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SEISMIC ANALYSIS OF CYLINDRICAL LIQUID STORAGE TANK

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ABSTRACT

The natural frequencies and the mode shapes for the three first modes of vibrations are evaluated for empty, partly filled, and completely filled tanks. The effect of the important parameters were considered including shell thickness, foundation and anchorage conditions of the tank, H/R ratio and t/R ratio. Finite elements method is used to solve the problem numerically. We have used SAP 90 program for modal analysis of the cylindrical tank.

KEYWORDS

Seismic analysis, ground supported storage tank, dynamic behavior, horizontal component of earthquake.

INTRODUCTION

In the earlier studies of seismic response of the liquid storage tanks, the tank shell was considered to be rigid and the attention was mostly focused on the dynamic response of the contained liquid. G.W. Housener (1963) developed a simplified method for calculating the hydrodynamic pressure of liquid filled rigid tanks.

New investigations show that, the rigid tank assumption may in some cases lead to underestimation of the earthquake loads. Otherwise the flexibility of the shell plays a significant role in the dynamic behavior of the tank. Several studies were carried out (Edwardo, 1969, Nash et al., 1978) to investigate the dynamic characteristics of flexible tank by finite element method.

Under the horizontal ground motion the liquid mass contained in the tank is divided into two distinct zones :
- The lower zone of liquid, which represents the stationary mass of the liquid, and moves in unison with the tank shell (impulsive mass).
- The upper zone of the contained liquid represents a mass which tends to move in sloshing mode (convective mass).

The response of the tank and its contained liquid is divided into an impulsive mode and a convective mode. API Standard 650 and BS 2654 also considered these two modes of response.

According to different investigations the liquid of the tank could be replaced by a system of lumped masses and springs. Such a system consists of a stationary mass, m_o rigidly attached to the container and an infinite number of oscillating (sloshing) masses m_n (n=1,2,3...) attached to the container with springs at elevation h_n. In other words, two separate systems are considered for the coupled shell-fluid system :

1) The shell along with the stationary mass
2) The sloshing mass

It is generally accepted to include only the spring-mass m_1, corresponding to the fundamental mode, (n=1, m=1) and yet not affecting the dynamic response of the system appreciably.

A free vibration analysis for the lowest mode (m=1, n=1) was presented by Haroun, (1980) and Tedesco, (1982). The steel cylindrical storage tank under consideration has the height H=21,9 m., the diameter D=14.6 m. and the thickness of t=10.9 mm. the tank was completely filled with water. The natural frequencies of the couple shell - m_o system (ω''), the sloshing mass m_1, (ω') and the shell - m_o system alone (ω_M) are obtained as :

ω = 120.5	Rad/sec	(f = 19.18 CPS)	empty tank
ω' = 1.57	Rad/sec	(f' = 0.25 CPS)	
ω'' = 23.208	Rad/sec	(f'' = 3.69 CPS)	
ω_M = 23.185	Rad/sec	(f_M = 3.69 CPS)	

Comparing ω' and ω_M, we can conclude that the frequency of sloshing mass is much lower than that of the shell - m_o system. It is clear that liquid sloshing does not interact with the free vibration of the shell - m_o system. It is distinctly evident that ω_M and ω'' are practically the same. Thus it is reasonable to assume that the sloshing mass frequency, ω' and frequency of the shell - m_o system ω_M (or ω''), are independent of one another. This vibrational independence of sloshing fluid mass and stationary fluid mass plays a key role in simplifying the dynamic analysis of liquid storage tanks (Shih, 1981, Tayel, 1984, Sarrafzadeh, 1995). Hence the effect of liquid sloshing inside the tank can be neglected in the formulation of the dynamic analysis of liquid storage tanks. The natural frequency of the shell system alone is significantly affected by the stationary fluid mass, m_o. The frequency of the empty tank was calculated to be 120.5 Rad/sec , versus 23.208 Rad/sec for the coupled shell - m_o system.

