Parametric studies on seismic response of buried pipelines

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ABSTRACT: A parametric study is made to investigate the effect of different factors upon the stresses induced in straight buried pipelines near the middle and the end of pipelength due to random ground motion. The parameters include the soil cross stiffness between different stations; embedment depth; shear wave velocity and associated PSDF for ground motion; fluid inside the pipe; and the pipe end conditions. For the response analysis, the buried pipeline is idealized as an assemblage of 2D beam elements and a discrete lumped mass model is employed to describe the pipe motion. The earthquake ground motion is considered as a stationary random process characterized by spectrum and cross spectrum. The soil resistance to dynamic excitation along the pipelength is obtained from static and dynamic continuum theories. A spectral analysis is performed to obtain the r.m.s. pipe response.

1 INTRODUCTION

A realistic evaluation of stresses induced by seismic excitation at different sections of buried pipeline is important both for assessing the adequacy of its design and for performing a seismic risk analysis. For such evaluation of stresses, the method of analysis should consider several factors such as the randomness of ground motion, a comprehensive description of soil reactions that includes finite embedment depth and cross soil stiffness between different stations, variable end condition for the pipelength, characteristics of soil medium and their effect on the ground motion, existence of liquid or gas within the pipe, flexibility of joints, pipe insulation and slippage, etc. It is not possible to consider all these factors in one analysis, and therefore, it is essential to study their relative importance and accordingly, incorporate them in the analysis. In previous works (Hindy & Novak 1979, 1980a, 1980b and Datta & Mashaly 1986), the effect of some of these factors have been studied. However, the literature search shows a need for further study in this direction.

In the present paper, a parametric study is made to specifically investigate the effects of the following factors on the stresses near the middle and the ends of pipelength produced by random ground motion: (i) the soil cross (dynamic) stiffness between different stations; (ii) embedment depth; (iii) shear wave velocity and associated power spectral density function (PSDF) for the ground motion; (iv) existence of fluid inside the pipe; and (v) the pipe end conditions. A discrete lumped mass model is used for the dynamic analysis which can take into account the soil cross stiffness and variable pipe end conditions. The earthquake random motion is considered as a stationary random process characterized by a PSDF. The response is obtained by a frequency domain spectral analysis.

2 THEORY

The buried pipeline is assumed to be elastic, circular, continuous (without any flexible joints) and idealized as an assemblage of 2D beam elements in infinite viscoelastic homogeneous soil medium with frequency independent material damping. A discrete lumped mass model (shown in Fig. 1) is used to describe the pipe motion and to obtain the response of buried pipeline to random ground motion. The representations of seismic excitation and soil reaction to pipe motion are described before the equation of motion is developed.

2.1 Seismic excitation

The ground motion is assumed as a stationary random and partially correlated process characterized by a power spectral density function (PSDF) for ground acceleration defined by (Datta & Mashaly 1986)

$$S_{\ddot{u}_g}(\omega) = S_o\,|H_1(i\omega)|^2\,|H_2(i\omega)|^2 \quad (1)$$

in which S_o is the spectrum of white-noise bed-rock acceleration, $|H_1(i\omega)|^2$, $|H_2(i\omega)|^2$ are the transfer functions of first and second filters representing the dynamic charateristics of the soil layers above the bed-rock, where

$$|H_1(i\omega)|^2 = \frac{1 + (2\xi_g\,\omega/\omega_g)^2}{[1-(\omega/\omega_g)^2]^2+(2\xi_g\,\omega/\omega_g)^2}$$

$$|H_2(i\omega)|^2 = \frac{(\omega/\omega_f)^4}{[1-(\omega/\omega_f)^2]+(2\xi_f\,\omega/\omega_f)^2} \quad (2)$$

in which ω_g, ξ_g are the resonant frequency and damping ratio of the first filter, and ω_f, ξ_f are those of the second filter.

For one sided spectrum, S_o will be then defined as

$$S_o = \sigma^2_{\ddot{u}_g}/\left[\int_0^\infty |H_1(i\omega)|^2\,|H_2(i\omega)|^2\,d\omega\right] \quad (3)$$

in which $\sigma^2_{\ddot{u}_g}$ is the variance of ground acceleration.

By defining the filter characteristics ω_g, ω_f, ξ_g, ξ_f and specifying a standard deviation for the ground acceleration $\sigma_{\ddot{u}_g}$, the PSDF as defined in equations (1) and (2) can be completely defined using equation (3). The PSDFs of ground displacement and velocity are related to $S_{\ddot{u}_g}(\omega)$ by

$$S_{u_g}(\omega) = S_{\ddot{u}_g}(\omega)/\omega^4; \quad S_{\dot{u}_g}(\omega) = S_{\ddot{u}_g}(\omega)/\omega^2 \quad (4)$$

The cross spectrum of ground acceleration between two stations can be defined as

$$S_{\ddot{u}_g}(y_1, y_2, \omega) = S_{\ddot{u}_g}(\omega)\,R(y_1, y_2, \omega) \quad (5)$$

in which $S_{\ddot{u}_g}(\omega)$ is the local spectrum of ground acceleration (equation (1)) which is assumed same for all points and $R(y_1, y_2, \omega)$ is the cross correlation function of the ground motion at two stations y_1, y_2 and may be described by (Hindy & Novak 1980a and Datta & Mashaly 1986)

$$R(y_1, y_2, \omega) = \exp\left[-C\left(\frac{r\,\omega}{2\pi V_s}\right)\right] \quad (6)$$

in which $r = |y_2 - y_1|$, separation distance between stations y_1, y_2 measured in the direction of wave propagation which is assumed to be in the direction of pipelength, V_s is the shear wave velocity of soil, ω is the frequency (rad/sec) of ground motion; and C is a constant depending on the distance from epicentre and inhomogeneity of the medium.

The ground excitation is assumed acting along the pipe axis or perpendicular to it and the axial displacements associated with the lateral vibration are negligibly small and vice-versa, therefore, the axial and flexural deformations of the pipe may be treated separately using two independent systems of equations of motion.

2.2 Soil reaction to pipe motion

A general analysis of pipeline requires a comprehensive description of the soil reactions that include finite embedment depth and cross stiffness between different stations. An approach has been suggested (Parmelee & Ludtke 1975, Hindy & Novak 1979 and Datta & Mashaly 1986) to achieve this objective by combining the static solution due to Mindlin with the dynamic plane strain solution. The soil matrices in lateral and axial vibrations which include the cross stiffness between different stations are given by

$$[K_s]_\ell = GS_{u1}(\nu, d/r_o, a_o)\,l\,[B]_\ell \quad (7)$$

$$[K_s]_a = GS_{w1}(d/r_o, a_o)\,l\,[B]_a \quad (8)$$

The corresponding soil damping matrices are

$$[C_s]_\ell = G\bar{S}_{u2}(\nu, d/r_o)\,\frac{r_o l}{V_s}\,[B]_\ell \quad (9)$$

$$[C_s]_a = G\bar{S}_{w2}(d/r_o)\,\frac{r_o l}{V_s}\,[B]_a \quad (10)$$

in which G, ν are the shear modulus and Poisson's ratio of soil; r_o, l are the radius and element length of the pipe; d is the embedment depth; $a_o = r_o\omega/V_s$; ω is the frequency (rad/sec); V_s is the shear wave velocity [$V_s = \sqrt{G/\rho_s}$]; ρ_s is the mass density of soil; S_{u1}, $\bar{S}_{u2}$, S_{w1}, $\bar{S}_{w2}$ are dimensionless parameters describing the soil stiffness and damping in lateral and axial vibrations, respectively; and $[B]_\ell$, $[B]_a$ are normalized stiffness coefficient matrices for lateral and axial directions, respectively. The details of the procedure are available in (Hindy & Novak 1979 and Datta & Mashaly 1986).

2.3 Response analysis

The equation of pipe motion in the lateral direction is

$$[M](\ddot{U})+[C_s](\dot{u})+[C_p](\dot{U})+[K_s](u)+[K_p](U)=0 \qquad (11)$$

in which [M] is diagonal mass matrix; $[K_s]$, $[K_p]$, $[C_s]$ and $[C_p]$ are the stiffness and damping matrices of soil and pipe corresponding to dynamic d.o.f. in the lateral direction; (Figure 1b); $(\ddot{U})$, $(\dot{U})$, (U) are vectors of absolute values of acceleration, velocity, and displacement; and $(\dot{u})$, (u) are the vectors of relative values of velocity and displacement in the lateral direction. Equation (11) is valid also in the axial direction with $(\ddot{U})$, $(\dot{U})$, (U), $(\dot{u})$ and (u) representing the acceleration, velocity and displacement in axial direction and $[K_s]$, $[K_p]$, $[C_s]$ and $[C_p]$ denoting the stiffness and damping matrices of soil and pipe corresponding to dynamic d.o.f. in axial direction. $[K_s]$ and $[C_s]$ are obtained by equations (7) to (10) and the pipe stiffness matrix in lateral direction can be obtained from the condensation of pipe stiffness matrix corresponding to Kinematic d.o.f. (Figure 1a). For axial direction, no matrix condensation is required since the stiffness matrices corresponding to kinematic and dynamic d.o.f. are the same. $[C_p]$ can be defined only in terms of modal damping.

Denoting the total stiffness of soil-pipe system as $[K] = [K_s] + [K_p]$ and $(U) = (u) + (u_g)$, equation (11) can be rewritten in terms of absolute displacement as

$$[M](\ddot{U}) + [C_s + C_p](\dot{U}) + [K](U) = [C_s](\dot{u}_g) + [K_s](u_g) = \{P(t)\} \qquad (12)$$

in which $(\dot{u}_g)$, (u_g) are the vectors of ground velocity and displacement.

