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1 # RECENT ADVANCES IN THE DYNAMIC ANALYSIS

2 # OF LIQUID FILLED TANKS

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4 ## ABSTRACT

Liquid storage tanks are important components of many civilian and military facilities. They have a vital role for storage of water and other liquids for use in military bases, industrial companies, nuclear reactor installations and water supply facilities. The dynamic behavior of these tanks under different forms of loading such as blasts, winds and earthquakes is of interest. The influence of fuel tanks in rockets on the flight control system is another matter of concern. Although the behavior of tanks under dynamic loadings has received considerable attention during the past three decades in civil, mechanical and aerospace engineering, recent results are not readily available in a comprehensive form suitable for design. The aim of the present paper is to address recent advances in the dynamic analysis of tanks, to bridge the gap between academic and practical applications, and to present a comprehensive review of the subject which makes it more understandable and useful to researchers and to practicing engineers. A review of current design practice is presented and recommended design provisions are described.

INTRODUCTION

The progress of scientific investigations into the dynamic behavior of liquid storage tanks reflects the increasing importance of these structures. With the advent of the space age, attention was focused on the behavior of fuel tanks of rockets to investigate the effects of liquid sloshing on the flight control system. In military bases, the use of above ground and under ground tanks for storage of strategic liquids necessitated the study of indirect blast loadings on such structures. The critical use of tanks in nuclear reactor installations, in municipal water supply and fire-fighting systems and in many industrial facilities for storage of water, oil, chemicals and liquefied natural gas, requires that their safety to wind and seismic loadings should not be compromised. All of these engineering fields have participated in advancing the understanding of the dynamic behavior of tanks although most of the recent studies are associated with

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the seismic problem. The present paper seeks to assess the effects and the relative importance of the numerous factors that influence the dynamic response in general and to identify those factors that dominate the design.

DYNAMIC BEHAVIOR OF GROUND-BASED TANKS

Ground-based tanks are classified to two categories depending on their support conditions: anchored and unanchored tanks. Because unanchored tanks are free to lift off their foundations in response to a strong dynamic loading, a nonlinear analysis is required to estimate their dynamic behavior. For an anchored tank, vertical motion of the shell at the foundation level is prevented, and therefore, its behavior can be analyzed by evaluating the natural modes of vibration and superimposing them properly. The free lateral vibration modes of this type of tanks are divided to the cosθ-type modes for which there is a single cosine wave of deflection in the circumferential direction, and to the cosnθ-type modes for which the deflection of the shell involves circumferential waves having n higher than 1. For a tall tank, the cosθ-type modes can be denoted beam-type modes because the tank behaves like a vertical cantilever beam. This is not true for a broad tank because both the amplitude and the axial distribution of the radial displacement are different from those of the circumferential displacement of the shell. The assumption of a shear beam behavior for this proportion of tanks in order to compute their natural frequencies is not recommended since it greatly overestimates those frequencies.

Tank response to ground excitation considers primarily two types of shell vibrational modes, namely, the n=0 and the n=1 modes; however, under blast or wind loadings, higher order circumferential modes are excited. Associated with each circumferential nodal pattern, there are vertical nodal patterns similar to those most often associated with a framed structure. The circumferential nodal pattern describes the "in plan" shape experienced by the flexible cylinder. For each circumferential nodal pattern, the vertical nodal patterns and the associated frequencies are obtained from an eigenvalue problem. It should be noted that the n=0 modes (axisymmetric) are excited by the vertical component of ground motion while the n=1 modes are excited by the horizontal components. Theoretically, the cosnθ-type modes cannot be excited under a seismic loading in a perfect circular tank; however, fabrication tolerances permit a departure from a nominal circular cross section and this tends to excite such modes. The effects of the irregularity of flexible tanks can be taken into consideration but the fact remains that the magnitude and distribution of fabrication errors cannot be predicted, and therefore, only a hypothetical analysis can be made. It should be noted that an experimental study of the buckling of water-filled plastic models showed that buckling of the shell is largely dependent on the stresses associated with the cosθ-type modes.

ASSUMPTION OF RIGID WALLS

Early developments of response theories of liquid storage tanks considered the container to be rigid and focused attention on the dynamic response of the contained liquid. Housner (9, 12) formulated an idealization, commonly applied in civil engineering practice, for estimating liquid response in seismically excited rigid, rectangular and cylindrical tanks.