NUMERICAL ANALYSIS

The main objective of the first phase of this investigation was to evaluate the vibrational characteristics and to present a simplified procedure for seismic analysis of the flexible cylindrical liquid storage tanks. The second phase of the research involves the assessment of the effects of soil flexibility, boundary conditions at the base, and the roof structures which complicate the dynamic behavior of the liquid storage tanks.

To obtain more comprehensive results, the dynamic characteristics of the tank are tabulated as a function of :

- Height to radius ratio, H/R (aspect ratio)
- Shell thickness to tank radius ratio, t/R
- liquid height to tank height ratio H_l/H

For convenience, each of these ratios is computed while the two others remain constant.
The investigation covers a wide range of the practical tank dimensions. The vibrational characteristics of cylindrical tank are studied for a class of tank whose height to radius ratio H/R falls within the range 0.2 to 3.4 inclusive. This range contains the categories of both shallow (H/R < 1) and tall (H/R > 1.5) tanks. The studies are carried out on the completely full, partly filled (75 %, 50 % and 25 % full with liquid) and empty tanks. The ratio of t/R equals to 0.001, 0.002, 0.003 and 0.004 are considered.
Of particular interest in this investigation are the modes of free vibration associated with axial wave number n equal to 1, 2 and 3 and circumferential wave number m=1. The latter may get excited by unidirectional lateral excitation of the base of uniformly supported cylindrical tank.

The finite element method was employed. The shell was discretized as a combination of rectangular four noeds shell. The computation involves the solution of the following equation for the Eigenvalues :

$$K\phi = M\phi\Omega^2$$

Where K is the stiffness matrix, M shows the diagonal mas matrix , Ω^2 presents the diagonal matrix of the Eigenvalues and ϕ shows the corresponding Eigenvector. SAP 90 program resolves the problem of the Eigenvalues. Both anchored and unanchored tanks are considered in order to evaluate the effect of the base fixation on the tank behavior. In the present investigation, three modes of free vibrations are considered, that corresponding to axial wave numbers n = 1, 2, 3 and only the Cosϕ type (circumferential wave number m = 1). The occurrence of Cosmϕ modes has been attributed to non-circular imperfections.

Results

Figure 1 presents the first three non-dimensionalized natural frequencies, $f_i\ H\ [P_l / E_s]^{0.5}$ for the aspect ratio, H/R between 0.4 to 3.4. It can be seen from these diagrams that the normalized frequenceies for the first mode of vibration increase up to H/R = 1.6 and then decrease with the increase of H/R. But the second and third modes of vibration increase always with the increase of H/R.

The influence of the shell thickness on the natural frequency of the tank is shown in fig. 2. In these figures the normalized frequencies $f_i\ H\ [P_l / E_s]^{0.5}$ are presented for the t/R ratios of 0.001, 0.002, 0.003 and 0.004. These diagrams are plotted for completely filled tanks. Unlike the empty tanks, the natural frequencies of fluid filled tank are not independent of their wall thickness. However, the natural frequency increase, as the thickness increases. It is also observed from a careful examination of fig. 2. That the variation in the tank frequencies is a function of the square root of the shell thickness. Otherwise, if the frequencies were normalized with respect to $f\ .\ H\ [(P_l / E_s)\ (R/t)]^{0.5}$ for all the above mentioned ratios of t/h, the normalized frequencies will be approximately the same. This is presented in fig. 3.

