EXPRIMENTAL AND NUMERICAL INVESTIGTION OF BURIED PIPELINE DUE TO AXIAL VIBRATION

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ABSTRACT

Literature shows that axial behavior of buried pipeline due to vibration or dynamic loading is an important factor for design procedure. Recently, many researchers are focused to improve design criteria for this type of structure in different geotechnical conditions and construction methods. Static and dynamic stiffness, damping coefficient, mass association of surrounding pipe material in many cases characterized the dynamic loading system in analytical model of buried pipelines. Therefore, in this paper an analytical model based on the laboratory testing method is presented to investigation some important factors which effects on buried pipeline structure. Based on the statistical interpretation for the laboratory testing results the actual data is applied to the presented model for understanding the sensitivity of the parameters which involves in pipeline structures. The concept of analytical model is based on the dynamic structures and mechanical vibration theory with using the Fourier transfer in time and frequency domain. The Winkler spring is also applied to provide facility for considering the linear and nonlinear behavior of surrounding material in the model of buried pipeline. The available loading and measurement equipments such as Loadcell, Actuator, and Computer network are applied with Servo-Hydraulic system in the laboratory investigation. In the laboratory work, the pipeline with a suitable scale is simulated with a box which the pipe is laid between the several compact layers of nominated soil. The reflection of the dynamic wave in the both end- boundaries of pipe was controlled through several plates which submerged in viscous fluid. The sensitivity of soil material parameters , depth of buried pipe, pipe diameter, pipe material , soil water content, soil compaction factor, amplitude and frequency of harmonic vibration and etc., are investigate in this research work. The study shows that: Stiffness between pipe and surrounding material in dynamic condition is less than static. Force-displacement relationship between pipe and soil in axial direction of pipe is nonlinear. Investigation shows that increasing the frequency of harmonic vibration decreases amplitude of axial force and dynamic stiffness between pipe and surrounding material.

KEYWORDS: Buried, pipeline, Earthquake, Experimental, Numerical, Axial Vibration

1. INTRODUCTION

The effect of waves produced by earthquake is one of the most important effects endangering the pipeline systems. Earthquake cause shaking of the ground which one of its important characters is its irregular moving and also, because of the difference of the phases, strain and curve between two points of pipe is produced. C.H. Loh and Wang analyzed a pipe line under the effect of various waves by analytic methods. They made models by means of mass and spring and because damping is small, they ignored of its effect. Their idea was to analyze the effect of moving earth on buried pipelines, and this showed that this displacement in very effective on pipelines. F.Y.Cheng and J.F.Ger analyzed the pipelines in three dimensions and with six components and examined each joint in dynamic state. An equation with respect to balanced dynamics and inertia and damping was extracted. In their investigation was shown that in the state of network behavior is very important and they must examine the three dimension problem. The same analysis by Wang and Change and S.Takada was done with the difference with ignoring the damping and inertia effect, because of the minority and they used a Cauchy static analysis. Important factor in analyzing such structures could be the behavior of pipe to the around soil in modeling of the beam on the elastic bed, this has been investigated by different experts who came up with different results. For this, we have to do different tests on different models with almost real situation which in this article an experimental model and a method of formulation has been suggested which the behavior of pipe to the shaking could be analyzed.

2. SUGGESTED FORMULATION

In real situation pipe is buried in soil, and there are related pressures from the soil which this pressure by Mareston theory or German is related to properties of soil and pipe characters. Usually a pipe is buried in soil. The equation of dynamic balance of axial shaking of an element from the buried pipeline without considering of soil weight can be written in this form:

$$\rho_P A_P \frac{d^2u(x,t)}{dt^2} - E_P A_P \frac{d^2u(x,t)}{dx^2} + C_a \frac{du(x,t)}{dt} + k_a u(x,t) = k_a u_g(x,t) \tag{1}$$

Which: ρ_p = special mass of pipe, A_p = cross section area of pipe, u(x,t)= function of pipe displacement , E_p= elasticity model of pipe, C_a= axial damping of pipe and soil, k_a= axial stiffness between soil, t= time variable ,x= distance variable and pipe, $u_g(x,t)$= function of earth displacement.
Equation(1) shows the relation of a continuous system which by solving this differential equation we could find the related displacement u(x,t) with respect to constants, k_a, C_a, E_p, A_p, ρ_p . Figure (1) shows the schematic form of one element. In the static form, soil and pipe system con be shown with figure (2) with 6 nodes, that the springs is the effect of soil around the pipe in Winkler model. The stiffness of soil around the pipe will cause $\frac{E_p A}{L}$ isn't true for equivalent stiffness but k_a is effective. L is length of pipe. The dynamic balance relation in axial in a discrete system and taking in to considering the added soil mass (M_{add}), we can write equation (2) for 2 nodes:

$$\begin{bmatrix} M_p + M_{add} & o \\ o & M_P + M_{add} \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} c & o \\ o & c \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} f_1(t) \\ f_2(t) \end{bmatrix} \tag{2}$$