It will be assumed that the pipeline response to the seismic excitation is also a stationary random process. Since the soil-pipe system is linear, the PSDF of the response can be related to the PSDF of the seismic force P(t) by

$$[S_{RR}] = [H(i\omega)]^* [S_{PP}] [H(i\omega)]^T \qquad (13)$$

in which $[S_{RR}]$ is the PSDF matrix of response quantity R(t); $[S_{PP}]$ is the PSDF matrix of exciting force P(t); $[H(i\omega)]$ is the complex frequency function matrix which varies depending upon the response quantity to be calculated; and *, T denote the complex conjugate and the transpose, respectively. The matrix $[S_{PP}]$ contains elements S_{pipj}, i = 1, ..., n, j = 1, ..., n (n is the size of load vector {P(t)}); each element S_{pipj} will involve the cross spectral density functions $S_{\dot{u}_{gi}u_{gi}}$, $S_{u_{gi}\dot{u}_{gi}}$, $S_{u_{gi}\dot{u}_{gj}}$, and $S_{u_{gj}\dot{u}_{gi}}$ (see equation (12)). Assuming local spectrum $S_{u_g}(\omega)$ to be the same for all stations, employing equation (6) to express the cross spectrum of displacement between two stations, and using the basic spectral relationship between two signals, any element of the matrix $[S_{PP}]$ can be determined in terms of two basic inputs, namely, $S_{u_g}(\omega)$ and $R_{ij}(y_i, y_j, \omega)$, i = 1,..,n and j = 1, ...,n. Evaluation of $[H(i\omega)]$ and $[S_{PP}]$ matrices have been presented by (Datta and Mashaly 1986). Assuming the response to be zero mean process, the r.m.s. response is obtained as the square root of the area under the PSDF curve of response.

3 PARAMETRIC STUDY

The following input data are used to conduct the parametric study:

1. Pipeline data: mass density $\rho_p = 0.984\ (t/m^3)/(m/sec^2)$; modulus of elasticity $E = 2.1 \times 10^7\ t/m^2$; pipe radius $r_o = 0.685m$; the ratio of the wall thickness 't' to the pipe radius, $t/r_o = 0.01622$; embedment depth $d = 30 r_o$ or variable; damping ratio of the pipe $\xi_p = 0.05$ and common for all modes; and the end condition is symmetrical guided (as shown in Figure 1) or different end conditions.

2. Soil data: mass density $\rho_s = 0.1628\ (t/m^3)/(\ m/sec^2)$; shear wave velocity for the soft soil V_s = 70 m/sec or variable according to soil condition; shear modulus $G = V_s^{\ 2} \rho_s = 798\ t/m^2$ or variable (according to V_s); Poisson's ratio ν=0.25; and the soil stiffness and damping parameters S_{u1}, $\bar{S}_{u2}$, S_{w1} and $\bar{S}_{w2}$ have the values 4.0, 9.1, 2.7 and 6.7, respectively which correspond to an embedment depth $d = 30 r_o$ and vary according to the variation of 'd' (as shown in Figure 2).

3. Seismic input: the PSDF of ground acceleration is obtained using equations (1) to (3) for a standard deviation of ground acceleration = 0.610 m/sec^2 and the characteristics of the filters representing the soft soil condition (V_s = 70 m/sec) are $\omega_g = 2\pi$, $\xi_g = 0.4$, $\omega_f = 0.1\omega_g$ & $\xi_f = \xi_g$. The PSDF of ground motions are modified for the soil condition by suitably changing the filter characteristics for the soil medium as shown in Figure 3. The normalized spectra of ground acceleration corresponding to different types of soil condition are shown in Figure 3. For defining the cross correlation function between any two stations by equation (6), the parameter C is taken as 0.5.

For studying the effect of inside fluid, it is assumed that the pipe is full of water with mass density 0.102 $(t/m^3)/(m/sec^2)$. Two types of solution are performed, namely, solution with considering the cross terms of soil stiffness and damping matrices (subsequently, it will be refered as solution-1) and solution without considering these cross terms (subsequently, it will be refered as solution-2).

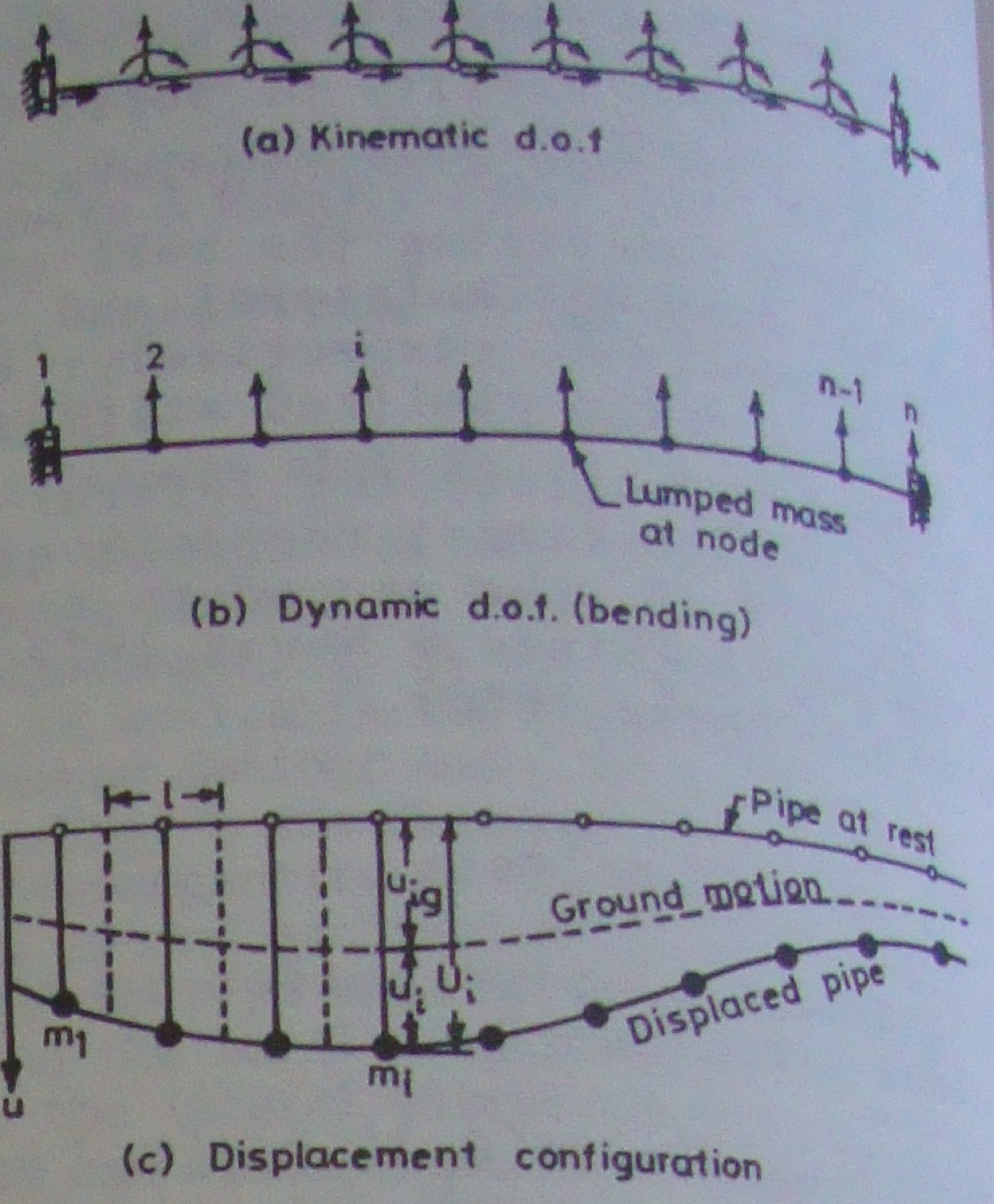

Fig.1 Lumped mass model of pipeline

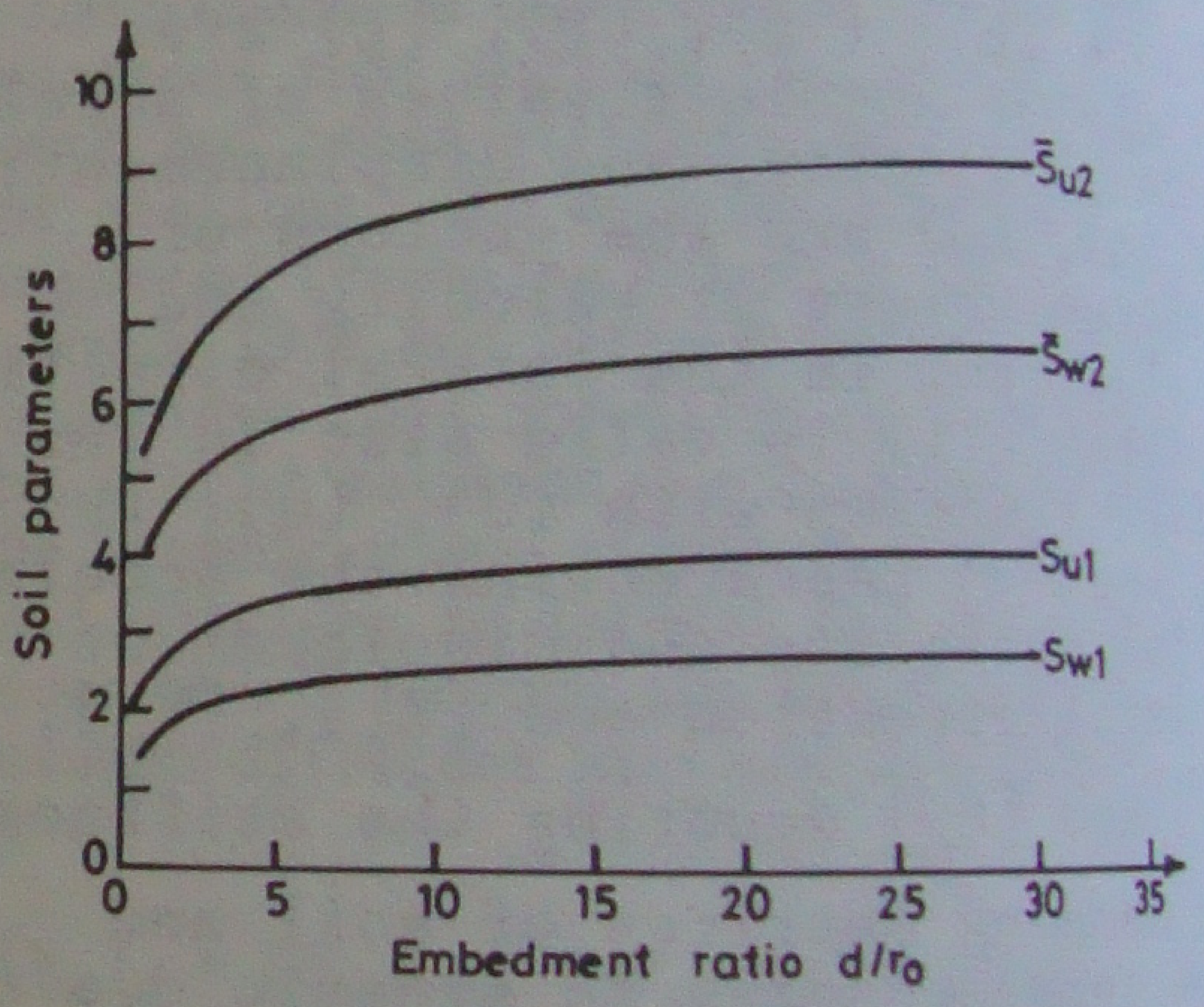

Fig.2 Variation of dimensionless soil stiffness and damping parameters with embedment depth in plane strain case (after Hindy & Novak 1979).