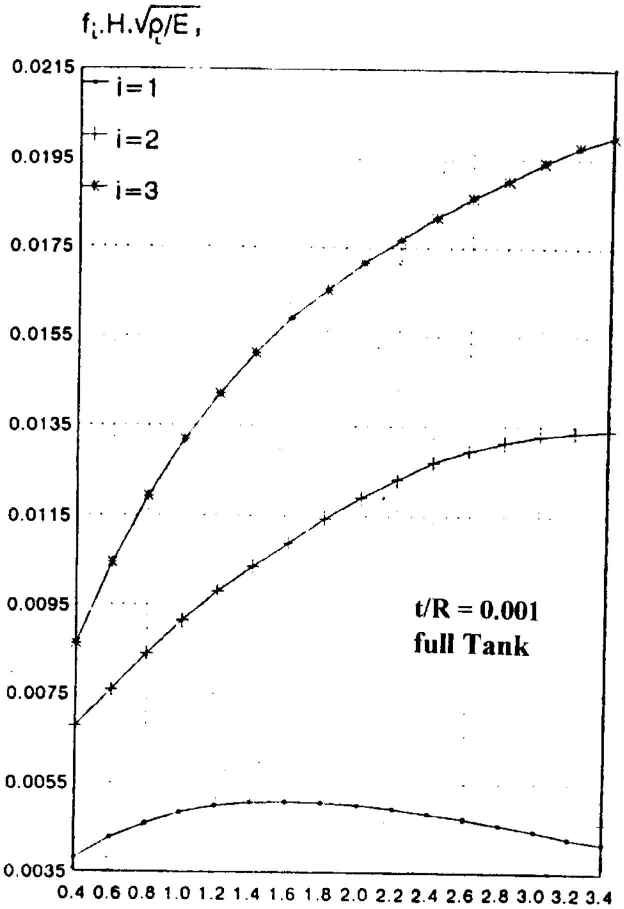

Fig. 1 : Non-dimensionalized frequencies

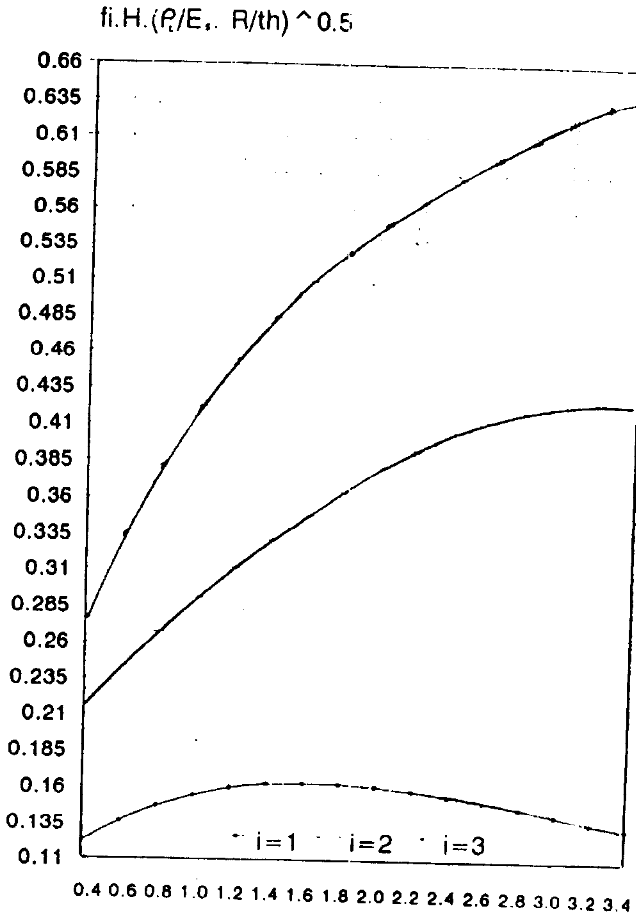

Fig. 3 : frequencies versus t/R

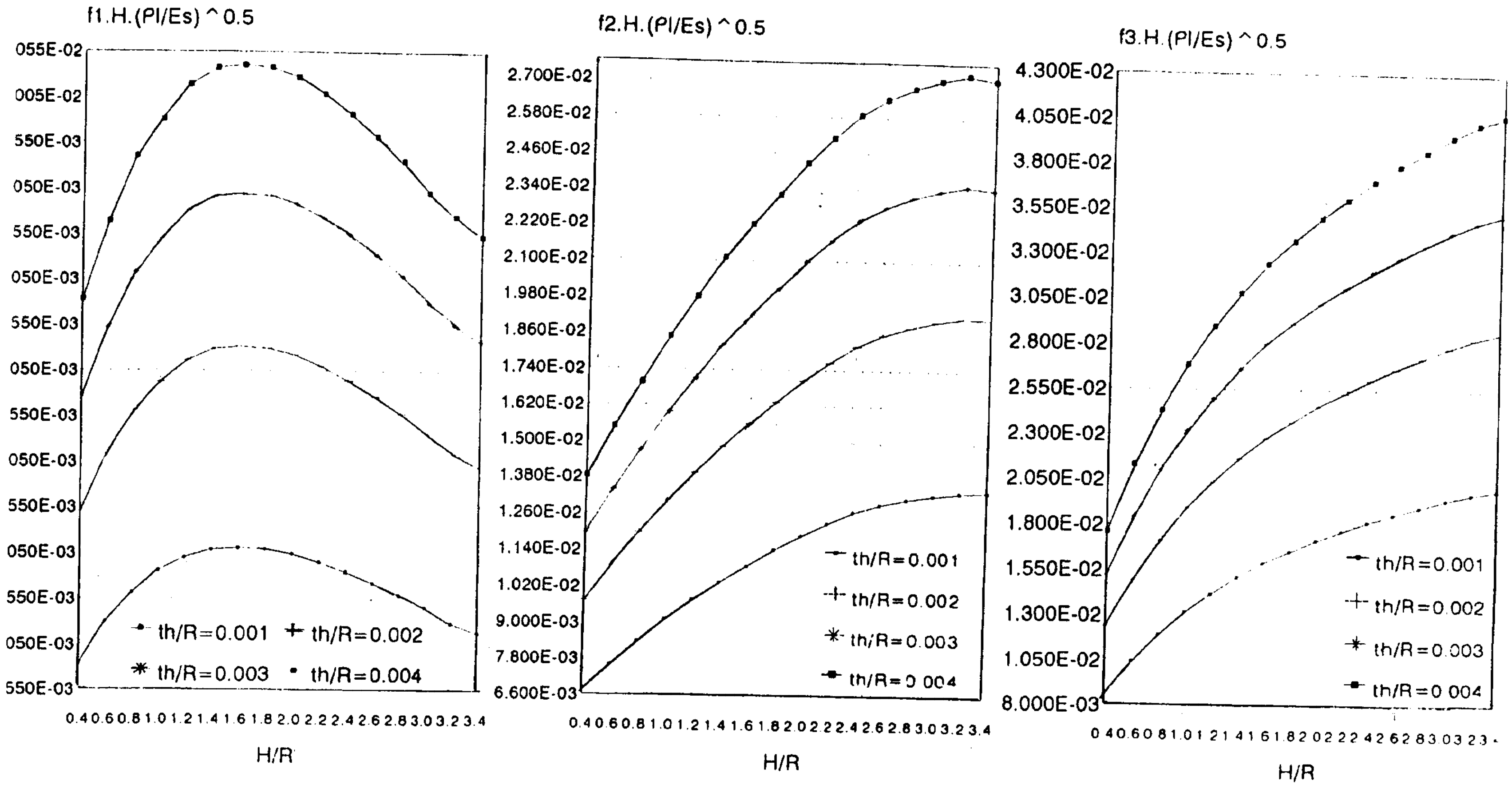

Fig. 2 : Non-dimensionalized frequencies versus shell thickness

The effect of liquid level in cylindrical storage tanks upon the natural frequency of the shell-fluid system is illustrated in fig. 4. In these figures the frequencies of completely filled and partly filled tanks (75 %, 50 % and 25 % filled) are compared with each other. In each case the values of natural frequency are non-dimensionalized with respect to $f_i \cdot H \quad [(P_l / E_s)(R/t)]^{0.5}$ for convenience sake, the same non-dimensionalizing factor was used for the completely full and partly filled cases.

