# EFFECT OF BOND IMPERFECTION ON THE STRESSES INDUCED IN BURIED THICK ORTHOTROPIC CYLINDRICAL FLUID FILLED SHELL DUE TO SHEAR WAVE

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*Abstract :* Earthquake is the most dangerous natural catastrophe among all natural calamities. Earthquakes have always been a serious threat to humanity, which always results in a serious loss of life and property. According to a survey our civilization is facing earthquake in almost every month. Thus it is the prime objective of scientists and engineers to study and analysis the earthquake motion and to find methods to reduce damaging effects of earthquake on different kinds of structure. In the past, large numbers of papers have been published which deal with the development of design criterion for structures to make them earthquake resistant. But these efforts have been concentrated mainly on the structures built above the ground. A major class of structural systems namely the lifelines did not draw attention of researchers till seventies. Lifelines (pipelines) have been included in the list of earthquake affected structures only recently when some heavy damages were reported. Therefore, the earthquake effects on buried pipelines are an important problem to deal with.

All the previous works done on the dynamic response of underground pipelines were mainly related to the assessment of the effect of different soil parameters of the continuum. Some researchers made an attempt to find the deformation in buried pipelines due to seismic action. It is still an important area of the research to find out the behavior of stresses that induced in the shell during earthquake/ seismic excitation.

Again no further steps were taken to investigate the stress in the fluid filled pipelines by treating it as thick cylindrical shell. An attempt has been made here to study the axisymmetric stresses (axial and hoop) induced in the shell. The shell has been modelled as an infinitely long circular cylindrical shell made of orthotropic material imperfectly bonded in a homogeneous, isotropic and elastic medium of infinite extent. A thick shell theory has been used whereas the effect of rotary inertia is neglected. The seismic excitation is considered in the form of secondary wave/ shear wave. It is assumed that the shell-soil is bonded together by a thin, elastic and inertialess bond.

Results have been shown in this thesis for different degrees of bond imperfection by varying the bond parameters. Also, different soil conditions around the shell and different angle of wave incidence have been considered for the empty shell along with the fluid filled shell. The effect of fluid inside the shell has also been studied; it is found that fluid has a significant effect on the stresses induced in the thick shell.

## I. INTRODUCTION

Earthquake is the most dangerous natural catastrophe among all natural calamities. Earthquakes have always been a serious threat to humanity, which always results in a serious loss of life and property. Thus it is the prime objective of scientists and engineers to study and analyze the earthquake motion and to find the methods to reduce damaging effects of earthquake on different kinds of structure. In the past, many research papers been appeared which deal with the development of design criterion for structures to make them earthquake resistant. But these efforts have been concentrated mainly on the structures built above the ground. A major class of structural systems namely the lifelines did not draw attention of researchers till seventies. Lifelines (pipelines) have been included in the list of earthquake affected structures only recently when some heavy damages were reported.

A characteristic that distinguishes a lifeline from other structures is that, essentially it extends parallel to the ground surface over a distance which is large compared to its other dimensions. The analysis and design of lifelines subjected to earthquake induced motion is different from that of buildings and other above ground structures. In the case of above ground structures it is customary to assume that the ground motion over the entire foundation plane is coherent, and the relevant response is the displacement relative to the ground. For lifelines, on the other hand, important component of the ground input is the incoherent motion. Also in the case of above ground structures horizontal inertia is most important factor which in case of lifelines is resisted by surrounding soil. Buried pipelines which are typical example of lifelines are playing an important role in today's transportation. Hence the earthquake effects on buried pipelines are an important problem to deal with.

## II. FORMULATION AND GOVERNING EQUATION

The description and details of the formulation of the problem of non-axisymmerric dynamic response of imperfectly bonded buried orthographic pipeline due to incident shear wave, have already been presented by Dwivedi et al. (1991). Therefore only those descriptions and equations are given, which are thought to be necessary and sufficient.