Which M_p= nodal mass of pipe, C= nodal damping, k_{ij}= equivalent stiffness between soil and pipe relating to horizontal node i, and vertical node j, $f_i(t)$ = equivalent force of horizontal node i, x_i= equivalent displacement in horizontal node i, $\dot{x}_i$ = equivalent Speed in horizontal node i , $\ddot{x}_i$ =equivalent acceleration in horizontal line i. Eq. 2 can be written in similar form:

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{f(t)\} \tag{3}$$

Which [M]= matrix of mass of soil and pipe system, [C]= matrix of damping of soil and pipe system , [K]= matrix of stiffness of soil and pipe system, {f(t)} = vector of equivalent force of horizontal node i, $[x]_i$= vector of equivalent displacement in horizontal node i, [$\dot{x}_i$]=vector of equivalent Speed in horizontal node i and [$\ddot{x}_i$] = vector of equivalent acceleration in horizontal line i. Figure 3 shows arrangement of displacement sensors.

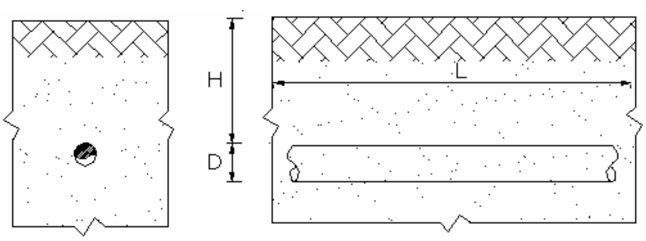

Fig.1- Schematic form of one element

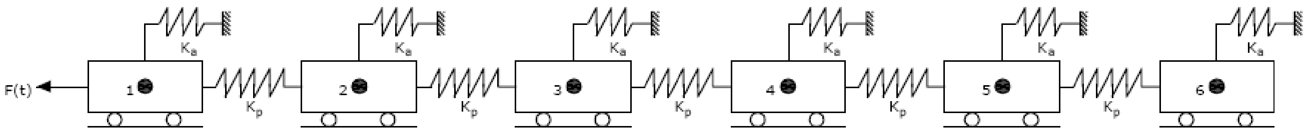

Fig.2- Simulation of the soil – pipe behavior by Winkler springs

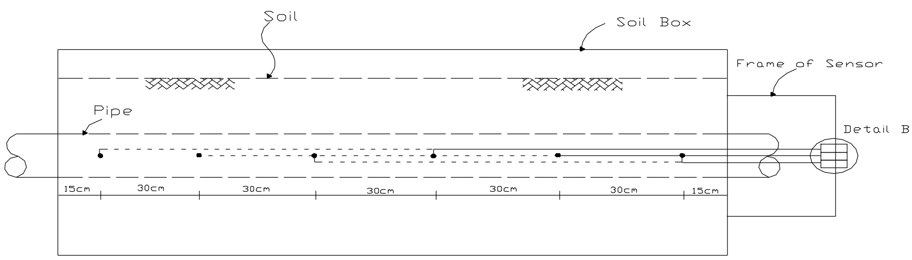

Fig.3- Axial section showing arrangement of displacement sensors

Analysis of other researchers slows that the amount of M_{add} is not effective and we can disregard it but in this article, M_{add} has been considered. We can use equation (3) for two degrees and in terms of using equation (3) to equation (4), K_d would be dynamic stiffness or impedance function:

$$[K_d]\{x(t)\} = \{f(t)\} \tag{4}$$

In case of one degree freedom, impedance function can be shown as equation (5):

$$K_d(\omega) = -\omega^2 M + K + i\omega C \tag{5}$$

That ω = excitation frequency (in radian per second). In static form, dynamic stiffness equal to static stiffness (K). In case of two degrees freedom, impedance function or matrix of dynamic stiffness would be as following form:

$$\begin{bmatrix} H_{11}(\omega) & H_{12}(\omega) \\ H_{21}(\omega) & H_{22}(\omega) \end{bmatrix} = -\omega^2 \begin{bmatrix} M_p + M_{add} & 0 \\ 0 & M_p + M_{add} \end{bmatrix} + \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} + i\omega \begin{bmatrix} c & o \\ o & c \end{bmatrix} \tag{6}$$

