such as friction) and thermal (such as heat transfer) between components are defined and applied. The restraints and the connections of the model must be defined and applied at this stage.

Loading and applying boundary conditions

Loading is in cyclic manner with the amount of 0.5 kg/cm^2 on a plane at the top of the pipe having width D. Generally, for modeling the traffic load which is defined in a trapezoid form, q (t) can be defined as below.

$$q(t) = \begin{cases} \frac{q_{\max}}{\alpha_1 t_0} t & 0 \le t \le \alpha_1 t_0 \\ q_{\max} & \alpha_1 t_0 \le t \le \alpha_2 t_0 \\ \frac{q_{\max}}{(1-\alpha_2)}\left(1 - \frac{t}{t_0}\right) & \alpha_2 t_0 \le t \le t_0 \\ 0 & t_0 \le t \le \alpha_3 t_0 \end{cases} \tag{1}$$

which in Fourier series is as follows,

$$q(t)=\frac{1}{2}a_0+\sum_{n=1}^{\infty}a_n\cos\left(\frac{n\pi t}{L}\right)+b_n\sin\left(\frac{n\pi t}{L}\right) \tag{2}$$

$$a_n=\frac{1}{L}\int_{-L}^{L}q(t)\cos\left(\frac{n\pi t}{L}\right)dt=\frac{2}{\alpha_3 t_0}\int_0^{\alpha_3 t_0}q(t)\cos\left(\frac{2n\pi t}{\alpha_3 t_0}\right)dt \tag{3}$$

$$b_n=\frac{1}{L}\int_{-L}^{L}q(t)\sin\left(\frac{n\pi t}{L}\right)dt=\frac{2}{\alpha_3 t_0}\int_0^{\alpha_3 t_0}q(t)\sin\left(\frac{2n\pi t}{\alpha_3 t_0}\right)dt \tag{4}$$

The Fourier coefficients are found and then are implemented in the software.
Numerical model boundary conditions are according to the conditions created by experimental model. It is assumed that there are no changes due to the applied loads in the environment beyond the boundary nodes. Otherwise, it is necessary to use specific boundary conditions (such as spring supports, absorbent borders and...) instead of closed boundary conditions. Because of selecting appropriate tank dimensions (3 to 4 times the pipe diameter from the center of the tank to the walls), especially for symmetric modes, rigid boundaries have no effect on system response. Thus simulation as rigid boundaries cannot create any problem. Figure 3 shows the finite element mesh and the boundary conditions. It must be noted that the numerical analysis presented in this paper is for the case of buried pipes while the loading plane is located at the center of the trench.

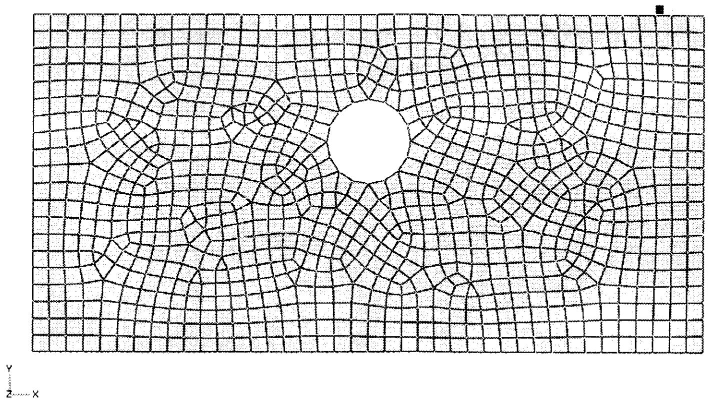

Fig. 3. Finite element mesh.

MODEL EVALUATION

In a suitable numerical analysis, matching much of the actual behavior of the model with empirical studies is of great importance. Therefore, for comparing numerical results with laboratory studies, understanding the model and determining the parameters is crucial. In general, among the behavioral models of ABAQUS program, Drucker Prager model has good compatibility with the behavior of dry sand. In the present model the relationship between stress and strain is approximated with a hyperbolic curve. Also, in this model the soil stiffness depends on the stress which is one of the other features of this model. Implementation of better numerical model with experimental model requires knowledge of the sensitivity of numerical model to its parameters. In order to measure this sensitivity, many analyses are performed for the situation of the pipe located at the center with burial depth D under cyclic stress of 0.5 kg/cm^2, and the history of deformation of the pipe crown is found for each case as shown in Fig. 4. The parameters ψ (angle of dilation of soil), **ν** (the Poisson ratio), φ (friction angle of soil) and E (modulus of elasticity of soil) are measured. According to the results obtained, it can be seen that the sensitivity of the model to the parameters φ and E is higher.