**Shell Equation of Motion:**

An infinitely long thick orthotropic cylindrical shell of radius R and thickness h is considered. cylindrical polar co-ordinate system (r, q and x) such that x-axis coincides with the axis of the shell. The stress –strain relation of the shell material is given by,

$$\begin{aligned}\sigma_{xx}&=E_{x1}\,\varepsilon_{xx}+E_{\nu 1}\,\varepsilon_{\theta\theta}\\ \sigma_{\theta\theta}&=E_{\nu 1}\,\varepsilon_{xx}+E_{\theta 1}\,\varepsilon_{\theta 5}\\ \sigma_{rx}&=G_{x1}\,(2\,\varepsilon_{rx})\end{aligned} \qquad (1)$$

Where $E_{x1}$ , $E_{\theta 1}$ , $E_{\nu 1}$ and $G_{x1}$ are independent Modulus of elasticity for the shell material.

Here we considered imperfectly bonded surrounding soil of the shell and it was assumed that the Shear waves (S -waves) moving along the shell axis. In the calculation of stresses the motion of the shell is assumed to be axisymmetric, which is a simplified version of the problem. The hard (rocky), medium and soft (sandy) soil conditions around the shell have been considered. The soil surrounding the shell is assumed to be perfectly elastic, homogeneous and isotropic.

Thus the response equation $S_{xx}$ and $S_{\theta\theta}$ (the non dimensional form of axial and hoop stress) as,

$$S_{xx} = U\, i\, \beta\, \bar{h} + \frac{\bar{h}^2}{12}\, \beta^2 W + \eta_2 W\, \bar{h} \tag{2}$$

$$S_{\theta\theta} = \eta_2 U\, i\, \beta \bar{h} + \eta_1 W \left( \bar{h} + \frac{\bar{h}^3}{12} \right) \tag{3}$$

Where $S_{xx}$ and $S_{\theta\theta}$ are, respectively, the axial and hoop stress.

## III. RESULT AND DISCUSSION

Result are presented here mainly to study the effect of axisymmetric stresses which is induced in a buried ortotropic thick pipeline with the presence of fluid inside it during incident of plane shear wave (S-wave). This effect is discussed by comparing the stresses induced in an empty shell with that induced in fluid-filled shell.

The effect of fluid on axial stress ($S_{xx}$) of the shell for the softer ($\bar{\mu} = 0.01$) and medium hard soil ($\bar{\mu} = 0.1$) was found to be negligible for grazing angle of incidence. Therefore the results for above mentioned cases are not shown here.

Figures 4.1 & 4.2 show the variations of axial stress ($S_{xx}$), at the incidence wave angle φ=60° & φ=80° respectively, when the surrounding soil condition is assumed to be medium hard ($\bar{\mu} = 0.1$) and axial bond stiffness coefficients ($\zeta_x$) is taken as parameter. It is clear from these two Figures that the fluid has very small effect on axial stress ($S_{xx}$) when compared with the empty shell. At φ=60° presence of fluid marginally decreases the axial stress ($S_{xx}$). However at the higher angle of wave incidence (φ=80°) as in Figure 4.2, axial stress ($S_{xx}$) for fluid filled shell is less comparable to that for empty shell. Although variation in $\zeta_x$ has large effect on axial stress.

Figures 4.3 & 4.4 plotted respectively at φ=5° & 60°, show the effect of fluid on axial stress ($S_{xx}$) under the hard soil condition ($\bar{\mu} = 1.0$). It is clear from the Figure 4.3 that fluid of density $\overline{\rho_f} = 0.132$ increasses axial stress ($S_{xx}$) but as the fluid density is increased ($\overline{\rho_f} = 0.33$ & $0.66$) this change is not as significant as observed for $\overline{\rho_f} = 0.132$. It can be observed from Figure 4.4 that in harder soil ($\bar{\mu} = 1.0$) condition and at higher angle of wave incidence (φ=60°) there is no significant effect on axial stress ($S_{xx}$) due to the presence of fluid inside the shell. Figure 4.3 & 4.4 indicate that variation in bond parameter $\zeta_x$ has more dominant effect on axial stress $S_{xx}$ as compared to the fluid presence when soil is very hard. This effect is more prominent when angle of incidence is increased to 60°.