Equation (6) is the improved equation (5) that shows the elements of dynamic stiffness in accordance with elements of mass matrix damping and static stiffness. We can use these equations by dynamic testing (axial vibration) at joints with respect to different frequencies; we can find members of matrix of dynamic stiffness under different conditions. The stiffness between soil and pipe (K), in the axial direction, is obtained from the following formulation and also from experimental results. Its magnitude and variations are determined by the interaction between soil and pipe. Application of the equilibrium principle to one element, gives relations (7) for element i (i=1, 6):

$$\Delta F_i = F_{i-1} - F_i \quad , \quad \Delta F_i = P \cdot L_i \cdot \tau_i \quad , \quad \tau_i = \frac{(F_{i-1} - F_i)}{P \cdot L_i} \tag{7}$$

Which: F_i= force between soil and pipe in axial direction of node i, P= perimeter of pipe, L_i=distance between node i and node i+1 and τ_i =shear stress of element i from pipe

Assuming constant strain throughout the element, the strain could be obtained in terms of the two joints displacements as:

$$\varepsilon_1 = \frac{u_2 - u_1}{L_1} \tag{8}$$

That u_i= axial displacement of node i of pipe. Therefore, F_1 is calculated as:

$$F_1 = E_P \cdot A_P \left(\frac{u_2 - u_1}{L_1} \right) \tag{9}$$

Considering that E_p, A_p, and L_1 are constant along the pipe, we can relate the frictional forces of each element to the relation displacement of element. Therefore, the external force exerted on each element, is proportional to the relation displacement of the two joints of elements. After that frictional forces of an element related to the external force have been found, the process could be repeated for the other external force of F_0. The interpolation method is used for calculating stiffness. Dynamic stiffness between soil and the pipe, the amount of damping, and added mass due to the effect of soil, are the dynamic parameters that should be determined from structural dynamics relations and experimental results. The dynamic stiffness k_d or the impedance function is expressed by Eq.(4). In the case of one degree of freedom, and in the frequency domain, the dynamic stiffness is calculated from Eq. (5). From structural dynamics theory, the dynamic displacement is expressed as:

$$u(t) = \frac{\dot{u}_0}{\omega_n \sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin\left(\omega_n \sqrt{1-\zeta^2}\right) t \tag{10}$$

That ζ = damping coefficient, $\dot{u}_o$ = initial velocity of harmonic displacement function and ω_n = natural frequency system of soil and pipe. The relation between damping coefficient (ζ) and amount damping (C) is obtained as:

$$C = 2\zeta m \omega_n = 2\zeta m \sqrt{\frac{k}{m}} \tag{11}$$

Where m is the mass of the pipe together with a soil mass association of surrounding pipe which interacts with the pipe, as could be seen from equations, dynamic stiffness (k_d), damping coefficient (ζ) and damping force per speed(C) are dependent on the mass of the soil system, and could be calculated through iteration methods. According equation (5), if m is included from pipe mass (M_p) and the added mass (M_{add}), we have:

$$K_d(\omega) = -\omega^2 (M_P + M_{add}) + K_A + i\omega C \tag{12}$$

Considering that equation (12) is in complex space, by equating the right side to the left side, we can find M_{add}, and recalculate C. Therefore the independent variation parameters could be calculated one after the other through iteration methods. On the right side of equation (12), the only unknown is M_{add}, and on the left side the dynamic stiffness is in frequency space. On the other hand, dynamic stiffness in the frequency space is defined as:

$$k_d(\omega) = \frac{F(\omega)}{x(\omega)} \tag{13}$$

The system excitation is simple harmonic, and the displacement function is also harmonic with difference phase. The excitation force is shown as:

$$f(t) = F_0 \sin \omega t \tag{14}$$

After a time lapse, the displacement function becomes:

