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Paper No. 1605. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

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AXIAL AND TRANSVERSE SEISMIC ANALYSIS OF BURIED PIPELINES

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ABSTRACT

The main objective of this study is to develop an analytical procedure for calculating upper bounds for stresses and strains for transverse and axial loading cases of continuous buried pipelines taking into account the soil–pipeline interaction effect.

The second objective of the study is to perform a sensibility analysis of some critical parameters, such as the apparent propagation wave velocity, pipe's diameter and the frequency content of the seismic ground excitation. A detailed parametric study, illustrates the influence of these parameters on the ratio of the pipe to ground displacement amplitudes and consequently to the induced pipe strains. Wide range of possible values, of frequencies for the harmonic seismic ground excitation ($1 \div 6\text{Hz}$), of apparent wave propagation velocity ($600 \div 1000\text{m/s}$) and of shear wave velocities for the foundation soil ($100 \div 400\text{m/s}$) have been used. Soil–pipe interaction effects are important for the critical axial response.

KEYWORDS

Lifelines; pipelines; earthquake engineering; underground structures; SSI effects.

INTRODUCTION

Deterministic approach of seismic wave propagation effects on buried pipelines is extremely complex. Pipelines extend continuously over long distances so they are subjected to non coherent ground shaking producing stresses in the buried structures. A completely accurate structural model for the pipeline is rather impossible because of the almost unpredictable path of seismic waves generated from the source through the "far field" and the variability of the local site effects.

From the earlier model proposed by Newmark (1967) and expanded on by Yeh (1974), considering that pipe "moves" together with the soil, many researchers simulated the buried pipeline as a Beam on Winkler

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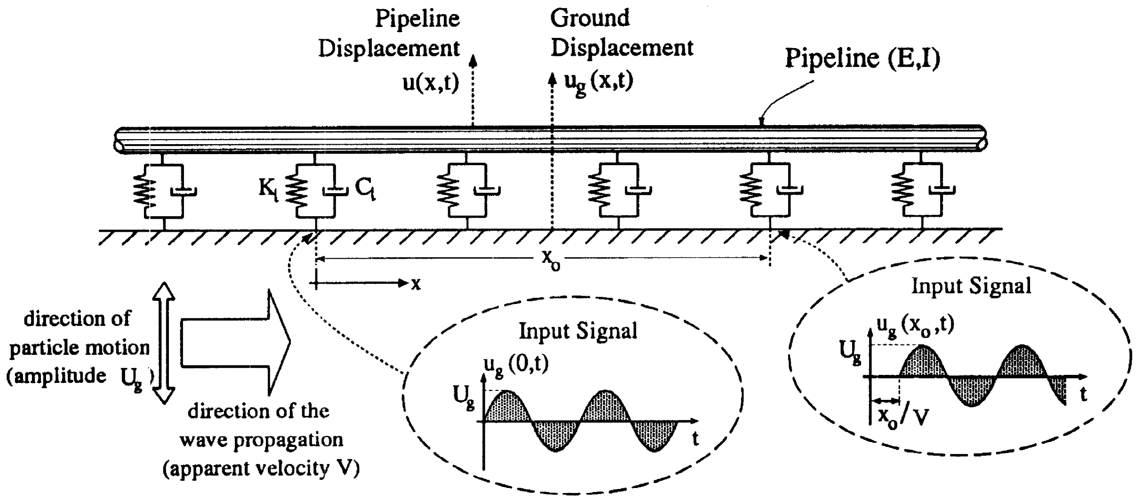

Fig. 1. Lateral response model

Foundation and they proposed to determine the instantaneous axial and bending strains of the structure due to seismic wave propagation (O'Rourke *et al.*, 1978; Mavridis, 1995). Recently, among other research tasks, a Boundary Element approach jointly with a 2D transversal Finite Element approach (Manolis *et al.*, 1995) in the framework of an important European research project (Pitilakis and Mavridis, 1993) indicated that soil–structure interaction effects should not be systematically ignored in seismic analysis of buried pipelines.

Among the most important factors affecting the seismic pipe behaviour are the apparent wave propagation velocity, the frequency content of the ground excitation, the geometry of the pipe and of course the soil rigidity. The purpose of this paper is to investigate in detail, the influence of these parameters to the SSI phenomenon using analytical expressions for the seismic response of a buried pipeline.