It can be observed that as the level of liquid decreases, the natural frequencies increase. This is an obvious result, since the mass of the tank increases with the level of liquid, while the stiffeness remains constant. More detailed examination of diagrams of fig. 4, reveals that the natural frequencies of partly filled cylindrical tank are the same for completely filled tanks if the height of the tank is equal to the liquid height. This fact is very important and simplifies the design procedure for the partly filled tanks. It can be conclude also that, if these diagrams were plotted for liquid height H_l instead of tank height, H, the diagrams for different levels of liquid will approximately coincide. This is presented in Fig. 5. The small discrepancies between the diagrams should be due to the effect of neglecting the mass of the tank shell.

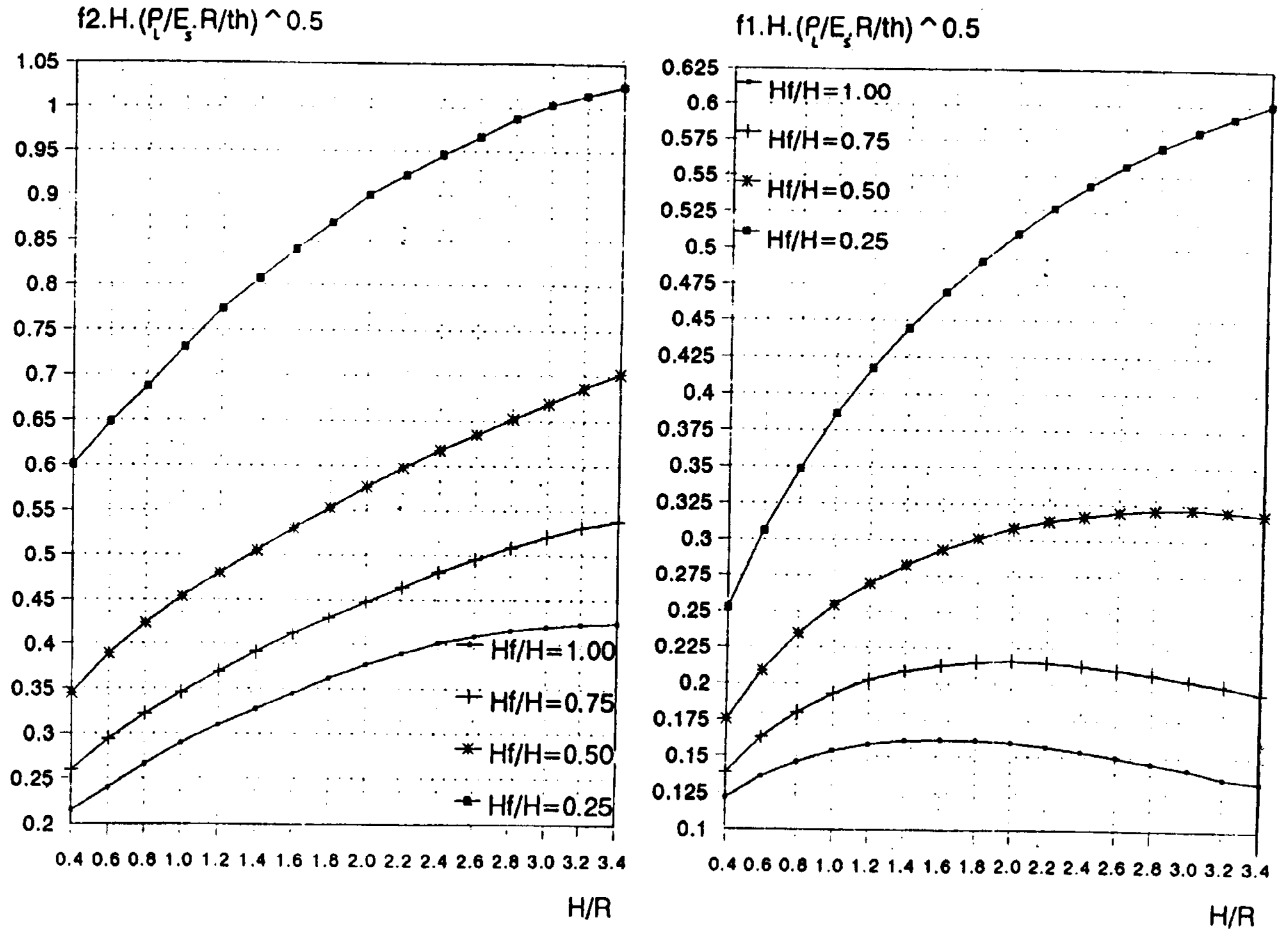

Fig. 4 : Non-dimensionalized frequencies for different level of liquid

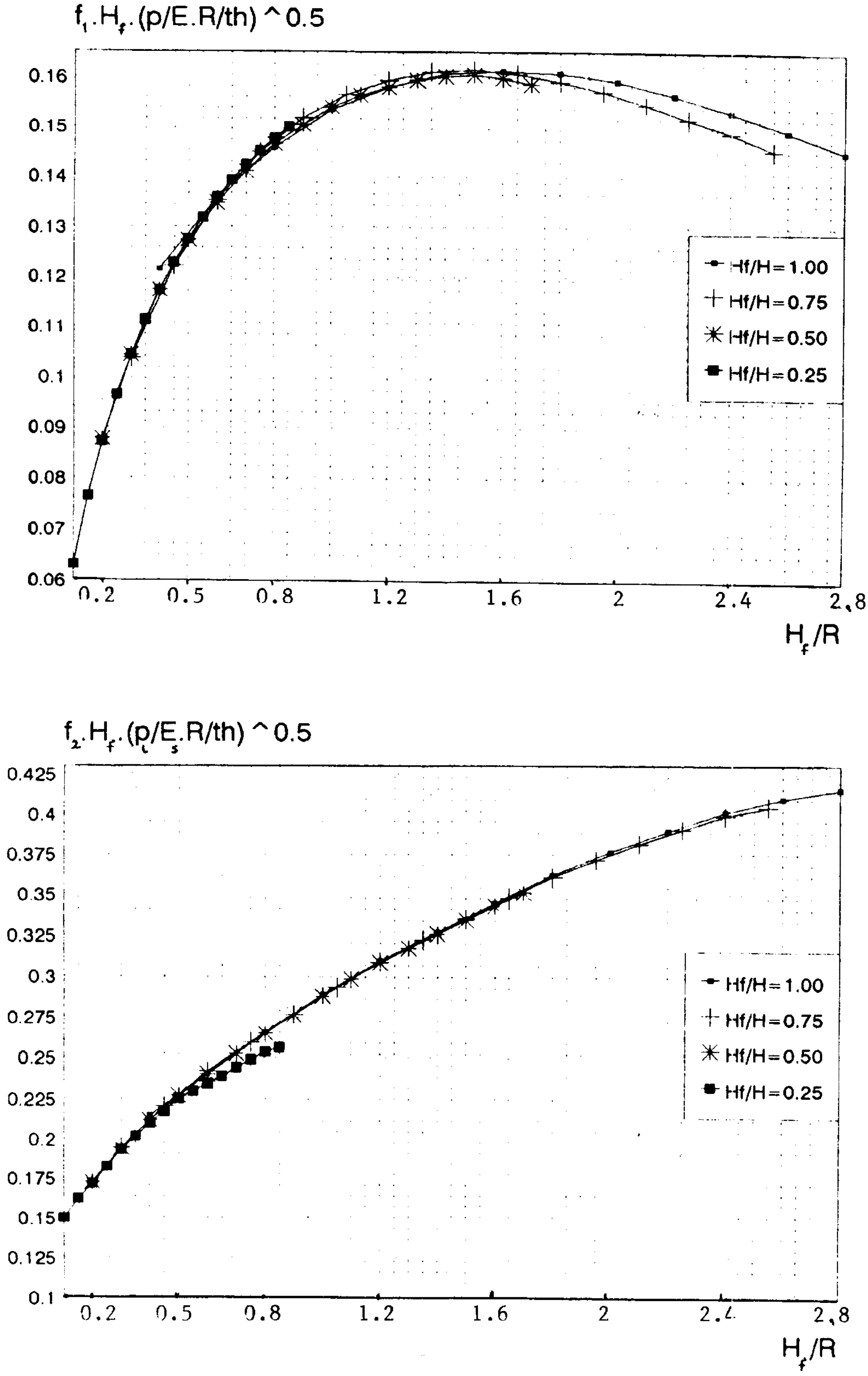

Fig. 5 : Non-dimensionalized frequencies versus liquid level

The SAP 90 program gives the ratio of the impulsive mass m_i participating in the first three modes of natural frequencies (m_1 , m_2 and m_3) with respect to the total mass M. Fig. 6 represents these ratios (m_1/M, m_2/M and m_3/M) versus different H/R between 0.4 to 3.4. It is interesting to note that as the aspect ratio increases, the ratio of impulsive mass to total mass increases also. The mass participating in the first mode is significantly more than the others. For the first mode the participating mass, m_1 increases up to H/R = 1.8 and remains relatively constant for H/R > 1.8

It can be concluded from fig. 7, that for the H/R < 1.2, only the first mode of vibration could be considered in the analysis of the tanks. In this range m_1, is approximately equal to the total mass. For H/R > 1.2 the second mode should be considered also. The sum of the mass participating in the first and second modes gives at least 95 % of the total mass. Hence, consideration of only the first mode of vibration for the impulsive mass, which is proposed by some codes and standards, seems to be relatively approximative for the tall liquid storage tanks.