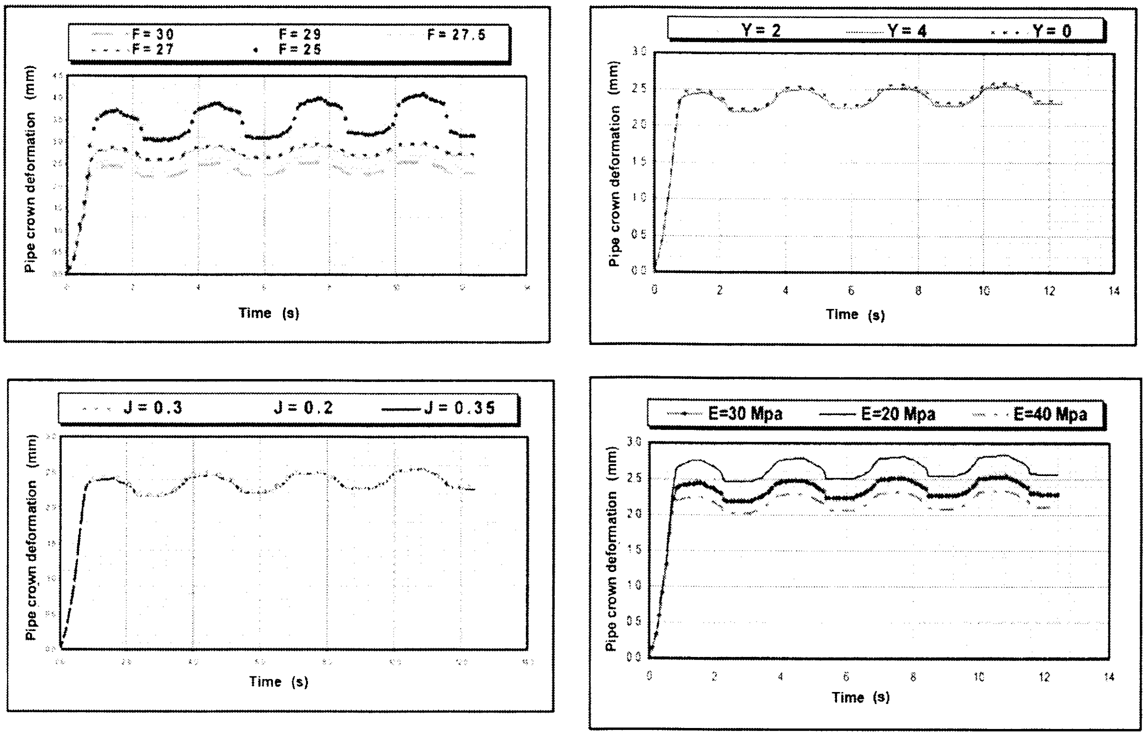

Fig. 4. Sensitivity of the model with respect to different parameters.

For better simulating the numerical model with physical model, values of the model parameters are determined based upon the results of sensitivity analysis using try and error method; and with comparison of numerical and physical model concerning the test of the pipe buried at depth D in the center, under cyclic stress of 0.5 kg/cm^2, (see Table 1).

Table 1. The selected values for the model parameters

dγ	wet γ	ϕ	ψ	E_{50}^{ref}	E_{ur}^{ref}	ν	m	R_f
kN/m^3	kN/m^3	Degree	Degree	kN/m^2	kN/m^2	-	-	-
16	18	31	0.3	30	150	0.2	0.5	0.8