DESCRIPTION OF THE MODEL

Two analytical models based on the Beam–On–Dynamic–Winkler–Foundation (BDWF) approach have been used which permit the calculation of both transverse and axial pipeline's displacements; it is assumed that the two directions may be examined independently. Continuously distributed springs and dashpots, are excited at their support by the free field displacements and they are transmitting the excitation to the pipe, producing stresses and strains. Pipeline is considered continuous in the sense that the material properties of the joints are the same as those of the body of the pipe. The soil is assumed to be homogeneous, linear viscoelastic with material damping of frequency independent hysteretic type. Buckling is not considered.

Seismic excitation is considered as an harmonic function of both time and space variable defining a seismic S–wave travelling along the pipeline, causing displacements perpendicular to it's longitudinal axis in the transverse analysis and parallel to it's axis in the axial response.

Lateral response of the pipe

The proposed model is shown in Fig. 1; the harmonic free field excitation (S-waves propagate along the longitudinal pipe axis) has the form:

$$u_g(x,t) = U_g e^{i\omega(t-x/V)} \tag{1}$$

where $u_g(x,t)$ = is the complex transverse soil displacement; U_g = amplitude of ground displacement; ω =

circular frequency; V = velocity of the wave propagation along the pipeline axis (apparent wave velocity); t = time; x = space coordinate; and $\sqrt{i} = -1$.

If $U(x)$ denotes the unknown complex amplitude of pipe displacement, the pipe response $u(x,t)$ in the transverse direction can be expressed as:

$$u(x,t) = U(x)e^{i\omega t} \tag{2}$$

The governing differential equation of the motion of the pipe is:

$$EI\frac{\partial^4 u(x,t)}{\partial x^4} + m\frac{\partial^2 u(x,t)}{\partial t^2} + C_l\frac{\partial u(x,t)}{\partial t} + K_l u(x,t) = C_l\frac{\partial u_g(x,t)}{\partial t} + K_l u_g(x,t) \tag{3}$$

where E, I = Young's modulus and moment of inertia of the pipe; m = mass of the pipe per unit length; C_l, K_l = damping and stiffness parameters, respectively. The force (per unit length of pipe) to displacement ratio of the Winkler medium defines the complex valued frequency–dependent impedance

$$S_l = K_l + i\omega C_l \tag{4}$$

The solution of eq. (3) for harmonic excitation as described by eq. (1) satisfying boundary conditions that pipe displacement is finite at infinity, is:

$$u(x,t) = \frac{S_l}{EI\,(\omega/V)^4 + S_l - m\omega^2} U_g e^{i\omega(t-x/V)} \tag{5}$$

The complex ratio R_u of the pipe displacement to the soil displacement:

$$R_u = \frac{u(x,t)}{u_g(x,t)} = \frac{K_l + i\omega C_l}{EI\,(\omega/V)^4 + K_l + i\omega C_l - m\omega^2} \tag{6}$$

expresses the relative displacement and the phase between pipe and soil. Newmark's model (Newmark, 1967) assumes that R_u is equal to unity, independently of the parameters involved. The maximum bending strain in the pipe becomes:

$$\epsilon_b^{max} = r\frac{\omega^2 U_g}{V^2} R_u \tag{7}$$

where r is the radius of the pipe while $\omega^2 U_g$ is the particle acceleration in the lateral direction.

Axial response of the pipe

The proposed model for the axial response is shown in Fig. 2; the harmonic free field excitation (S-waves propagate along the longitudinal pipe axis) has the form:

$$w_g(x,t) = W_g e^{i\omega(t-x/V)} \tag{8}$$

where $w_g(x,t)$ = the complex axial soil displacement; and W_g = amplitude of ground displacement.

If $W(x)$ denotes the unknown complex amplitude of pipe displacement, the pipe response $w(x,t)$ in the longitudinal direction can be expressed as:

$$w(x,t) = W(x)e^{i\omega t} \tag{9}$$

The governing differential equation of the axial motion of the pipe is:

$$-EA\frac{\partial^2 w(x,t)}{\partial x^2} + m\frac{\partial^2 w(x,t)}{\partial t^2} + C_a\frac{\partial w(x,t)}{\partial t} + K_a w(x,t) = C_a\frac{\partial w_g(x,t)}{\partial t} + K_a w_g(x,t) \tag{10}$$