$$u(t) = u_0 \sin(\omega t - \phi) \tag{15}$$

That ϕ is the difference phase corresponding to the excitation ware force. In the laboratory, a load cell measures F_0 for different frequencies and excitation amplitudes, and the magnitude of F_0 could be read from the monitor attached to a Servo-Hydraulic system. In order to produce a dynamic excitation, the amplitude of vibration and the excitation frequencies are applied to the damper and static experiments derive as inputs. Then the maximum dynamic force F_0 is read. From the monitoring, the maximum amplitude of displacement in the axial direction is measured by an exact sensor, and then recorded. The excitation frequency has the same frequency as the displacement, but the displacement wave lags behind by deference phase ϕ due to the existence of damping in the system. The amplitude and deference phase are obtained from the following relations:

$$u_0 = \frac{F_0/K}{\sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2}} \quad , \quad \phi = \tan^{-1}\frac{2\zeta\left(\frac{\omega}{\omega_n}\right)}{1-\left(\frac{\omega}{\omega_n}\right)^2} \tag{16}$$

For obtaining the dynamic stiffness from equation (13), we must calculate $F(\omega)$ and $X(\omega)$, which are the Fourier transformations for dynamic force and dynamic displacement respectively. Considering that the harmonic function has a period T, and $t \geq 0$, we can write:

$$F(\omega) = \frac{1}{2\pi(1-e^{-i\omega T})}\int_0^T f(t)e^{-i\omega t}dt \quad , \quad X(\omega) = \frac{1}{2\pi(1-e^{-i\omega T})}\int_0^T u(t)e^{-i\omega t}dt \tag{17}$$

Therefore, $k_d(\omega)$ is obtained from (13) as:

$$K_d(\omega) = \frac{\int_0^T f(t)e^{-i\omega t}dt = R_a}{\int_0^T u(t)e^{-i\omega t}dt = R_b} = \left(\frac{F_0}{u_0}\right)\frac{0+\cos\phi\left(\frac{T}{2}\right)^2 + i\sin\phi\left(\frac{T}{2}\right)^2}{\left(-\sin\phi\, T/2\right)^2 + \left(\cos\phi\, T/2\right)^2} = \frac{F_0}{u_0}(\cos\phi + i\sin\phi) \tag{18}$$

By setting equal the real and imaginary parts of (12) and (18), we will have:

$$M_{add} = \frac{K - \frac{F_0}{u_0}\cos\phi}{\omega^2} - M_p \quad , \quad C = \frac{F_0}{\omega u_0}\sin\phi \tag{19}$$

In static conditions, ϕ is equal to zero. Therefore, from Eq.(19), C is also equal to zero, and K is calculated as F_0/U_0 for the static case. The angular frequency is calculated from $\omega = 2\pi f$ where f is the measured frequency in Hertz.

3. THE EXPRIMENTAL MODEL

Parameters such as static stiffness, dynamic stiffness, damping, and the added mass due to interaction with soil, should be obtained from the relevant formulas and also from the experimental model developed for this purpose. These parameters are effective in the axial dynamic behavior of the pipe, and different factors can affect them, including the change of pipe diameter, the material of the pipe, the depth at which the pipe is buried, the type of soil, humidity, the compactness of the soil, and the static and dynamic conditions. The laboratory model developed consists of different parts. Fig.(4) and Fig.(5) show the arrangement(plan and lateral view) of the various parts of the model. The static or dynamic force generated by the Actuator of the Servo- Hydraulic systm (part1) is applied to the transformation system (part2), where the normal force is converted into a horizontal force and applied to the and of the buried pipe (part3). The total force between soil and the pipe is transferred through a second converter from part 2 to the Load cell of the Servo-Hydraulic generator, and shown on the monitor screen. The axial displacements of certain points along the pipe are measured by precise sensors (part4), and stored in a computer (part 5), and also shown on the monitor screen.