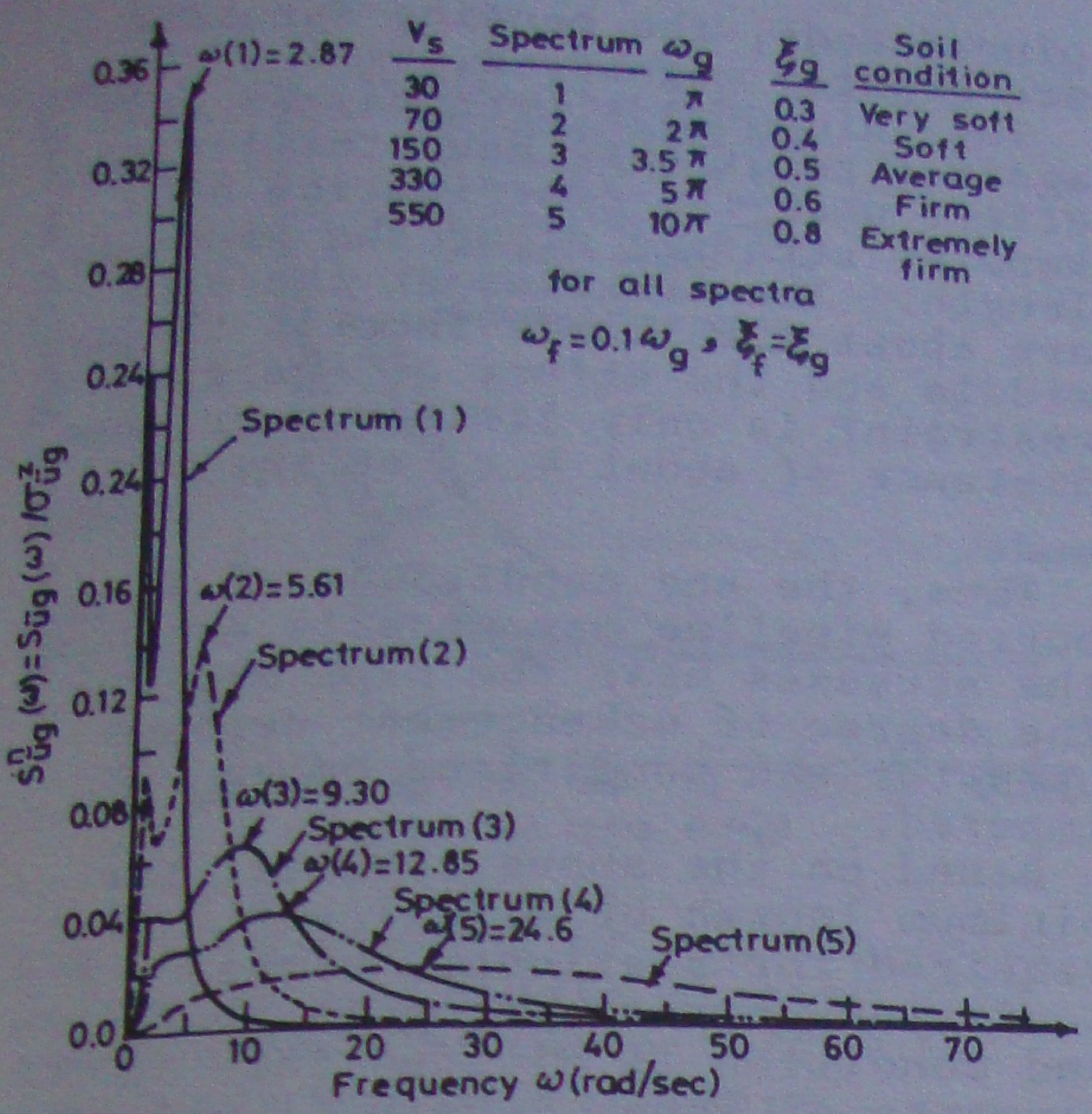

Fig.3 Normalized spectra of ground acceleration

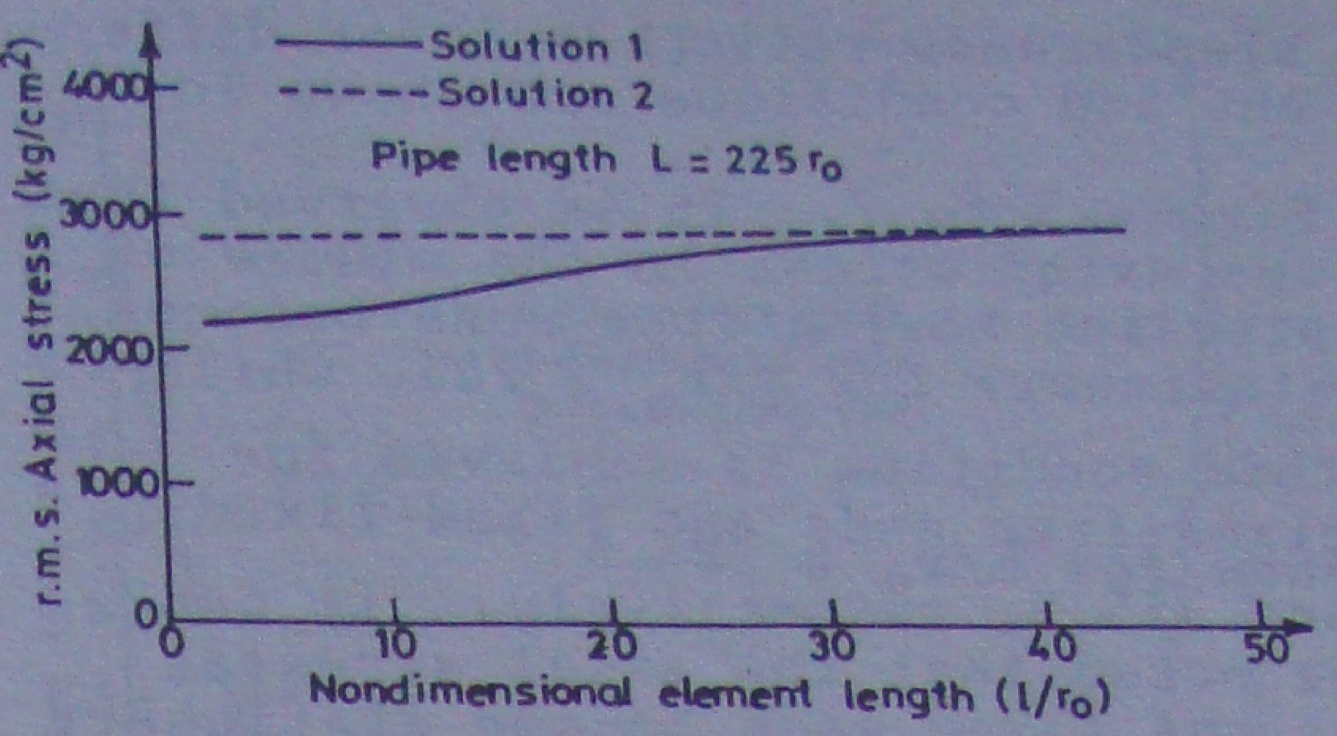

Fig.4a Variation of r.m.s. axial stress in the middle of pipe with the element length l