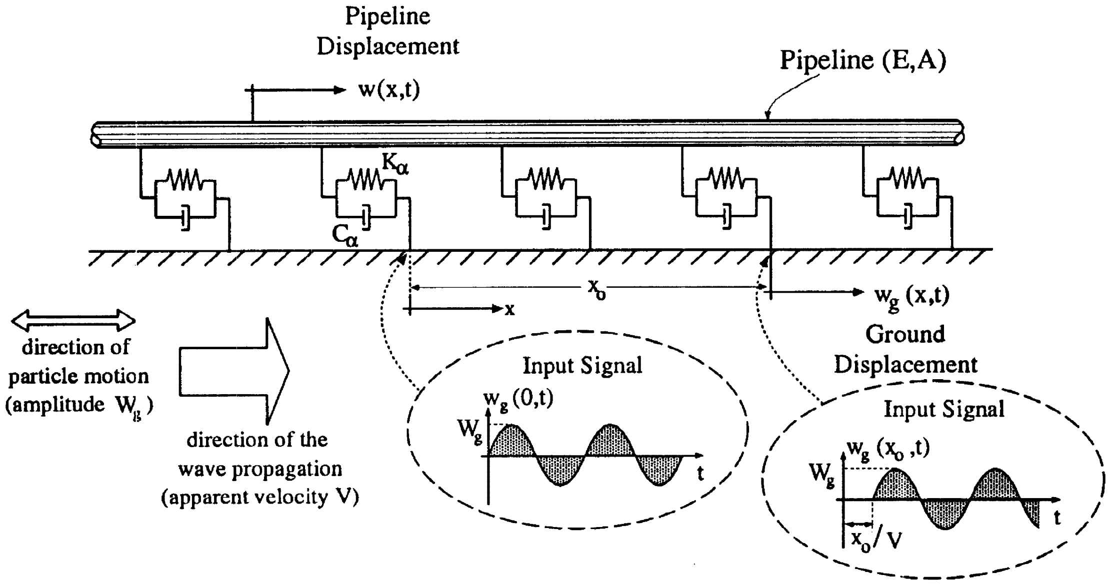

Fig. 2. Axial response model

where A = cross sectional area of the pipe; and C_a, K_a = damping and stiffness parameters for the axial response, respectively. Similar to the transverse analysis, the complex valued frequency–dependent impedance

$$\mathcal{S}_a = K_a + i\omega C_a \tag{11}$$

defines force to displacement ratio of the Winkler medium. The solution of eq. (10) for harmonic excitation as described by eq. (8) satisfying boundary conditions that pipe displacement is finite at infinity, is:

$$w(x,t) = \frac{\mathcal{S}_a}{EA\,(\omega/V)^2 + \mathcal{S}_a - m\omega^2} W_g\, e^{i\omega(t-x/V)} \tag{12}$$

The complex ratio R_w of the pipe displacement to the soil displacement:

$$R_w = \frac{w(x,t)}{w_g(x,t)} = \frac{K_a + i\omega C_a}{EA\,(\omega/V)^2 + K_a + i\omega C_a - m\omega^2} \tag{13}$$

expresses the relative displacement and the phase between pipe and soil. Also for the axial analysis, Newmark's model (Newmark, 1967) assumes that R_w is equal to unity, independently of the parameters involved. The maximum axial strain in the pipe becomes:

$$\epsilon_a^{max} = \frac{\omega W_g}{V} R_w \tag{14}$$

where ωW_g is the particle velocity in the axial direction.

MAIN PARAMETERS OF THE PROBLEM

One of the basic parameters of eqs. (5) and (12) is the propagation velocity V of seismic waves with respect to the ground surface. Extended studies on this problem were reported by O'Rourke *et al.*(1980, 1982), leading to the conclusion that the apparent propagation velocity for body waves is always larger than the shear wave velocity in the bed–rock; they also proposed a method for calculating the apparent propagation velocity which applied to the 1971 San Fernando and 1979 Imperial Valley earthquake data, leads to $V = 2.1$ km/s and 3.76 km/s respectively. Committee on Gas and Liquid Fuel Lifelines (1983) indicated that so high values ignoring changes in the wave shape from one point to other, would be not appropriate for analysis and so they suggested a reasonable design value equal to $V = 600 \div 915\,\mathrm{m/s}$. It will be shown that the value of the apparent propagation velocity combined with some other parameters of the problem has an important influence on the manifestation of soil–pipe interaction effects.