CASE STUDIES

As mentioned earlier, the effects of various factors on the behavior of the pipes buried in soil under vertical cyclic loading (such as wheels of the vehicles like cars and trains) are of particular importance. Considering the efficiency and capability of the system designed, the number and diversity of the cases investigated are chosen such that to quantitatively and qualitatively express the effects of burial depth on the pipe, the effect of eccentricity, the effect of using two pipes instead of a pipe and considering the effect of the burial depth on the arcing phenomena. In order to facilitate identification of each test, the cases are coded as follows:
1PXYZ(A) or $2P_i$XYZ((A) in which,
1P or 2P: indicates the number of pipe (1P: one pipe and 2P: two pipes)
X: indicates the position of the pipe from the centre of the tank which varies from zero to 2D.
Y: indicates the position of the load from the centre of the tank which varies from zero to 2D.
Z: indicates the buried depth of the pipe which varies from zero to 2D.
A: indicates the maximum amount of stress of the cyclic load.
i: In case of two pipes indicates the distance between two pipes which varies from 0.5D to D.
For example, 1P021 (0.5) means that the test is performed for a pipe buried in the center tank and depth D, under a cyclic load with amplitude of 0.5 kg/cm^2 and with an eccentricity of 2D.

Effect of Burial Depth

Figure 5 shows the burial depth of the pipe for compressed state of soil in the first cycle of loading. In this analysis, the concerning depths are: D, 1.5D and 2D, as is observed. For a specific cycle of loading, the slope of the graph between burial depths D to 1.5D is much greater than the slope of the graph between 1.5D to D. This fact states that in more burial depth, the amount of the stress incurred at the top level of the pipe due to the arcing action of the soil located on the pipe is reduced significantly, (About 80%). Hence, increasing the burial depth of pipes decreases the pipe and the soil deformation.

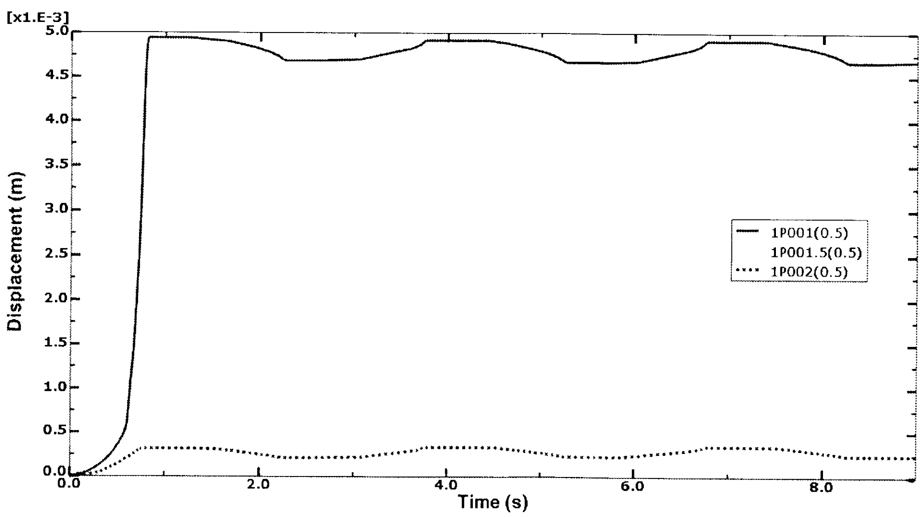

Fig. 5. Amount of deformation of the pipe crown in the first cycle for the cases: 1P001(0.5), 1P001.5(0.5) and 1P002(0.5).

Effects of Load Eccentricity

Figure 6 shows the effects of three amounts of the load eccentricity; zero, 1D and 2D, obtained from the numerical analysis for the case of compact soil and the pipe located in the center and under cyclic stress of 0.5 kg/cm^2. As Fig. 6 indicates, regardless of the load cycle, the maximum deformation is reduced considerably. Therefore, it can be said as a general result, the worst case of the pipe deformation, in other words, the least load for pipe failure is when the plane of loading and the pipe are concentric, (Tajaddini, 2009).