He divided the hydrodynamic pressure of the contained liquid into two components: the impulsive pressure caused by the portion of the liquid accelerating with the tank and the convective pressure caused by the portion of the liquid sloshing in the tank. The convective component was modeled as a single degree of freedom oscillator. The values of equivalent masses and their locations that would duplicate the forces and moments exerted by the liquid on the tank were presented. Housner's model is widely used to predict the maximum seismic response of storage tanks by means of a design spectrum. For tanks of ordinary proportions, the rigidly attached component of the liquid contributes the larger effects. The same approach can be used in evaluating the response of tanks to shock loadings using shock spectra.

ASSUMPTION OF FLEXIBLE WALLS

The assumption of rigid walls is valid for many of the fuel tanks of space vehicles; however, the dimensions of storage tanks in civil engineering applications violate such an assumption. The first attempt to handle the effects of wall flexibility was reported by Veletsos (13). He presented a simple procedure for evaluating the hydrodynamic forces induced in flexible liquid-filled tanks. The tank was assumed to behave as a single degree of freedom system, to vibrate in a prescribed mode and to remain circular during vibrations. The hydrodynamic pressure distribution, base shears and overturning moments corresponding to several assumed modes of vibrations were presented. However, the method did not provide explicit values for the fundamental natural frequency of the system which is needed for the determination of the spectral acceleration from a response spectrum. Later, Veletsos and Yang (14) provided a diagram between the fundamental natural frequency of the liquid-shell system and the height-to-radius ratio; however, such a relation is applicable only to a shell thickness-to-radius ratio of 0.001.

A comprehensive study conducted by Haroun (2) led to the development of an efficient method for analyzing the dynamic behavior of deformable tanks. The study included a theoretical treatment of the liquid-shell system by the finite element method and the boundary solution technique, an extensive experimental investigation of the dynamic characteristics of full-scale tanks, and a development of an improved design procedure.

MECHANICAL MODELS

All of the aforementioned studies have shown that the dynamic effects in a flexible tank can be substantially greater than those in a similarly excited rigid tank. A mechanical model which allows, from the engineering point of view, a simple, fast and sufficiently accurate estimate of the dynamic response of flexible tanks was developed. Its parameters are displayed in charts to facilitate the computation of the effective masses, their centers of gravity and the periods of vibrations. Three equivalent masses m_r, m_f and m_s corresponding to the forces associated with ground motion, wall deformation relative to the ground, and liquid sloshing, were evaluated.

Convective Component

It was confirmed (2) that the coupling between liquid sloshing modes and shell vibrational modes is weak, and consequently, the convective dynamic pressure can be evaluated with reasonable accuracy by considering the tank wall to be rigid. The fundamental natural frequency of sloshing in a tank of radius R filled with a liquid to a height H is given by

$$\omega_s^2 = (1.84g/R)\ \tanh(1.84H/R)$$

where g is the acceleration of gravity. The maximum pressure due to the fundamental mode of sloshing only, p_s, is proportional to the spectral value of the psuedo-acceleration S_{as} corresponding to the sloshing frequency. The equivalent mass m_s is evaluated from the hydrodynamic pressure via

$$m_s = \int_0^H \int_0^{2\pi} p_s(R,\theta,z)\ R\cos\theta\ d\theta\ dz/S_{as} = 0.455\pi\rho_\ell R^3\ \tanh(1.84H/R)$$

where ρ_ℓ is the mass density of the liquid. The center of gravity of m_s, to produce the bending moment, is at a distance H_s from the base given by

$$H_s/H = 1 - (R/1.84H)\ \tanh(0.92H/R)$$

A similar expression H_{sb} can be used to compute the base moment (overturning).

Impulsive and Short-period Components

Considering the fundamental mode of vibration of the deformable liquid-filled shell, the base shear force can be expressed as

$$Q(t) = m_r\left(\ddot{x}_f(t) + \ddot{G}(t)\right) + (m_r - m_f)\ \ddot{G}(t)$$

One recognizes that the maximum values of $|\ddot{x}_f(t) + \ddot{G}(t)|$ is the spectral acceleration S_{af} corresponding to the natural frequency ω_f. The bending and the overturning moments due to the dynamic excitation applied at the bottom of the shell and at the center of the base, respectively, can be expressed as

$$M(t) = m_f\ H_f\ \ddot{x}_f(t) + m_r\ H_r\ \ddot{G}(t)$$

$$M_b(t) = m_f\ H_{fb}\ \ddot{x}_f(t) + m_r\ H_{rb}\ \ddot{G}(t)$$

A best fit formula has been derived (5) to compute the fundamental natural frequency of wall vibration; it can be expressed as

$$\omega_f = \sqrt{4\pi^5 Eh/m}\ \left(0.01205\ (H/R)^2 - 0.08466\ (H/R) + 0.17042\right)$$

where m is the total mass of the liquid, and h and E are the thickness and Young's modulus of the shell, respectively. The parameters of the model are displayed in references (3) and (5).