The next important parameter is the description of the dynamic soil stiffness and damping. The complex dynamic stiffness developed by Novak *et al.*(1978), for a rigid cylinder and infinite homogeneous medium is used in the present study

$$\mathcal{S}_l = G\left[S_{u_1}(\alpha_0, \nu_s, D_l) + iS_{u_2}(\alpha_0, \nu_s, D_l)\right] \tag{15}$$

$$\mathcal{S}_a = G\left[S_{w_1}(\alpha_0, D_s) + iS_{w_2}(\alpha_0, D_s)\right] \tag{16}$$

in which $\alpha_0 = \omega D/V_s$ with D the diameter of the pipe, V_s shear wave velocity; ω = frequency; ν_s = Poisson's ratio; G = shear modulus; and D_l, D_s parameters denoting hysteretic material damping. Real parts of eq. (15) and (16) represent soil stiffness and the imaginary (out–of–phase) parts describe the damping. The damping of the pipe itself is much smaller than the damping derived from the soil (Hindy and Novak, 1979; Zerva *et al.*, 1988), so it is neglected.

NUMERICAL RESULTS AND PARAMETRIC STUDY

For the parametric sensibility analysis, a common steel pipe is considered with the following properties: Young's modulus $E = 210\mathrm{GPa}$, weight unit $\gamma = 78\mathrm{kN/m^3}$, $t = h/D = 0.01$ where h is the thickness of the pipe. For the soil, it was assumed: weight unit $\gamma_s = 18\mathrm{kN/m^3}$, Poisson's ratio $\nu_s = 0.30$ and material damping $D_s = D_l = 10\%$ (hysteretic damping ratio $\beta = 5\%$).

Ratios R_u and R_w are complex numbers. In the results presented herein only the amplitude of these numbers is plotted. In an extended analysis of a real seismic recording, the phase of the complex numbers should also be used, in order to take into consideration the phase of the response of each harmonic oscillation through Fourier analysis. An extended presentation of the whole parametric study is impossible due to space limitations. Some selected examples will be presented and discussed herein.

Figure 3 illustrate the variation, for the case of the bending model, of the pipe to soil displacements ratio R_u with the outside diameter D of the steel pipe, for frequencies f = 1, 2, 3 and 6 Hz of the seismic excitation. A wide range of soil stiffness V_s = 100, 200, 300, 400 m/s is been used while the apparent velocity V has been assumed equal to V = 600, 800 and 1000m/s. It is obvious that there is no SSI effects between soil and pipe for this case and the pipe follows the deformations of it's surrounding soil. It should be remarked that numerical results for higher frequencies vary a lot from those pointed out in fig. 3. For example the combination $D = 300\,\mathrm{cm}$, $V_s = 100\,\mathrm{m/s}$, $V = 600\,\mathrm{m/s}$ and $f = 15\,\mathrm{Hz}$, leads to $R_u = 0.978$; so high frequencies as 15 Hz, may affect the pipe seismic response but as in general the contribution of these frequencies to a real seismic recording is rather small, the SSI effects for the lateral response may be considered practically negligible.

The influence of the same parameters on the ratio of the pipe to soil displacements ratio R_w for the axial model, is shown in fig. 4. In general it is demonstrated that pipe displacements are lower than the corresponding ground displacements; especially when the soil is soft and the excitation frequency is high. In the extreme case of a large diameter $D = 3.00\,\mathrm{m}$ pipe buried in a soft soil $V_s = 100\,\mathrm{m/s}$, with apparent wave velocity $V = 600\,\mathrm{m/s}$ and frequency $f = 15\,\mathrm{Hz}$, the pipe displacement amplitude is only 32% of the displacement amplitude of the free filed ground motion. The apparent velocity is really a very important factor especially when the soil rigidity is low.

The soil spring stiffness has an important influence on R_w values. As well in general when the spring becomes "softer" (lower values of soil's shear wave velocity) the difference between the pipe and the soil