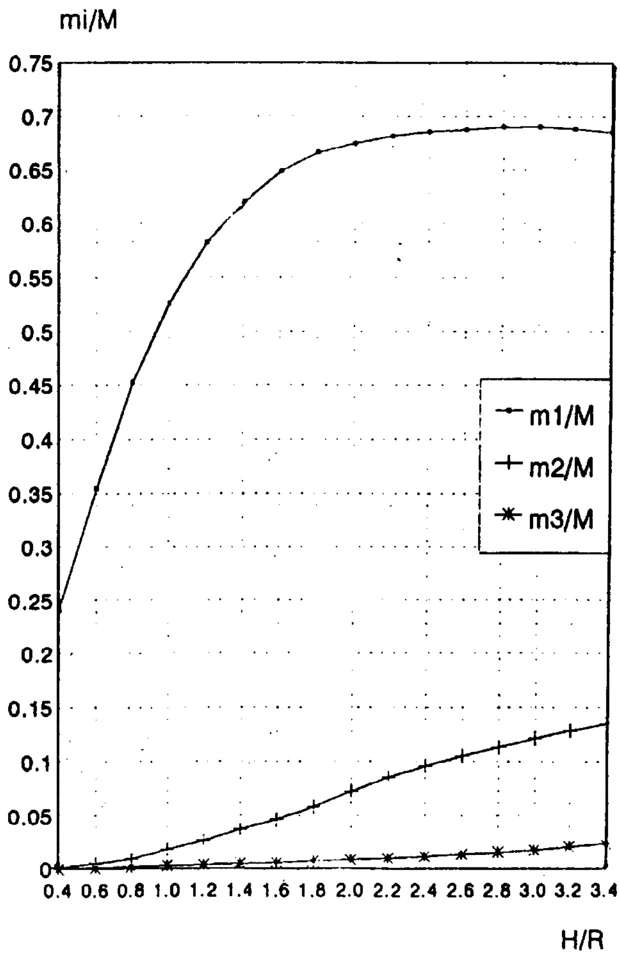

Fig. 6 : Impulsive mass to total mass ratio

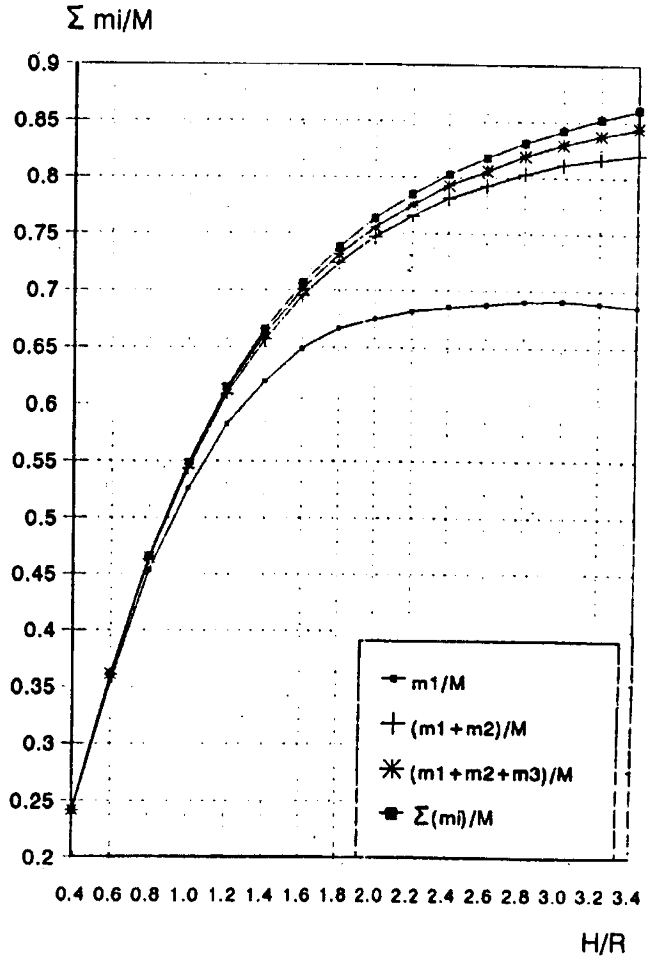

Fig. 7 : Impulsive mass to total mass ratio

CONCLUSION

Liquid sloshing does not interact with the vibrations of the liquid-shell system and should be treated independently. Thus in this investigation the effect of liquid sloshing inside the tank was neglected for the dynamic analysis of liquid storage tanks.

The main results obtained during this investigation are briefly presented as follows :

1- As the shell thickness increases the natural frequencies of the tank also increase, the rate of which depending on the square root of the shell thickness.

2- Partly filled liquid storage tanks can be analyzed by considering the tank as completely filled with wall height equal to the liquid height. Their natural frequencies and the mode shapes are approximately the same. This approach considerably simplifies the computing procedure.

3- The support deformation and soil-storage tank interaction should be considered for the first mode of vibration. The support deformation decreases the natural frequency of the tank. As the soil stiffness decreases the frequency also decreases. The soil-tank interaction effect on the higher modes are negligible.

4- The tank base conditions, its stiffeners and the anchorage system connecting the cylindrical tank to the foundation have a negligible effect on the dynamic behavior of the tank.

5- The impulsive mass contribution to the first mode of vibrations is more than others and the portion of the third mode is practically negligible. For broad tanks with height to diameter ratio (H/D) up to 0.6, considering only the first mode of vibration gives a relatively good approximation. In the case of tall liquid storage tanks (H/D > 0.6) the portion of the second and third modes of vibration are considerable. Thus, the assumption of a system with one degree of freedom and taking only the first mode of vibration could produce the erroneous results in the case of tall cylindrical liquid storage tanks.

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