The effect of the fluid on the axial stress ($S_{xx}$) with the axial damping coefficient of the bond ($\Gamma_x$) as the parameter is shown in Figure 4.5 for the medium hard soil ($\bar{\mu} = 0.1$) and at wave angle of 60°. It is clear from the Figure that the variations in $\Gamma_x$ have almost same kind of effects as was realized in Figure 4.1 due to the variations in the axial stiffness coefficient ($\zeta_x$). At the other values of $\bar{\mu}$ & φ the variations of $\Gamma_x$ were found to give similar effects as it was due to the variation in $\zeta_x$ .It has also been realized that the radial damping and radial stiffness parameters have very little effect on axial stress ($S_{xx}$), Therefore effect of $\zeta_r$ & $\Gamma_r$ on axial stress has not been shown here.

As shown in Figure 4.6 the effect of fluid presence on hoop stress ($S_{\theta\theta}$) due to variation of $\zeta_r$ in soft soil conditions ($\bar{\mu} = 0.01$) is clearly visible when angle of incidence is 80°. Figure shows that effect of fluid presence is very prominent in loose bond $\zeta_r = 10^{-1}$, and changes in hoop stress ($S_{\theta\theta}$) brought out due to variation of $\zeta_r$ and $\overline{\rho_f}$ are almost comparable. When angle of incidence is 60° or less then that fluid presence does not bring out any remarkable changes in hoop stress ($S_{\theta\theta}$) and therefore such plots have not been shown.

Figures 4.7 & 4.8 are plotted respectively for the angle of incidence φ=60° & 80°, which show the effect of fluid presence on the hoop stress ($S_{\theta\theta}$) in the medium hard ground condition ($\bar{\mu} = 0.1$). It is clear from Figure 4.7 that the presence of fluid affects hoop stress ($S_{\theta\theta}$) more significantly. However, as $\zeta_r$ increases fluid effect decreases and, at $\zeta_r = 10$ it becomes insignificant. Figure 4.8 indicates that effect in $S_{\theta\theta}$ occurs only for $\overline{\rho_f} = 0.66$ and that too when $\beta > 0.7$.

Figures 4.9 & 4.10 are drawn, respectively for φ=5° & φ=60°, for harder soil conditions ($\bar{\mu} = 1.0$). Figure 4.9 indicates that at the lower angle of incidence (φ=5°) fluid of density $\overline{\rho_f} = 0.132$ has some effect on hoop stress ($S_{\theta\theta}$) whereas at $\overline{\rho_f} = 0.33$ & 0.66 this effect is insignificant. From Figure 4.10 it is observed that when angle of incidence is increased a fluid of density $\overline{\rho_f} = 0.66$ has very small effect on hoop stress ($S_{\theta\theta}$) upto $\beta \approx 0.7$ and after that the response suddenly shoots up at around $\beta \approx 0.95$. From Figures 4.6 – 4.10, it may be concluded that the fluid presence has insignificant influence on hoop stress on the shell as compared to changes observed due to variations in the radial stiffness coefficients ($\zeta_r$) of the bond imperfection. Only at the certain value of β and for higher density $\overline{\rho_f}$, fluid plays important role in deciding the magnitude of hoop stress ($S_{\theta\theta}$).

Figure 4.11 indicates the effect of fluid presence on the hoop stress $S_{\theta\theta}$ for medium hard soil condition and for the wave incidence angle of 60°. In this figure the radial damping coefficient is varied. It is evident from the figure that the variation in damping coefficient parameter gives the results identical to that is observed in figure 4.7 when radial stiffness coefficient was varied for identical values of $\zeta_r$ & $\Gamma_r$, the effect of change in $\overline{\rho_f}$ is also found to be identical.

The variation in the axial stiffness and the axial damping coefficient $\zeta_x$ & $\Gamma_x$, were seen to bring negligible changes in the hoop stress. The fluid effects on hoop stress at different $\zeta_x$ & $\Gamma_x$ values were also found to be insignificant and therefore, it was not felt necessary to show the plots for these cases.