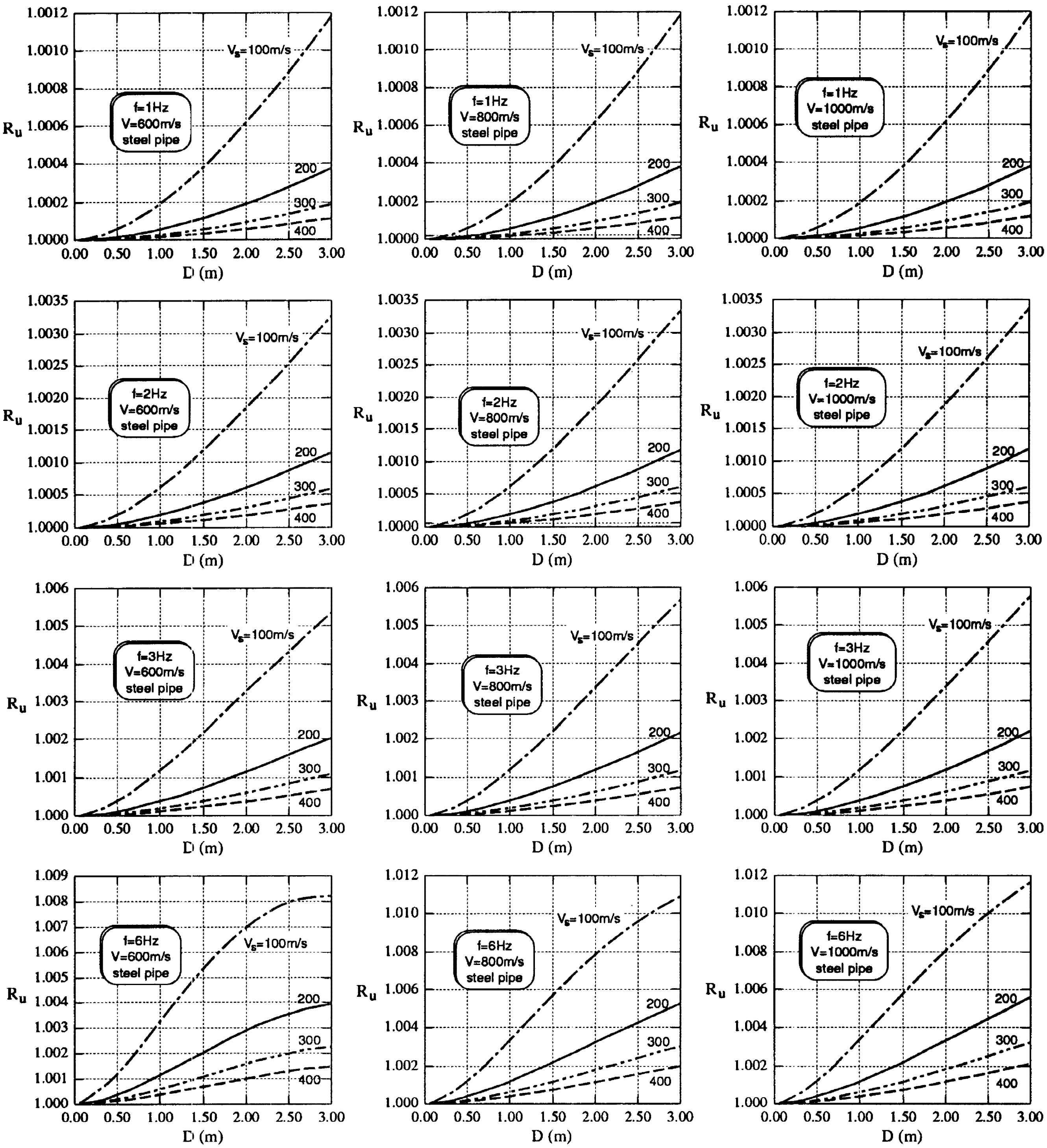

Fig. 3. Variation of R_u ratio (pipe to soil displacement amplitude) with the diameter D of the pipe for the transverse analysis - $f = 1 \div 6\text{Hz}$, $V = 600 \div 1000\text{m/s}$

motion are magnified and consequently the Newmark's assumption becomes very conservative. On the contrary when the soil shear wave velocity increases, the soil–pipe interaction becomes less significant. Small pipes ($D < 0.50\,\text{m}$) are less sensible to SSI effects, especially for low frequencies. For these pipes the SSI effects become significant for frequencies higher than 5 Hz and for soft soils.