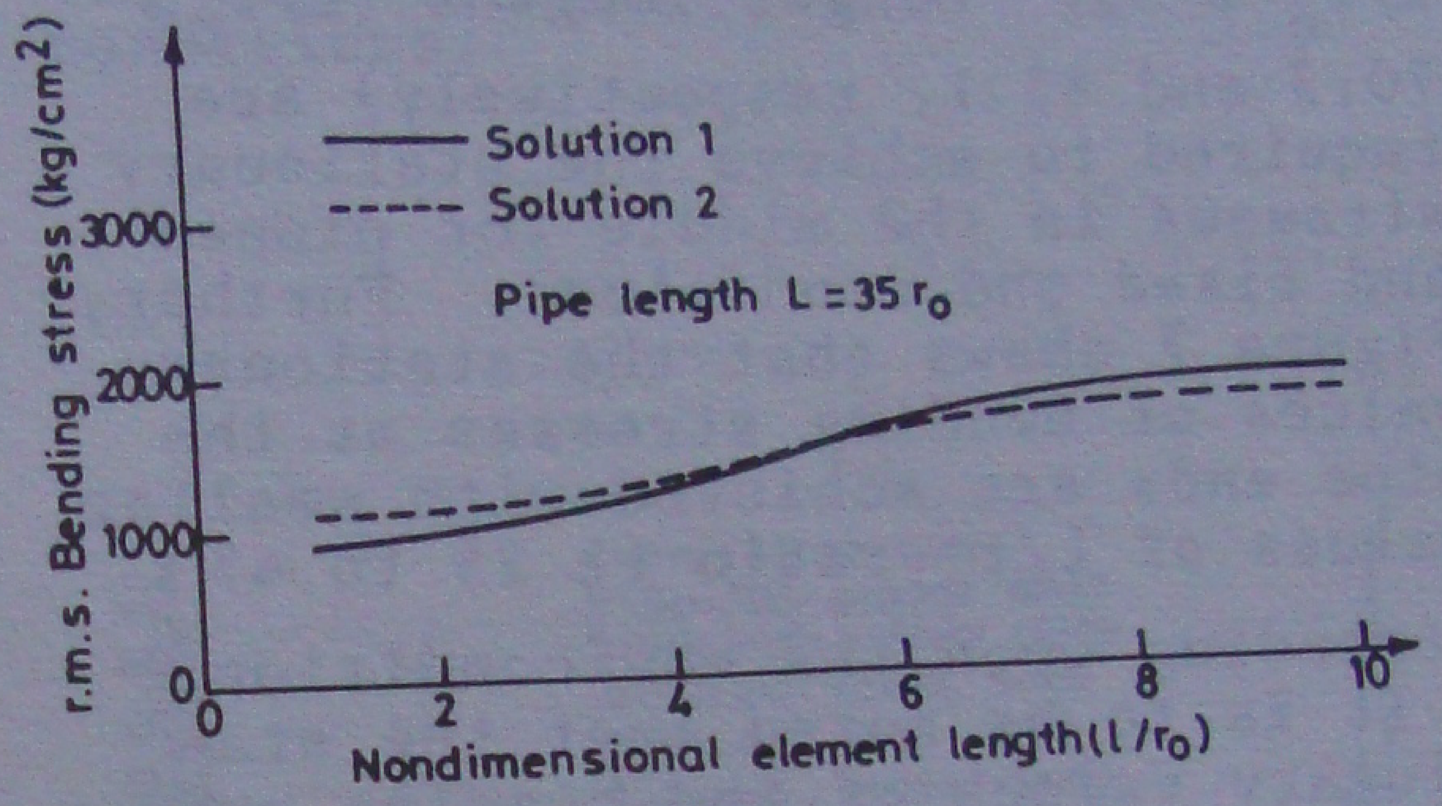

Fig.4b Variation of r.m.s. bending stress in the middle of pipe with the element length l.

3.1 Effect of element length on the pipe stresses

The stresses in the middle of buried pipeline (having length L) are obtained using different element lengths. The ends of pipelengths are assumed to be on guided supports (Figure 1). It is seen from Figure 4a that the axial stresses obtained from solution-2 are not sensitive to the element size. However, the axial stresses obtained from solution-1 decrease with the decrease in element length. The reduction of stresses remains nearly constant for element length $l \leqslant 12r_o$.

Figure 4b shows that the bending stresses decrease as the element length is reduced and they attain almost a stationary value for element length $l \leqslant 2r_o$.

3.2 Effect of end conditions on the pipe stresses

For different pipe end conditions, the stresses near the ends and in the middle of pipelength depend upon the length of pipe being analyzed. The pipe stresses are obtained for different end conditions by solution-2 using different pipelengths and keeping the element size (l) same for all ($l = 1.85\ r_o$ for lateral vibration and $l=11.85r_o$ for axial vibration).

The variations of r.m.s. axial and bending stresses with the slenderness ratio(L/r_o) for different end conditions are shown in Figures 5 to 7. It is observed that the axial stress in the middle of pipeline having free ends becomes stationary for $L/r_o \geqslant 225$, while this condition is achieved for fixed-free ends and fixed-fixed ends, for $L/r_o \geqslant 284.4$ and 355.5, respectively. It can be noted that the axial stresses at the fixed ends become stationary at less values of L/r_o ratio, i.e. about 107 and 214 for fixed-free and fixed-fixed end conditions, respectively.

The bending stress in the middle reaches the stationary state at less values of L/r_o. For free or guided ends or a combination of the two, the stationary value of the middle stress is achieved for $L/r_o \geqslant 35$. Longer lengths ($L/r_o \geqslant$ 70.3 and 85.1, respectively) are required to achieve the stationary stresses in the middle for pinned and fixed end conditions. Further, Figure 7 shows that the stationary values of bending stresses at the pipe ends are achieved with smaller values of L/r_o ratio ($\geqslant$ 25 to 45 depending upon the end condition).

It is to be noted that the stationary values of the bending and axial stresses in the middle of the pipeline are the same for all end conditions. Thus, beyond a certain length of pipeline (being analyzed), the stresses at the mid-length are independent of pipe end condition; the minimum pipelength required depends upon the boundary condition imposed at the pipe ends.

Figures 8 and 9 show the distributions of the stationary values of the normalized axial and bending stresses, respectively (w.r.t. the stresses in the middle of pipe having free-free ends) along the pipelength. It is seen that the axial and bending stresses at the fixed ends are respectively about 10.3 and 54 times those in the middle. The effect of fixity extends over a length of 80 r_o and 25 r_o for axial and bending stresses, respectively. Further, over a length of about $20r_o$ near the pinned ends, the bending stresses are greatly magnified.

The guided ends (restrained only against rotations) have the least effect upon the distribution of bending stresses along the pipelength. The stresses at the ends are about 1.45 times those in the middle and the effect of the end restraint is only limited over a distance of about 4 r_o at the pipe ends.

Thus, the end conditions of a buried pipeline may greatly enhance the stresses near the pipe ends. The degree of enhancement depends upon the end conditions being imposed.

Based on the above results, the minimum length of pipeline (L) required for stationary stress condition corresponding to every end condition is divided into 'n' elements of equal length ($l = 1.85r_o$ in lateral vibration and $l = 11.85r_o$ in axial vibration) and used for the parametric study.

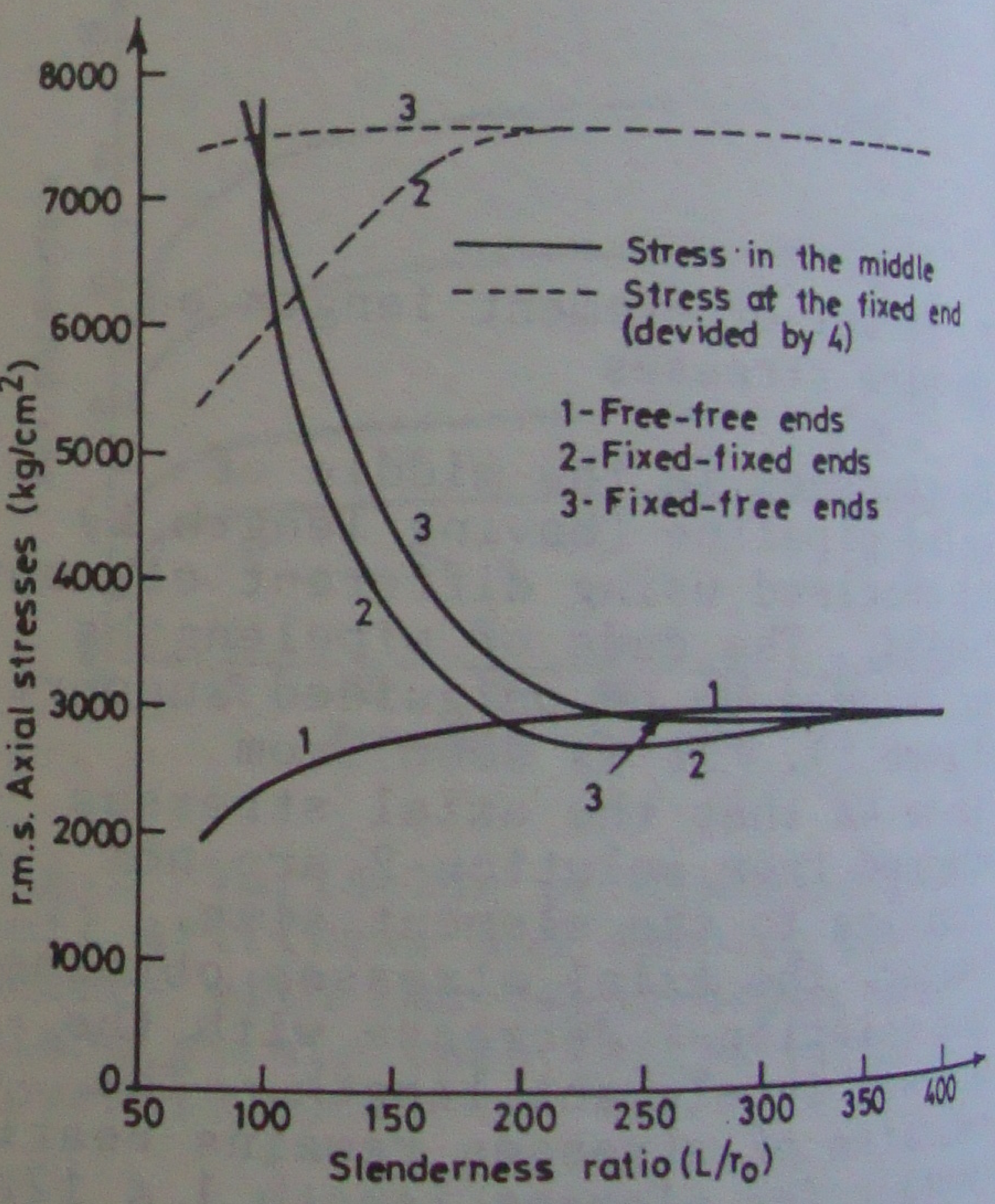

Fig. 5 Variation of r.m.s. axial stresses in the middle and at the end of pipe with the slenderness ratio (L/r_o) for different end conditions.