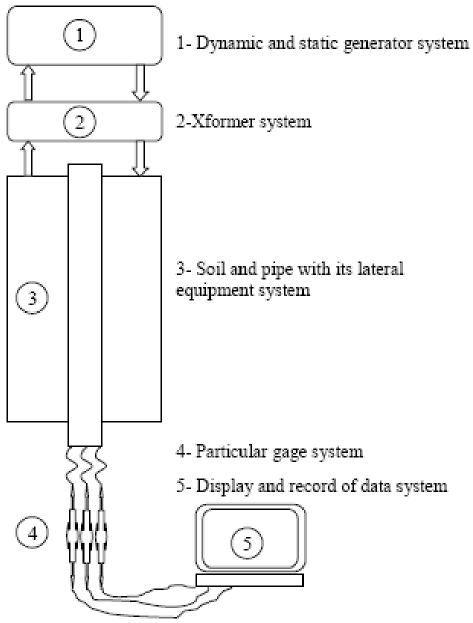

Fig.4- Plan of variation part of model

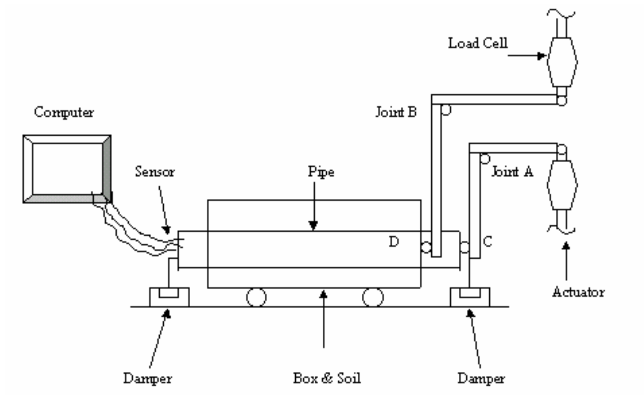

Fig.5- Arrangement of the various parts of the model

4. COMPARISION OF RESULTS

Static stiffness between pipe and soil in the axial direction is suggested, based on the experimental results from the model, and also the proposed formulation. A nonlinear analysis by ANSYS software was performed, using the static stiffness was obtained, together with other geometric and loading information. Then the ANSYS results were compared with experimental results. Fig. (6) is an example of experimental results. Fig. (7) Compares these results with the results obtained from ANSYS analysis. The comparisons show the results to be close. The greater displacement obtained from ANASYS software could be due to experimental errors, and also because of the behavior of the pipe as a shell, as well as an axial structure.

In axial behavior, strain occurs only along the pipe in one direction, while if the pipe behaves as a shell, other components of strain in the 3D space occur, and this could explain the disparity in the results. Parameters like dynamic stiffness between soil and pipe, amount of damping, and added mass due to the axial effect of soil on the performance of the system, are among the dynamic parameters determined by the proposed model.

A conversion factor was applied to the result. The displacement amplitude was measured by sensors. In this example, the static stiffness obtained from the suggested formulation method was K= 971.0 kg/mm. the mean dynamic stiffness for 0.5 HZ frequently is:

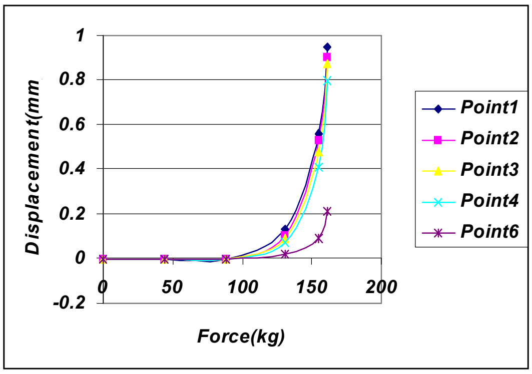

Fig.6- Displacement variation vs. force at different points along the pipe

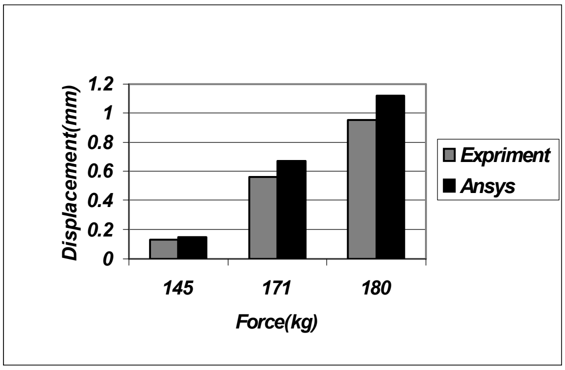

Fig.7- comparison of experimental results with ANSYS results

$$\left|K_d(\omega)\right| = \left|\frac{F_0}{u_0}(\cos\phi + i\sin\phi)\right| = \frac{F_0}{u_0} = 828.0\ {}^{kg}\!/\!_{mm}$$

This is less than the static stiffness. This confirms the results obtained by S.Takada. Takada's investigations show that the behavior and variations obtained by him are in agreement with the results of this model. The dynamic to static stiffness ratio is $\frac{828.0}{971.0} = 0.85$ which less than 1 is.