It is also important to notice that SSI effects are significant in cases of low values of the apparent wave velocity V. Those cases are critical for the seismic design because pipe's strain (as a derivative of pipe's

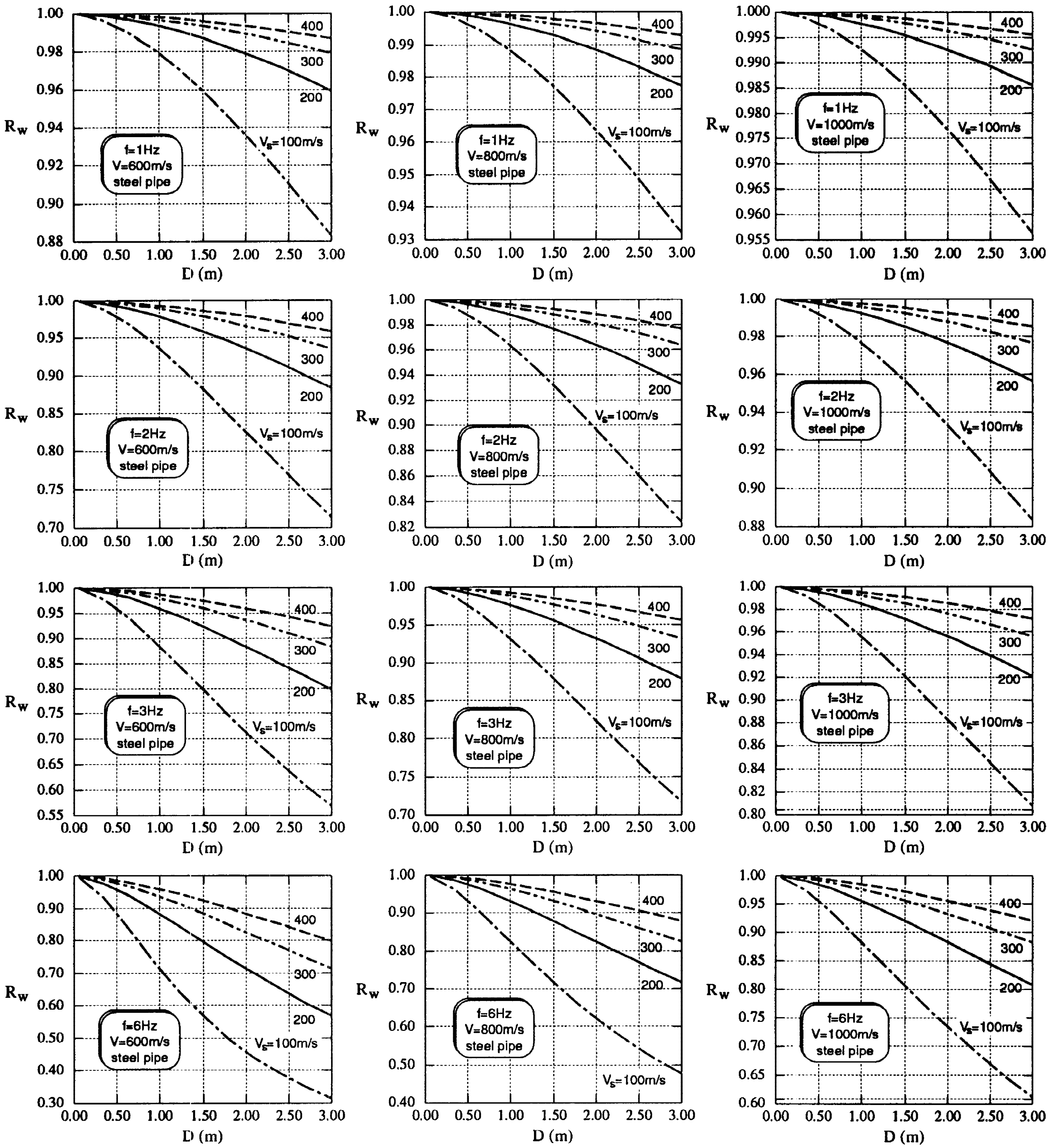

Fig. 4. Variation of R_w ratio (pipe to soil displacement amplitude) with the diameter D of the pipe for the axial analysis - $f = 1 \div 6\text{Hz}$, $V = 600 \div 1000\text{m/s}$

displacement) is becoming larger for lower values of V.

CONCLUSIONS

An improved analytical model for the seismic behaviour of buried pipelines for both transverse and axial shaking have been developed, based on the BDWF approach. A parametric study shown that Newmark's assumption is reasonable only for the case of pipe's bending (transverse analysis). Dynamic soil–pipe interaction effects for the axial analysis of the pipeline are significant and they should be taken into consideration. It should be remarked that in general the critical analysis is the axial.

ACKNOWLEDGEMENT

This research was partially supported by research grants from European Community under the framework of the Research Programme EPOCH (EPOC-CT91-0039 DGXII) and supported by the State Scholarship Foundation Board of Greece. This support is greatly appreciated.

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