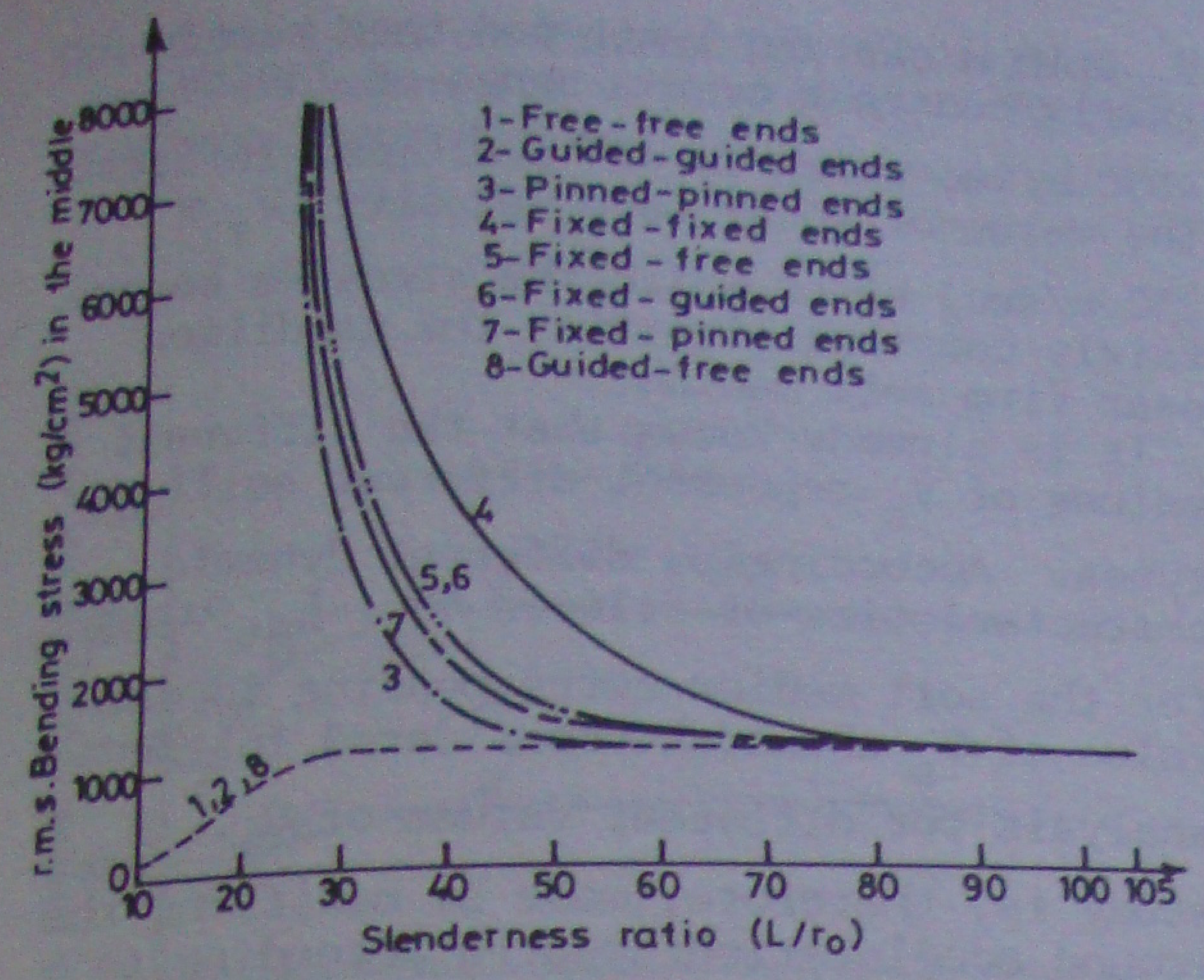

Fig. 6 Variation of r.m.s.bending stress in the middle of pipe with the slenderness ratio (L/r_o) for different end conditions.

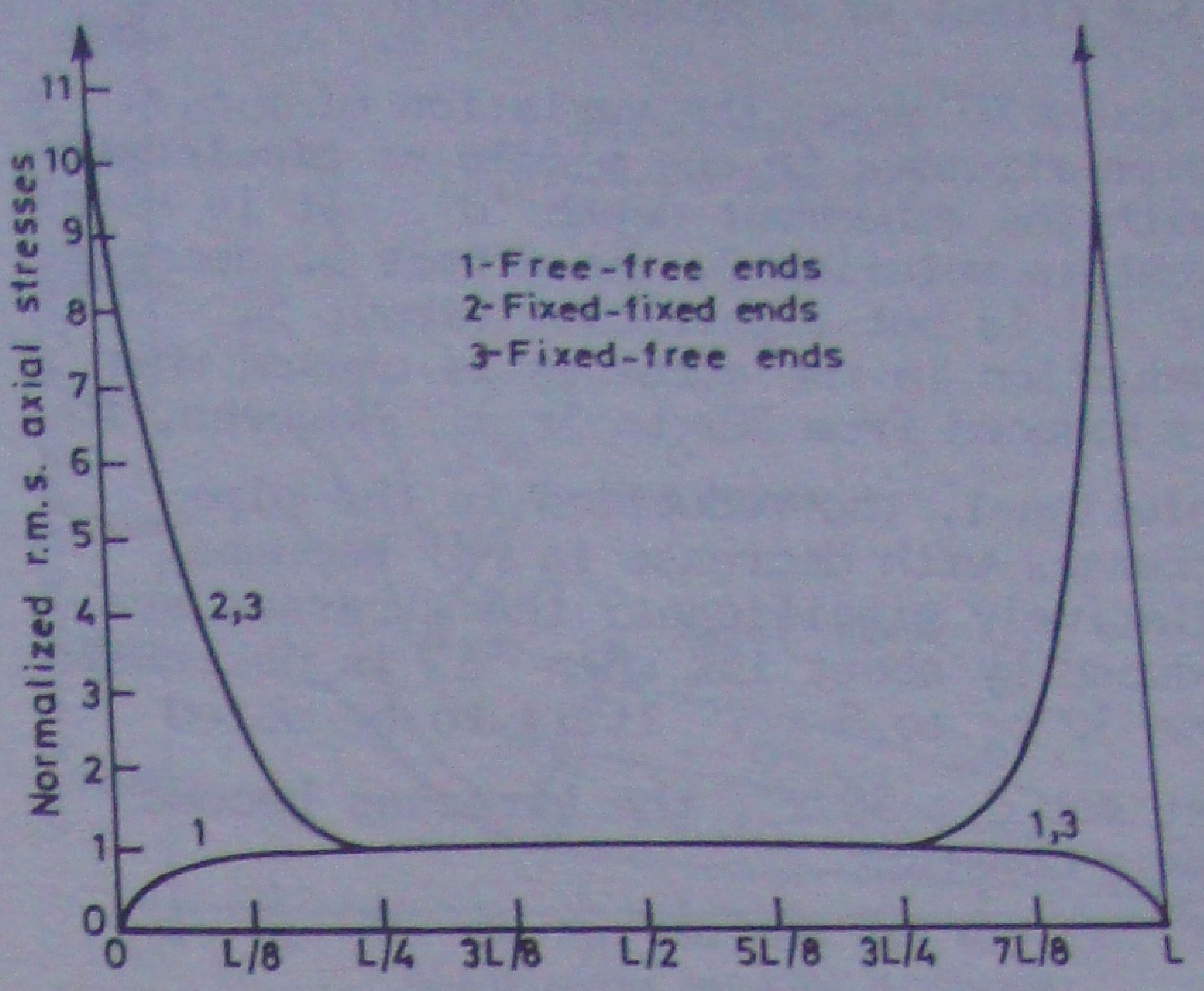

Fig. 8 Distribution of the normalized r.m.s. axial stresses (w.r.t. stress in the middle) along the pipelength for different end conditions.

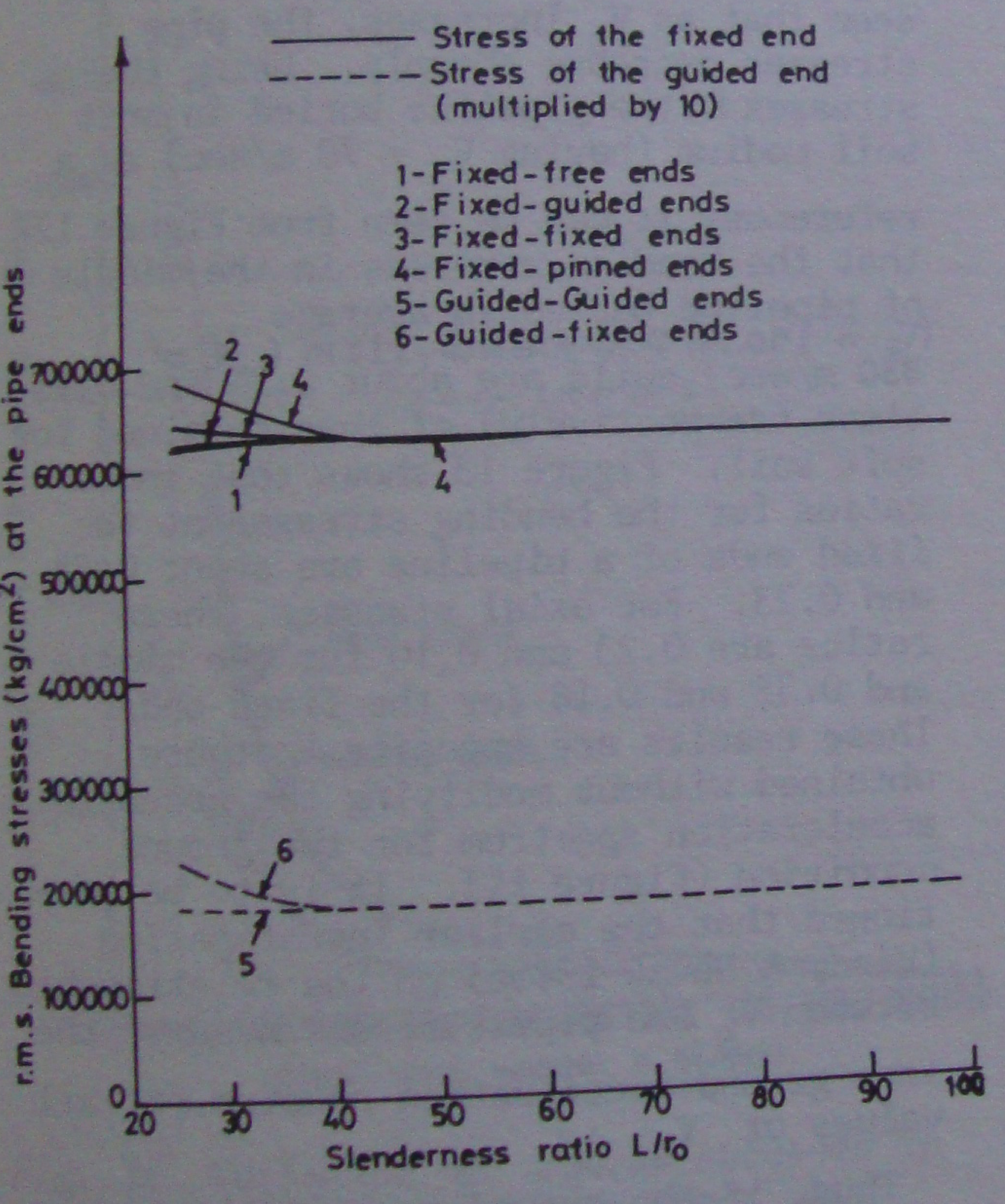

Fig. 7 Variation of r.m.s. bending stresses at the pipe ends with the slenderness ratio (L/r_o) for different end conditions.