COMPUTER SOFTWARE

A main frame computer program as well as a complementary microcomputer version were developed by Haroun and Warren (4); both are based on an earlier version developed by Haroun (2). The program allows for the coupling between the fluid and the shell without resorting to the classical finite element modeling of the fluid. The program is written in modules to enable independent research to be integrated with current software at later stages. Recent additions to the program include internal stiffeners, different roofing structures as well as the effects of vertical vibrations of the liquid-filled tank.

MISCELLANEOUS EFFECTS

Effects of Vertical Excitations

The effects of the vertical component of ground motion was studied by Haroun and Tayel (6). Natural frequencies were evaluated for fixed and partly fixed tanks. Tank response under the simultaneous action of both vertical and lateral excitations was calculated to assess the relative importance of the vertical component of ground acceleration which has been shown to be important. It was assumed, though, that the vertical ground motion is specified at the tank base level with no allowance for the modification of ground motion by the motion of the tank itself. In addition, the effects of radiation damping in the underlying soil was not taken into consideration. Haroun and Abdel-Hafiz (7) recently analyzed the interaction of tanks with their foundation under vertical motions and showed that such interaction can reduce the response by as much as 50%. The effects of a vertical excitation (axial thrust) on fuel tanks of rockets have been extensively studied in the aerospace industry.

Effects of the Hydrostatic Hoop Stress

In typical analyses, it is assumed that the only stresses present in the shell are those arising from the vibratory motion. However, tank walls are subjected to hydrostatic pressures which cause hoop tensions and their presence affects the frequencies of the shell, especially the cosnθ-type which are excited by wind or blast loadings. It should be noted that the cosθ-type modes, excited by seismic motion, are unaffected by the hydrostatic pressure (2).

Interaction of Liquid Sloshing Modes with Shell Vibration Modes

The dynamic interaction of liquid sloshing waves and shell vibrations was shown to be weak. Physically, the coupling can be neglected on the ground that the significant sloshing modes are of a much lower frequencies than those of the vibrating shell. It was shown that the two uncoupled cases of the liquid-shell system alone and of the free surface gravity waves in a rigid tank should be considered rather than analyzing the liquid-shell-free surface wave system.

Dynamic Interaction of Lateral Shell Motion and Foundation Soil

Few studies dealt with the dynamic interaction of ground-based tanks and the supporting soil during a dynamic loading. A simplified model of the soil was used with a finite element model of the wall to exhibit the fundamental characteristics of the system and to assess the significance of the interaction. Since the cosnθ-type deformations of the shell produce no lateral force or moment, only the influence upon the cosθ-type modes was investigated. Furthermore, rocking motion is most pronounced for tanks having aspect ratios (height to radius ratio) > 1. Thus, the soil-tank interaction problem is governed by a beam-type, rather than by a shell-type, behavior. The system was therefore modeled as a vertical cantilever beam supported by a spring-dashpot model to represent the flexibility of and the damping in, the foundation soil. It was found that the interaction reduces the fundamental natural frequency of the tank and, contrary to the

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case of vertical excitations, it amplifies the response.

Effects of the Roof on Shell Vibration

An analysis of the effects of the fixed roofs on the dynamic characteristics of tanks requires the consideration of the equations of motion of the roof simultaneously with the equations of motion of the shell, and the enforcement of the conditions of continuity of the generalized forces and displacements at the junction. Such an analysis showed that the effect of the roof on the beam type modes, from a practical point of view, is negligible. On the other hand, higher frequencies of vibration are exhibited for the cosnθ-type modes.