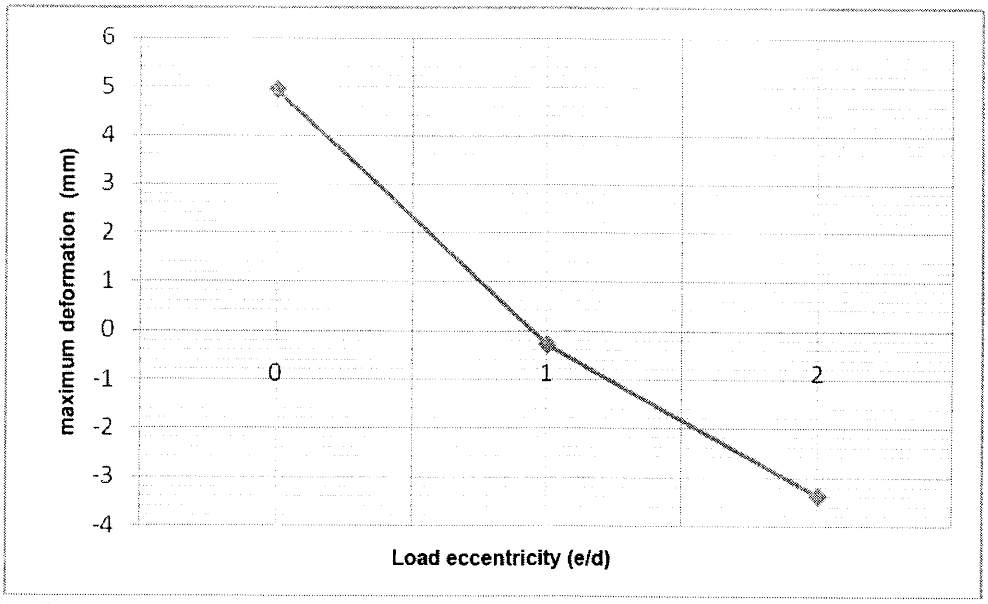

Fig. 6. Effect of load eccentricity on the maximum pipe crown deformation.

Using Two Pipes Instead of One Pipe

Using two pipes in a trench for the same flow as is for one pipe one can dramatically reduce the deformation caused in the pipe crown. The distance between two pipes also influences the vertical and horizontal deformation, (Figures 7 and 8), (Tajaddini, 2009).

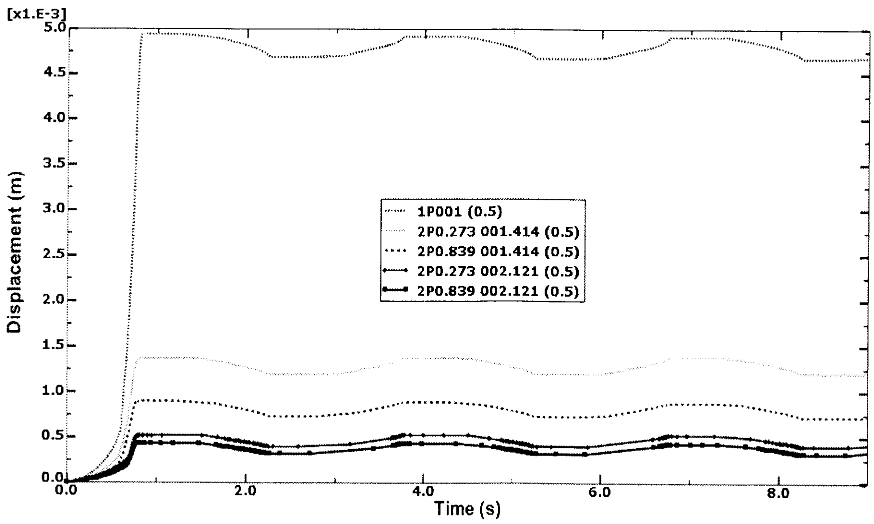

Fig. 7. Comparing the deformation of one-pipe and two-pipe cases.

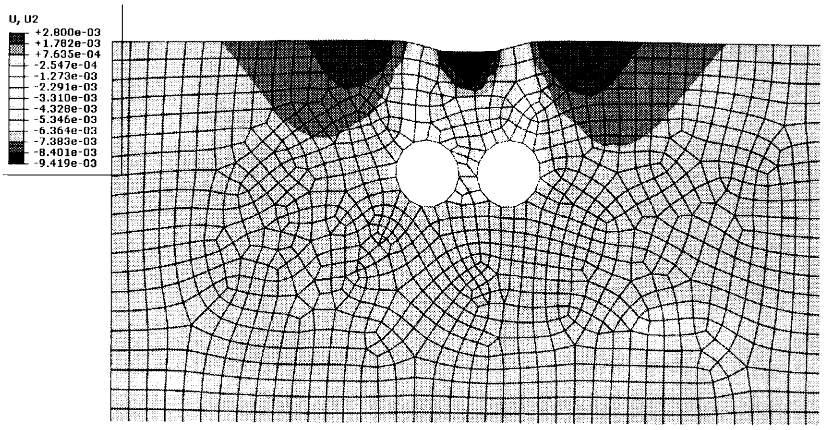

Fig. 8. Deformation curves for $2P_{0.273}$ 001.414 (0.5) case.