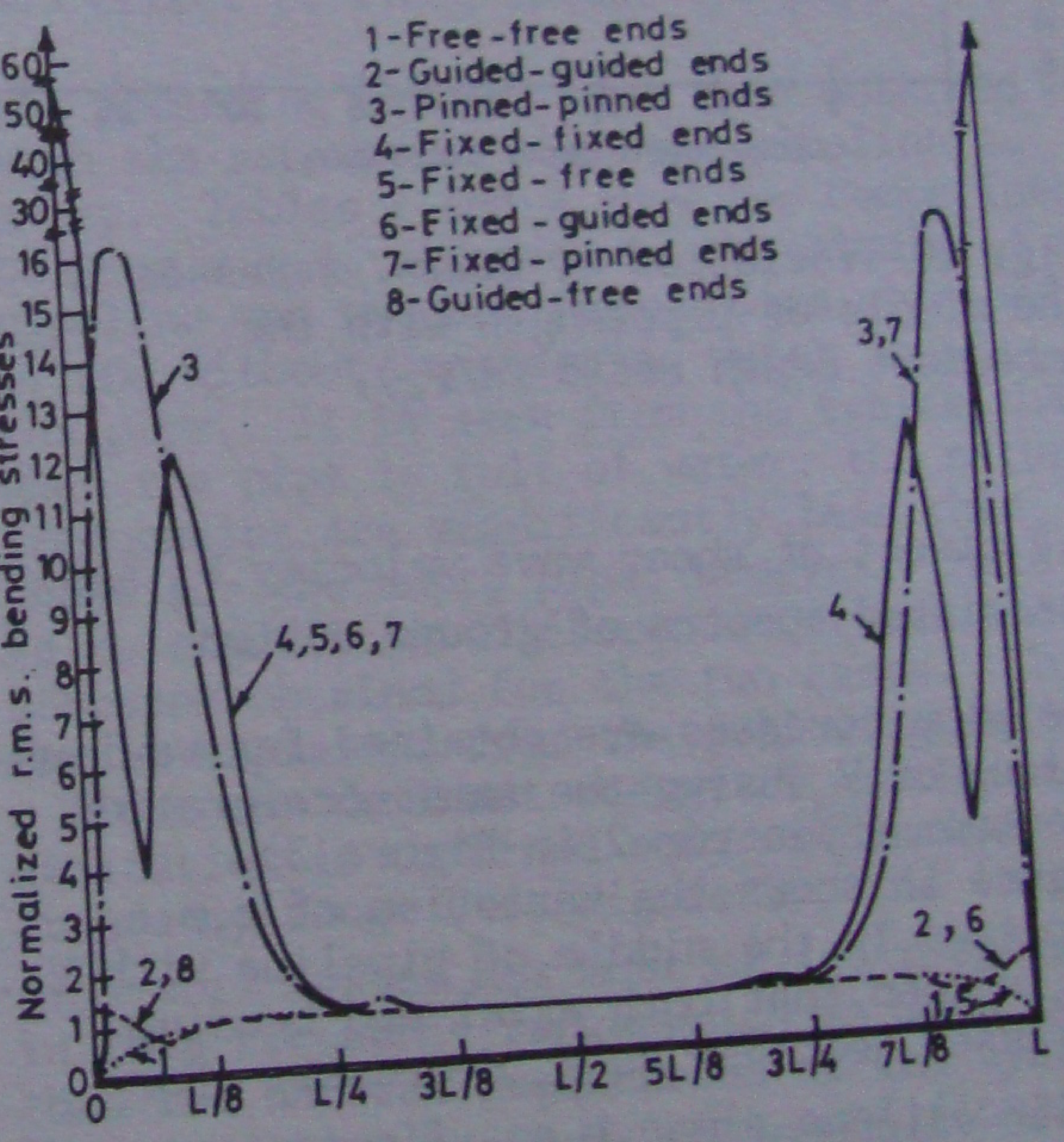

Fig. 9 Distribution of the normalized r.m.s. bending stresses (w.r.t stress in the middle) along the pipelength for different end conditions.

3.3 Effect of embedment depth

Figure 10 shows the variation of r.m.s. pipe stresses in the middle of pipelength with the embedment depth 'd'. It is seen that in solution-2, the effect of decrease of 'd' is not significant (about 5% reduction in the stresses is caused when 'd' is reduced from $30r_o$ to $5r_o$). However, in solution-1, the reduction in the pipe stresses with decrease in 'd' becomes relatively significant; the stresses are reduced by about 15% when 'd' is decreased from 30 r_o to 5 r_o. It is to be noted that for $d \geqslant 30\ r_o$, the stresses become almost constant.

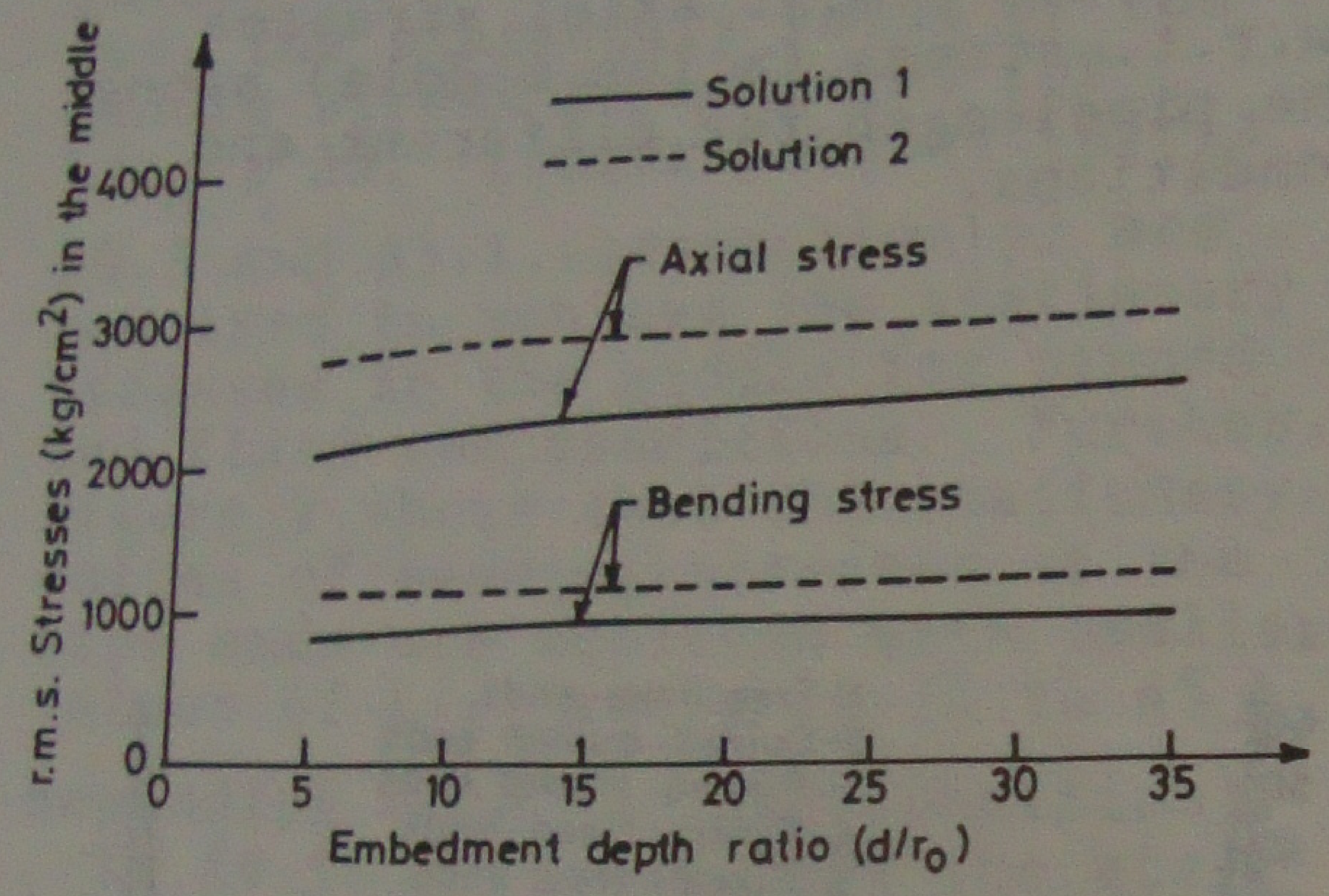

Fig. 10 Variation of r.m.s. stresses in the middle of pipelength with the embedment depth ratio (d/r_o).