Figures (8-9) show variation dynamic stiffness vs. static stiffness for ratio of excitation frequency to natural frequency and for various added mass and various damping factor. As it be seen from figures, dynamic stiffness for $\frac{\omega}{\omega_n}$<1 don't increase, but for value larger than 1, it will be increasing as for $\frac{\omega}{\omega_n}$>2 it will increased 5-7 times. With increasing of damping coefficient, dynamic stiffness increased and for $\frac{\omega}{\omega_n}$=1, with increasing of damping factor, dynamic stiffness increased. In $\omega < \omega_n$, dynamic stiffness is smaller than static stiffness. But in high damping coefficient ($\rho > 0.5$), dynamic stiffness is larger than static stiffness. In $\omega > \omega_n$, relation of dynamic stiffness to static stiffness increased quickly. Added mass was considered in this paper. Natural frequency of a degree freedom with consideration of added mass are calculated as following equation:

With added mass $\omega_n = \sqrt{\frac{K}{M}} = \sqrt{\frac{K}{M_p + M_{add}}}$, without added mass $\omega_n = \sqrt{\frac{K}{M_p}}$

With added mass equal to $0.5m_p$ $\quad \bar{\omega}_n = \sqrt{\frac{K}{M}} = \sqrt{\frac{K}{M_p + 0.5M_p}} = \frac{1}{\sqrt{1.5}}\omega_n$

With added mass equal to $1m_p$ $\quad \bar{\omega}_n = \sqrt{\frac{K}{M}} = \sqrt{\frac{K}{M_p + 0.5M_p}} = \frac{1}{\sqrt{2}}\omega_n$

As be seen, natural frequency is related to pipe mass and added mass. When M_{add} is considered, a complete couple is occurred in problem. Because M_{add} is function of excitation frequency and angle of difference phase and amplitude of harmonic force and amplitude of harmonic displacement are function of M_{add} . In result, it needs to solve dynamic problem contemporary.

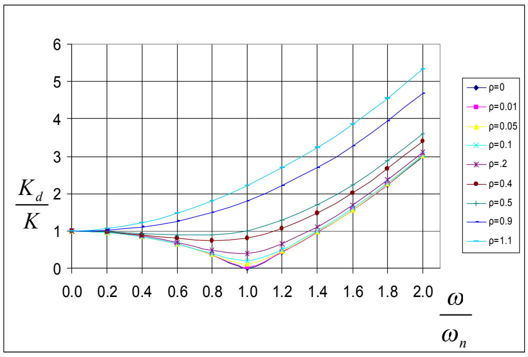

Fig.8- Drawing of $\frac{K_d}{K}$ Vs. $\frac{\omega}{\omega_n}$ for various damping coefficient and $M_{add} = 0$

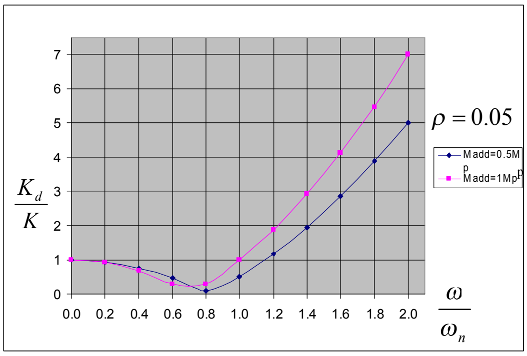

Fig.9- Drawing of $\frac{K_d}{K}$ vs. $\frac{\omega}{\omega_n}$ for various M_{add} and damping coefficient =5%

5. CONCLUSION

Static stiffness in Winkler model, and other dynamic parameters such as damping of the pipe-soil system, dynamic stiffness, and the added mass of soil effective on the dynamic and vibration behavior of the system, can be determined by using the proposed formulation method, and also the experimental model. The effect of factors like depth of buried, pipe diameter, compactness of soil, humidity, and excitation frequency and amplitude have been studied on the static an dynamic stiffness between the pipe and soil. It is shown that these factors are very effective on the static and dynamic stiffness, as well as damping and added mass of soil.

Some other conclusions are: 1- Dynamic stiffness between soil and the pipe is less than the static stiffness. 2- The static behavior between soil and the pipe is nonlinear in the axial direction. 3- With increasing the excitation amplitude, amplitude of the force between soil and the pipe is increasing. 4- Increasing the excitation frequency causes a decrease in the amplitude of force between soil and pipe. 5- Increasing the excitation frequency causes a decrease in the dynamic stiffness between soil and the pipe. 6- Damping between soil and pipe is high (unlike ordinary structures). 7- Increasing the damping between soil and the pipe causes an increase in the difference phase between the harmonic displacement and the harmonic force.

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