SLOSHING PHENOMENON

Liquid sloshing in tanks is important for the design of the tank roof or cover. Numerous events of damage to the shell and to the roof systems of large liquid storage tanks have been reported in past seismic events. Under the assumption of small amplitude sloshing, the theoretically computed moments are negligibly small when compared to those due to the impulsive and the short period pressures. Although it is evident that large amplitude sloshing can be excited by the long period components of an earthquake motion, only small amplitude theory is used in practice to calculate sloshing heights. If insufficient freeboard to the fixed roof system is allowed, sloshing motion creates high localized impact pressures on the roof causing structural damage. There are many problems associated with liquid sloshing, most of which have not been addressed to date. These problems can be conveniently classified to two categories: those related to the fluid motion alone and those arising because of the interaction of the liquid and the fixed or floating type roofs. Recently, a series of buckling tests conducted on models of anchored and unanchored tanks showed that unanchored tanks can suffer shell buckling at a much lower level of excitation in the frequency range of the liquid sloshing. For design purposes, the maximum vertical displacement of the free surface occurs at its junction with the shell and on the excitation axis; it is given by

$$\xi_{max} = 0.837\ R\ S_{as}/g$$

Attempts to include the nonlinear effects of liquid sloshing in the design of tanks are underway. It should be noted that such effects can be classified to three categories: effects arising primarily as a result of the geometry of the container and are apparent even for rather small amplitudes of excitation and liquid response, effects arising as a consequence of large amplitude excitation and effects involving different forms of liquid behavior produced by coupling or instabilities of various lateral sloshing modes.

DESIGN CODES

The two most common standards and codes currently used for the design of tanks are the API 650 (11) and the AWWA 100 (1). Dynamic loads in these standards are based on the mechanical model derived by Housner for rigid tanks. Recognizing the importance of wall flexibility, recent codes have adopted an increase in the acceleration coefficient to an ad hoc value representing the short period amplified acceleration due to shell deformation. It should be noted that such acceleration is specified independent of the tank dimensions and of the support condition. Under a seismic loading, lateral base shear force is determined from a number of coefficients for site location, natural period and soil profile. The input requirements for such computations consist of zone coefficient, a site factor, the response period, the effective masses and their elevations. The use of a response spectrum is encouraged by AWWA standard for sites that might experience severe ground motion during the life of the structure. When the response spectrum provisions are selected, the accelerations obtained from the spectrum are substituted for the seismic coefficients. The bending moment at the shell base is used for evaluating the compressive and tensile forces in the shell. Earthquake allowable compressive stress consists of the static allowable stress plus a stabilizing stress due to the internal liquid pressure with the sum being increased by one-third. The stabilizing stress depends on geometric terms and on a pressure stabilizing buckling coefficient which in turn depends on the hydrostatic pressure. Overturning moments, including those arising from the pressure variation on the base, are computed for the design of the foundation.

UNANCHORED TANKS

The foregoing analyses of tanks apply to ground based tanks that are anchored at the base. Because anchored tanks must be connected to sufficiently large foundations and because improperly detailed anchors can cause damage to the shell under loadings, it is common, particularly for large tanks, to support the tank wall on a ringwall foundation without anchor bolts and the bottom plate to rest on a compacted soil, though sometimes the ringwall is omitted. For such tanks, the overturning moment caused by the hydrodynamic pressure tends to lift the shell off the foundation. As the shell displaces upward, it pulls against the tank bottom causing the bottom plate to pick up liquid to provide resistance to the upward shell movement. On the opposite side, high compressive stresses are developed which may cause buckling of the shell. The first attempt to treat such a problem was developed in association with blast loads on ground based tanks in military bases. Recently some approximate procedures have been developed (15) in connection with seismic loadings to estimate the maximum stresses induced in the walls of unanchored tanks but these are not based on a rigorous treatment of the actual behavior. Improved methods of analysis are being developed to predict the observed highly nonlinear response of model tanks during experimental tests.

TANK PERFORMANCE DURING PAST EARTHQUAKES AND BLAST EXPERIMENTS

Based on the damage sustained by tanks during past seismic events and during blast experiments, the following criteria should be satisfied in the design of tanks:

1. The height to radius ratio has played a significant role in the reported performance of storage tanks. Assuming identical design and fabrication procedure, tanks with larger values of (H/R) tends to suffer more damage.
2. The performance of anchor bolts at the tank base has been poor in many cases. Anchor bolt failure during many dynamic events showed that more thoughts should be given to their detailings.
3. In many cases, insufficient freeboard led to damage of the roof due to

liquid sloshing. Enough freeboard must be provided to prevent the sloshing waves from contacting the roof system.

4. Rigidly attached piping has been a familiar reason for the release of tank contents. Flexible joints which allow for expected relative motion between the tank and the pipes should be used.