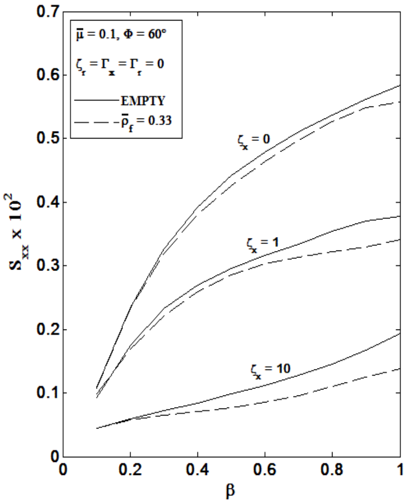

Fig.4.1
Axial stress ($S_{xx}$) versus wavelength parameter (β) for $\bar{\mu} = 0.1$ , $\overline{\rho_f} = 0.33$ and φ=60° with ζx as a parameter

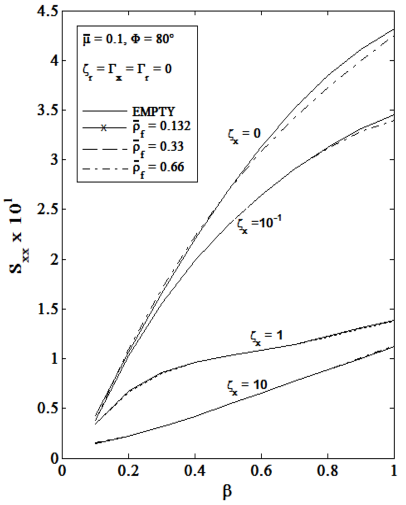

Fig.4.2
Axial stress ($S_{xx}$) versus wavelength parameter (β) for $\bar{\mu} = 0.1$ and φ=80° with ζx and $\overline{\rho_f}$ as a parameters

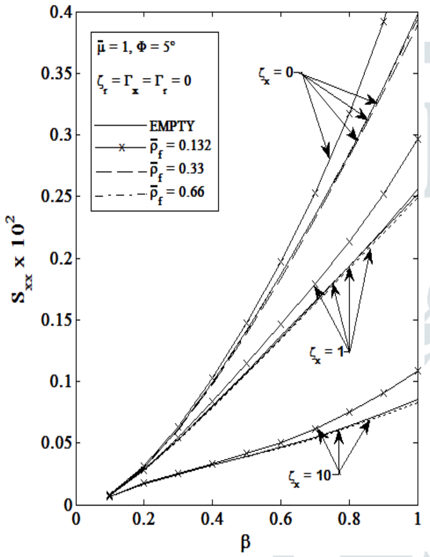

Fig.4.3
Axial stress ($S_{xx}$) versus wavelength parameter (β) for $\bar{\mu} = 1.0$ and φ=5° with ζx and $\overline{\rho_f}$ as a parameters

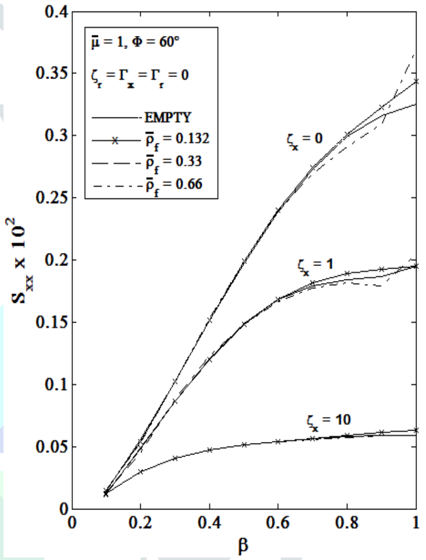

Fig.4.4
Axial stress ($S_{xx}$) versus wavelength parameter (β) for $\bar{\mu} = 1.0$ and φ=60° with ζx and $\overline{\rho_f}$ as a parameters

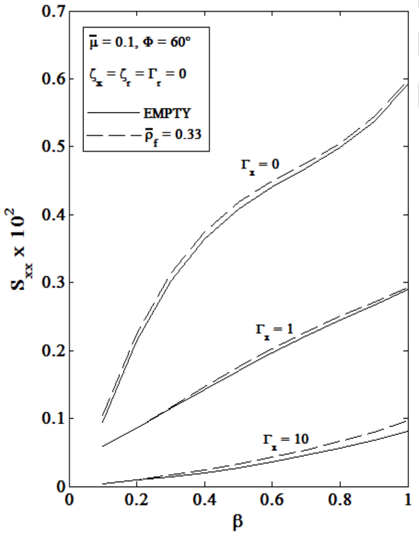

Fig.4.5
Axial stress ($S_{xx}$) versus wavelength parameter (β) for $\bar{\mu} = 0.1$ , $\overline{\rho_f} = 0.33$ and φ=60° with Γx as a parameter