3.4 Effect of shear wave velocity V_s and associated spectra of ground motion

The pipe stresses are obtained for various values of V_s using the same acceleration spectrum (Spectrum-2 in Figure 3). Figure 11 shows the variation of r.m.s. stresses in the middle of pipeline with V_s. It is seen that both axial and bending stresses decrease as V_s decrease. For lower values of V_s, the reduction is more pronounced. It may be noted that an increase in V_s implies two counteracting effects; (i) increase in the degree of correlation (equation (6)) which reduces the pipe stresses and (ii) increase of soil stiffness which increases the pipe stresses. However, the net effect is to increase the stresses with the increase in V_s upto a certain limit and then remain fairly constant over a range of $250 < V_s < 550$ m/sec which is of practical interest. The value of shear wave velocity ($V_s \cong 250$ m/sec) after which the stresses become fairly constant signifies the condition near firm soil medium.

It is already known that the different values of V_s represent different soil types. Accordingly, different dynamic characteristics of filters (ω_g, ξ_g, ω_f, ξ_f) for the soil medium corresponding to each value of V_s should be considered in the analysis for different values of V_s. A study is, therefore, made by modifying the ground acceleration spectra according to the soil condition (represented by V_s). For each soil condition, a shear wave velocity V_s and a set of filter characteristics ω_g, ξ_g, ω_f, ξ_f are assumed (see Figure 3). The corresponding ground acceleration spectra are shown in Figure 3.

Using the above data, the pipe stresses are obtained and plotted versus V_s in Figures 12 and 13, from which it can be seen that as V_s increases, the pipe stresses decrease sharply. Using the stresses in the pipeline buried in soft soil medium (having V_s = 70 m/sec) as a reference, it can be seen from Figure 12 that the bending stresses in the middle of pipeline buried in average (V_s = 150 m/sec) and firm (V_s = 330 m/sec) soils are about 0.26 and 0.15 times (respectively) of that obtained for soft soil. Figure 13 shows that these ratios for the bending stresses at the fixed ends of a pipeline are about 0.38 and 0.23. For axial stresses, these ratios are 0.23 and 0.10 for the middle and 0.33 and 0.16 for the fixed ends. These results are opposite to those obtained without modifying the ground acceleration spectrum for the ground condition (Figure 11). It is to be mentioned that the earlier investigation (Hindy & Novak 1980a) on the relationship between V_s and pipe stresses assumed the same ground acceleration spectra for all values of V_s.

Thus, if the ground acceleration spectrum is not modified for the soil condition (characterized by V_s), the pipe stresses will be grossly under-estimated for very soft soil condition (V_s < 70 m/sec; see dot-dash lines in Figure 12) and will be over-estimated for values of $V_s > 70$ m/sec (compare Figures11 and 12).

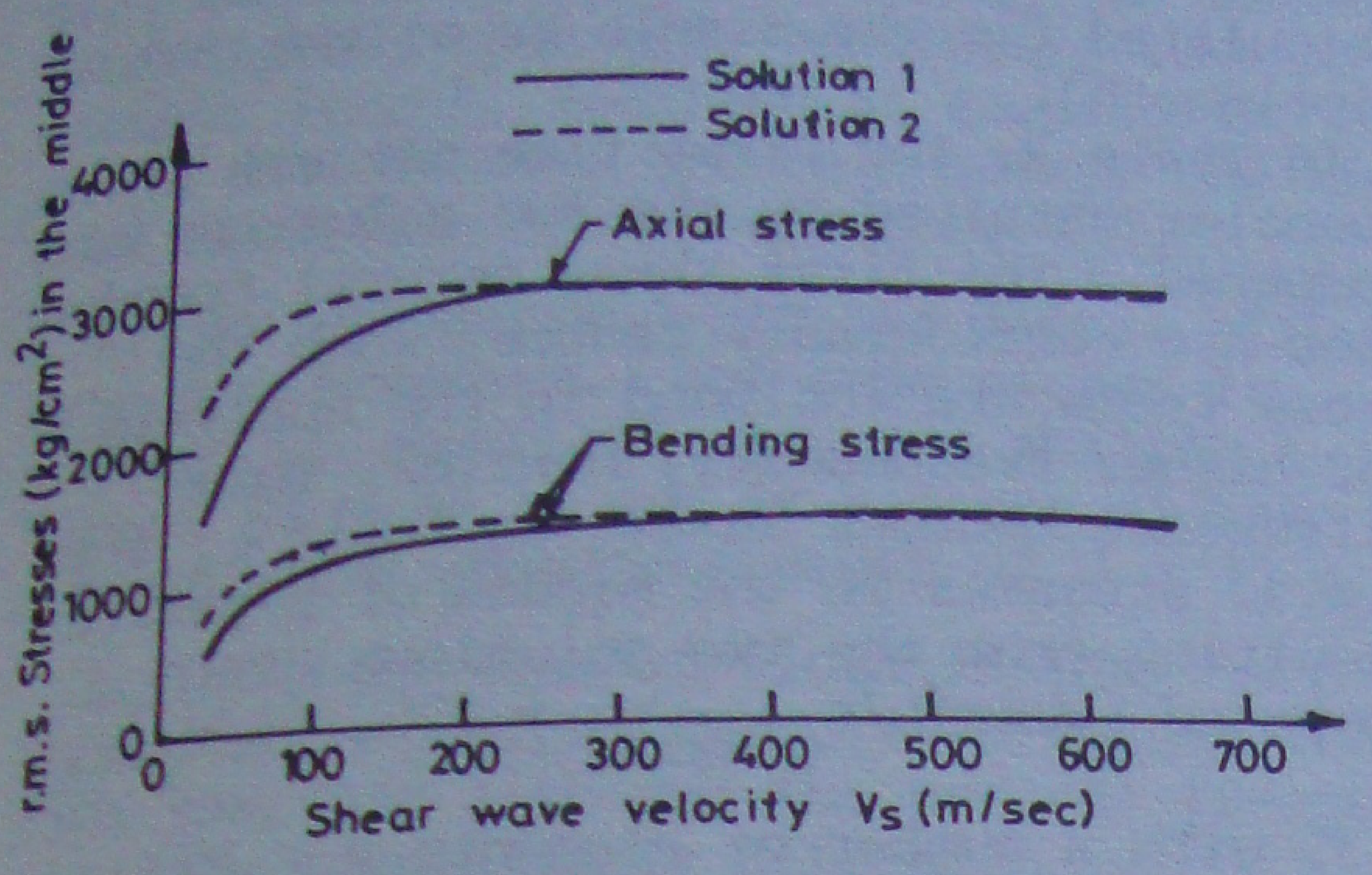

Fig. 11 Variation of r.m.s. stresses in the middle of pipeline with shear wave velocity using same acceleration spectrum.

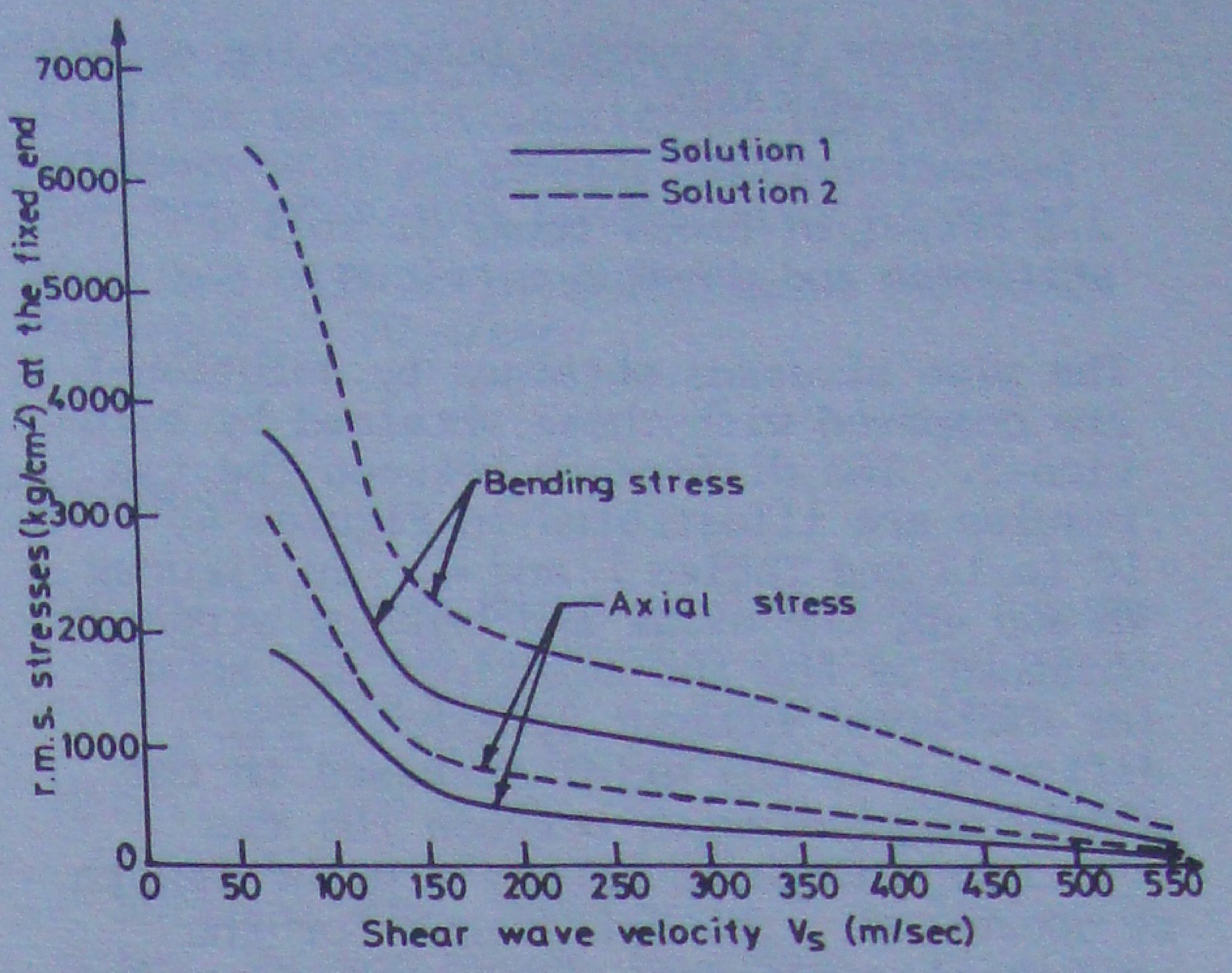

Fig. 13 Variation of r.m.s. stresses at the fixed end of pipeline with shear wave velocity using the corresponding ground spectra.