Burial Depth and Arcing Phenomenon

Burial depth of pipe is one of the most important factors affecting deformation and stress of the pipe crown, (Fig. 9). Effect of burial depth on the pipe deformation and on the ratio of normal stress on the pipe to the local free stress is called "arcing phenomenon". Figure 9 indicates this phenomenon for the first and fourth cycle of loading. Increasing burial depth from D to about 2D decreases significantly the deformation and the maximum stress of the pipe crown, while for the burial depth more than 2D the slope of the curves is reduces. Thus, regardless of loading cycle, burial depth of 2D is considered as an adequate safety margin.

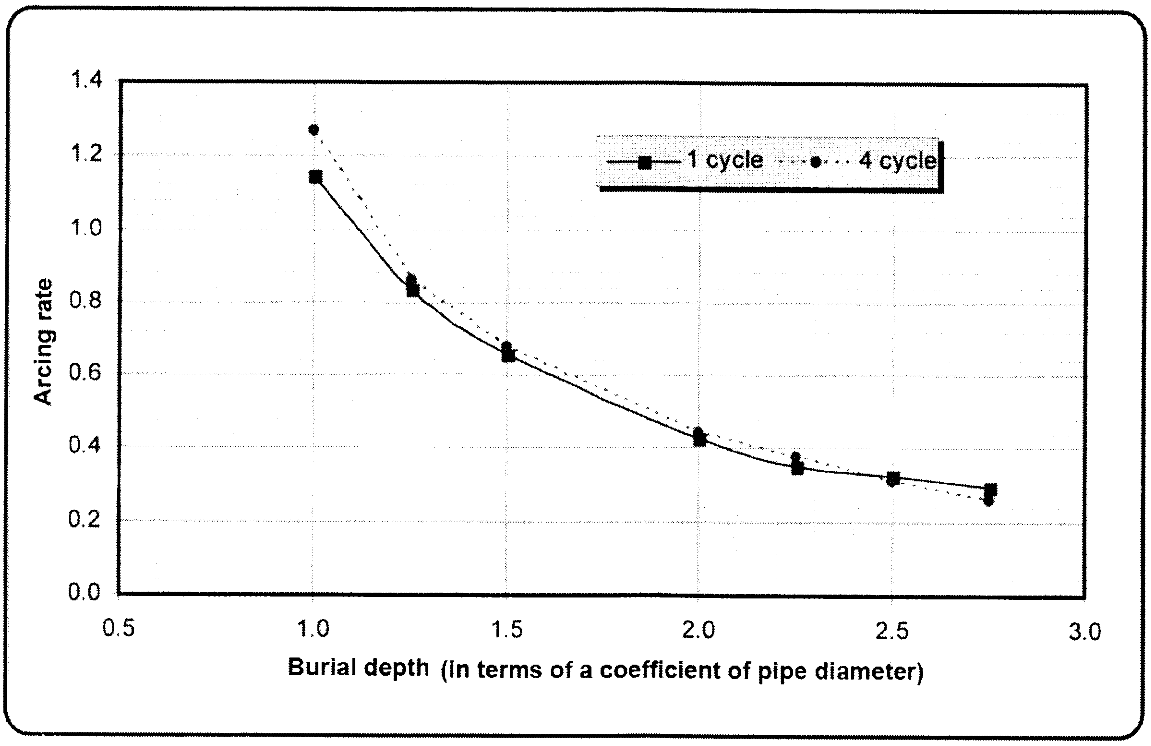

Fig. 9. Effect of burial depth on arcing rate.

CONCLUSIONS

According to surveys conducted in this work, in order to simulate and predict experimental results with numerical model, it is found that the time history of deformation of pipe in all analysis cases is similar to the experimental results and also has an error rate within acceptable engineering errors. Hence, regarding the acceptable compliance of the results, stress distribution and deformation in the soil-pipe environment can be obtained by numerical analysis whenever the experimental results are not available. In the case studies mentioned, concerning the arcing phenomenon and the deformation of the pipe crown, it is found that the burial depth of 2D is a suitable safety margin for the depth of burying the pipes for conveying water, sewage, gas, etc. Also, existing of two pipes instead of one pipe for the same flow rate reduces dramatically the deformation in the crown of the pipe.

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