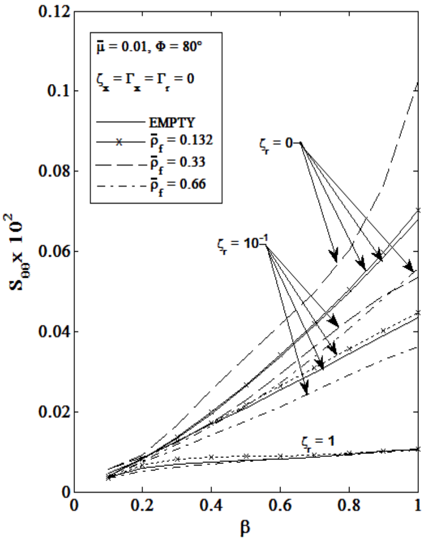

Fig.4.6
Hoop stress ($S_{\theta\theta}$) versus wavelength parameter (β) for $\bar{\mu} = 0.01$ and φ=80° with ζr and $\overline{\rho_f}$ as parameters

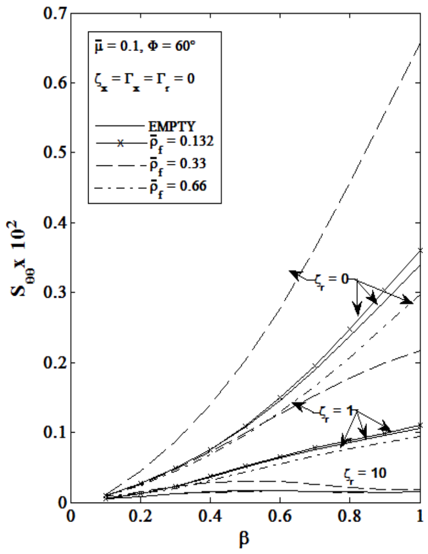

Fig.4.7

Hoop stress ($S_{\theta\theta}$) versus wavelength parameter (β) for $\bar{\mu} = 0.1$ and ϕ=60° with $\zeta_r$ and $\overline{\rho_f}$ as a parameters

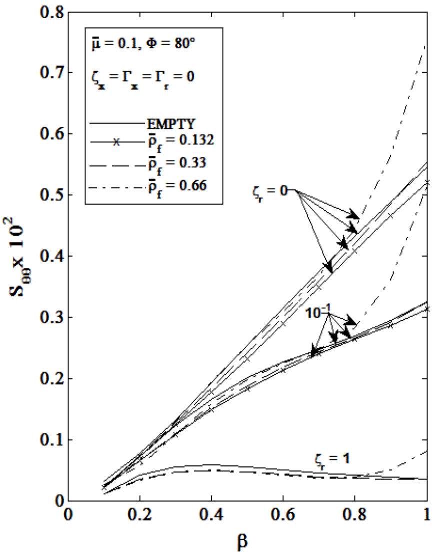

Fig.4.8

Hoop stress ($S_{\theta\theta}$) versus wavelength parameter (β) for $\bar{\mu} = 0.1$ and ϕ=80° with $\zeta_r$ and $\overline{\rho_f}$ as a parameters

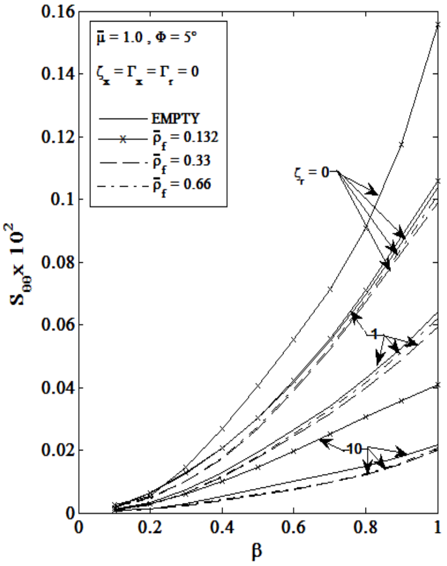

Fig.4.9

Hoop stress ($S_{\theta\theta}$) versus wavelength parameter (β) for $\bar{\mu} = 1.0$ and ϕ=5° with $\zeta_r$ and $\overline{\rho_f}$ as a parameters