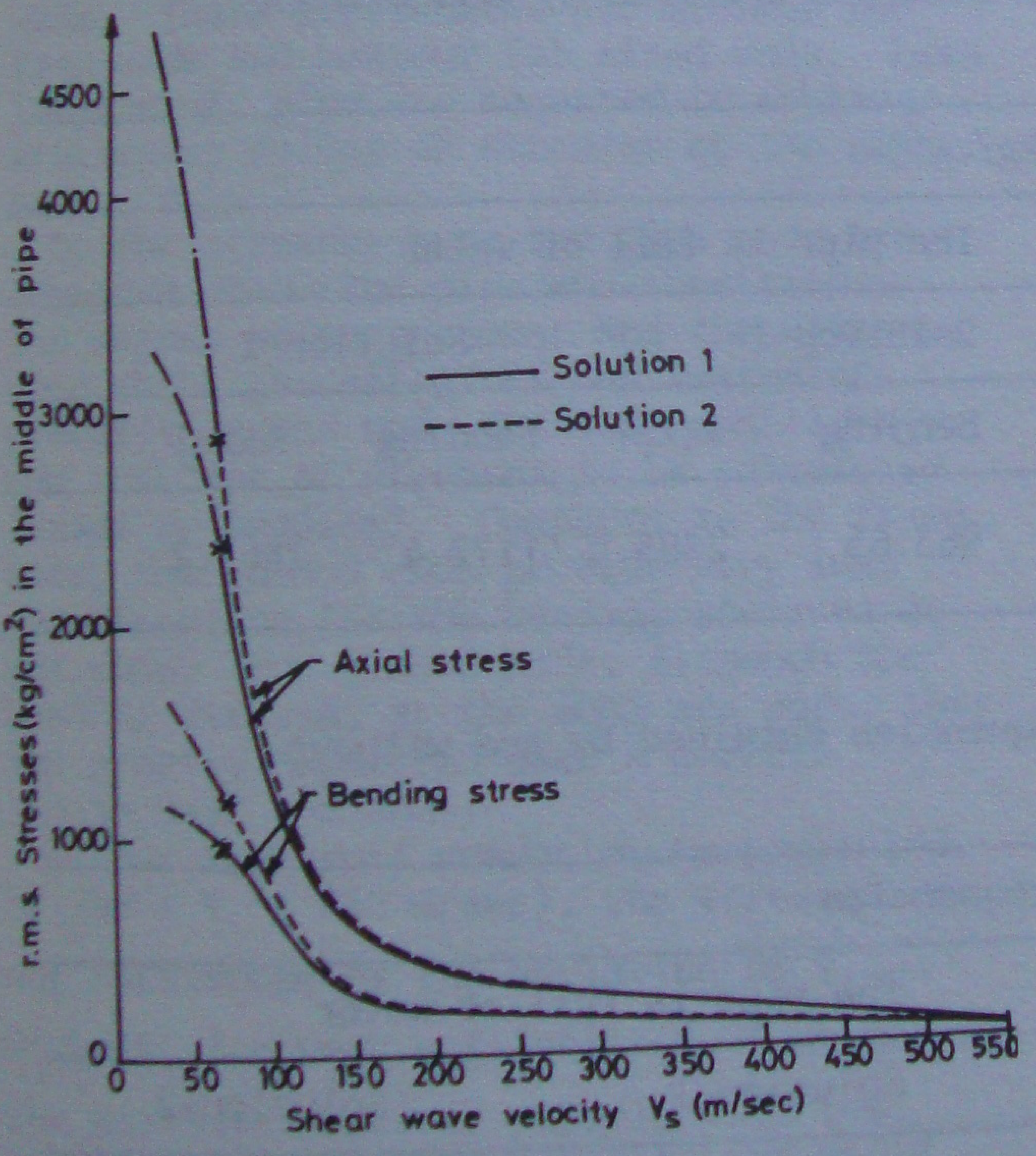

Fig. 12 Variation of r.m.s. stresses in the middle of pipeline with shear wave velocity using the corresponding ground spectra.

3.5 Effect of fluid inside the pipe

The preceding results have been obtained with the assumption that the pipeline is empty. Tables 1 and 2 show the comparison between r.m.s. stresses in the middle of pipeline and natural frequencies obtained by and without considering water inside the pipe. It is seen from the tables that when the pipe is full of water, the natural frequencies are significantly less than those for the empty pipe; however, there is no significant difference between the stresses obtained for the two cases. This can be explained from the following facts:

Since the dominant energy of earthquake excitation is confined only within low frequency range (see Figure 3), the (empty) pipe-soil system has most of its response in this frequency range which is much less than the natural frequencies of the system. Thus, practically,no dynamic amplification of the response is caused and the system responds in a pseudo static manner. For the pipe with water full condition, the natural frequencies are reduced by about 50%, however, they remain higher than the frequencies over which the dominant energy of the acceleration spectrum is confined. As a result, the system again behaves pseudo statically. Thus, no significant difference is observed between the stresses for the two cases.

3.6 Effect of cross terms of soil stiffness and damping matrices

The pipe stresses obtained by solution-1 are compared with those obtained by solution-2. The difference between the two results are illustrated in Figures 4, 10 to 13 and Tables 1 and 2. In Figures 4a and 4b, the axial and bending stresses obtained by the two solutions are shown for different element lengths. The difference in the axial stresses in the middle of pipelength between the two solutions increases as the element length is decreased. The difference for the bending stresses does not vary uniformly as in the case of axial stresses. For larger and smaller elements, this difference is more, whereas, it becomes negligible for intermediate sizes of the element.

From Figures 4 and 10 to 13, it is to be noted that generally, the stresses are less when the cross terms are included in the analysis (solution-1). The amount of reduction depends upon the element length, shear wave velocity, and the location of the section at which the stresses are calculated (in the middle or at the end of pipelength).

In Table 2, the first five natural frequencies obtained by the two solutions are compared. The first three natural frequencies are considerably reduced when the cross terms are included in the analysis. For higher frequencies, however, this difference becomes less. In Table 1, the r.m.s. stresses in the middle of pipeline resulting from the two solutions are compared (when $(L/r_o)_{axial} = 225$, $(L/r_o)_{lat.} = 35$ with a number of elements $n = 19$). The axial and bending stresses are reduced by about 17-18% when the cross terms of soil stiffness and damping matrices are considered.

Table 1. Comparison between the r.m.s. pipe stresses obtained by and without considering the water inside.

r.m.s. stresses in the middle of pipeline (kg/cm^2)							
The pipe is empty				The pipe is full of water			
Solution-1		Solution-2		Solution-1		Solution-2	
Bending	Axial	Bending	Axial	Bending	Axial	Bending	Axial
963.6	2383.4	1172.4	2861.2	963.65	2383.5	1172.4	2861.2

Table 2. Comparison between the natural frequencies obtained by and without considering the water inside.

Mode No.	Natural frequencies							
	The pipe is empty				The pipe is full of water			
	Solution-1		Solution-2		Solution-1		Solution-2	
	Lateral	Axial	Lateral	Axial	Lateral	Axial	Lateral	Axial
1	153.2	125.2	256.2	210.5	75.7	61.8	126.5	103.9
2	189.8	178.5	259.3	230.6	93.7	88.1	128.0	113.8
3	256.5	249.2	302.2	281.8	126.6	123.0	149.2	139.1
4	418.6	329.3	442.7	349.9	206.7	162.6	218.6	172.7
5	680.2	412.3	692.0	425.3	335.8	203.6	341.7	210.0

4. CONCLUSIONS

The following conclusions can be drawn from the parametric study:

1. Consideration of cross terms of soil stiffness and damping matrices in the analysis, reduces the pipe stresses; the reduction depends upon many parameters such as element length, location of section at which the stresses are calculated, and the soil condition (represented by V_s).

2. The embedment depth has little effect upon the stresses. The pipe stress is reduced by about 15% only for shallow burial ($d = 5r_o$), and it becomes almost constant for embedment depth of $d \geqslant 30\ r_o$.

3. The existence of fluid inside the pipeline does not significantly influence the pipe response although the natural frequencies are considerably altered.

4. Beyond certain length of the pipeline (being considered in the analysis), the stresses in the middle of pipelength are independent of the pipe end conditions. The minimum length of the pipe required to achieve this condition differs for axial and bending stresses and depends upon the boundary conditions imposed at the pipe ends. These pipelengths are minimum for free ends and maximum for fixed ends. Less lengths of pipe are required to achieve stationary values of stresses at the pipe ends.

5. The stresses near the pipe ends are enhanced due to the pipe end conditions. The degree of enhancement and the distance over which the effect of end restraints prevails depend upon the end conditions and the type of stresses to be calculated (axial or bending). Compared to the fixed ends, the guided ends provide very less magnification for the bending stresses at the ends. For pinned ends, although the bending stresses at the ends are zero, they are greatly magnified over a certain length near the ends.

6. For firm soil condition (represented by $250 < V_s < 550$ m/sec), the stresses are not influenced by the variation of V_s. However, for very soft soil ($V_s < 70$ m/sec), the stresses decrease rapidly with the decrease in V_s. These results are valid if the same ground acceleration spectrum is assumed for all values of V_s.

7. When the ground acceleration spectra are modified in accordance with the soil type (represented by V_s), the stresses decrease rapidly with V_s. Thus, if the ground acceleration spectrum is not modified for the soil condition, the pipe stresses will be grossly under-estimated for very soft soil condition ($V_s < 70$ m/sec) and will be over-estimated for soils having $V_s > 70$ m/sec.

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