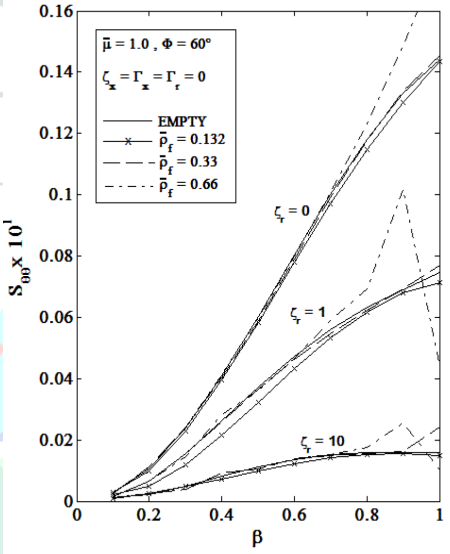

Fig.4.10

Hoop stress ($S_{\theta\theta}$) versus wavelength parameter (β) for $\bar{\mu}$ 1.0 and ϕ=60° with $\zeta_r$ and $\overline{\rho_f}$ as a parameters

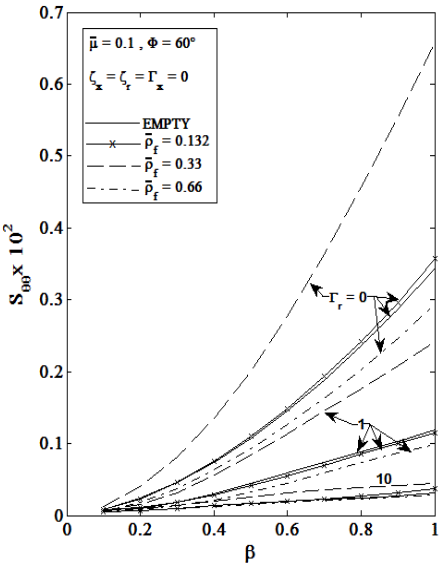

Fig.4.11

Hoop stress ($S_{\theta\theta}$) versus wavelength parameter (β) for $\bar{\mu} = 0.1$ and φ=60° with $\Gamma_r$ and $\overline{\rho_f}$ as a parameters

## IV. CONCLUSIONS

Based on the results following conclusions about the stress induced in imperfectly bonded buried orthotropic pipelines due to shear wave loading can be drawn:

1. Bond parameters $\zeta_x$ and $\Gamma_x$ influence the axial stress induced in the shell significantly, but they do not have any effect on the hoop stress induced in the shell. Likewise, bond parameters $\zeta_r$ and $\Gamma_r$ affect the hoop stresses induced in the shell in the same manner while the axial stress remains unaffected. This is true for all ground conditions and at all angles of incidence.
2. Non-zero values of $\zeta_x$ and $\Gamma_x$ reduce the axial stress of the shell but the hoop stress remains unaffected. Further non-zero values of $\zeta_r$ and $\Gamma_r$ reduce the hoop stress of the shell but they have practically no effect the axial stress of the shell.
3. Bond imperfection acts as a dominant parameter in controlling the stresses induced in the shell than the presence of fluid.
4. In a medium hard soil or a hard soil, the presence of fluid has a very drastic effect on the stresses at higher angles of wave incidence ($\Phi > 60^o$).
5. The effect of fluid is almost unremarkable as compared to the effect of bond imperfection under a soft soil condition and at all angles of wave incidence.

In hard and rocky ground condition, the stresses induced in a fluid-filled shell become fluctuating, if the angle of wave incidence is high. However, the variations can nearly be compared to the difference obtained between the perfectly and the loosely bonded shells.

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