CURRENT NEEDS AND CHALLENGES

The following are some of the needs and challenges associated with the dynamic response of tanks (10)

1. The effects of uplifting of the base of unanchored tanks during intense excitations and also of tanks anchored by bolts of insufficient strength to hold them down during dynamic events must be studied.
2. A better understanding is required of the buckling phenomenon of the walls of a liquid containment structure under dynamic conditions of loading, and of the effects of such buckling on the overall integrity of the tank.
3. Because the distortional vibrations of the tank cross section arises, at least in part, from the effects of initial out-of-roundness or irregularities, an effort should also be made to define the magnitude and distribution of such irregularities in actual structures.
4. The influence of nonlinear liquid sloshing should be investigated, particularly as it affects the integrity of the tank and the roof.
5. A realistic evaluation of risk should be made for large capacity tanks containing liquid gases, such as liquefied natural gas, liquefied petroleum gas, or ammonia. Unique features of the design of these structures are the interaction of the double shell through a common base, the influence of the insulation and the effects of elevated pile caps.

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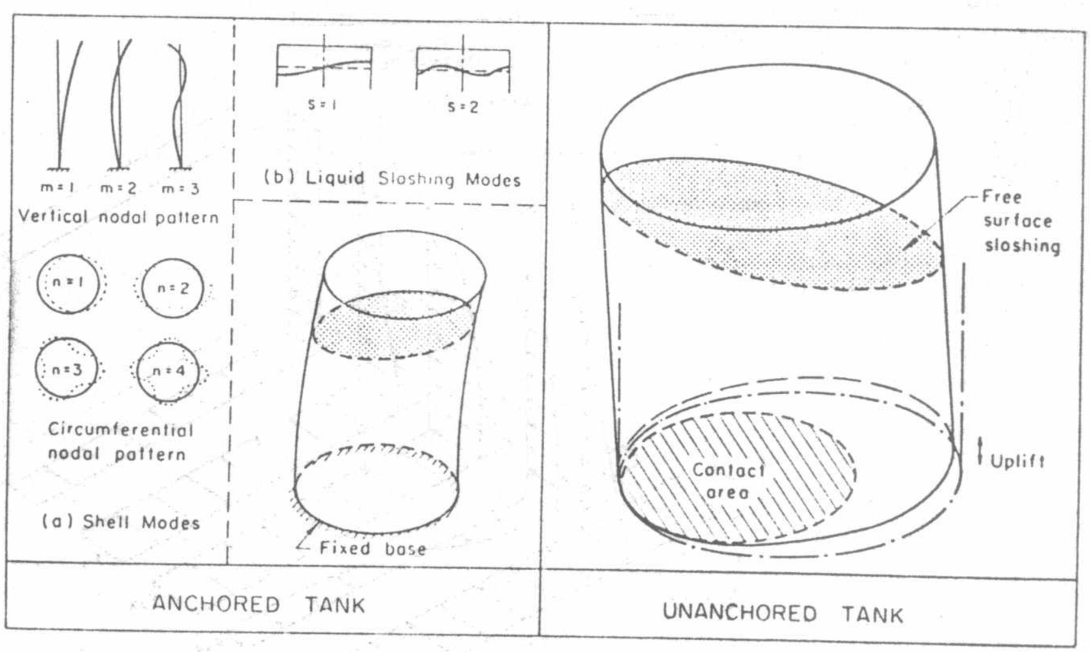

Fig. (1). Dynamic response of anchored and unanchored tanks

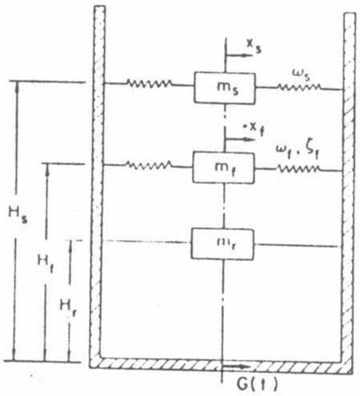

Fig. (2). Equivalent mechanical model

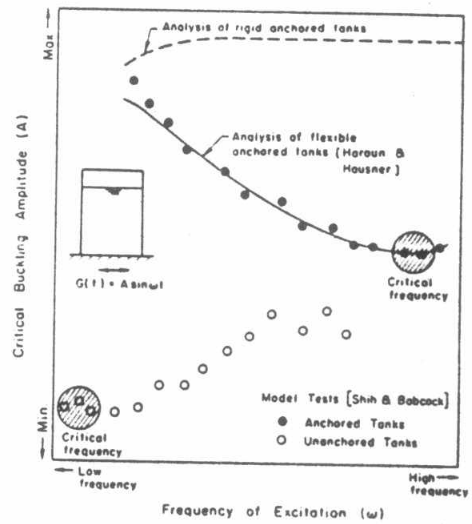

Fig. (3). Dynamic buckling tests of liquid filled models

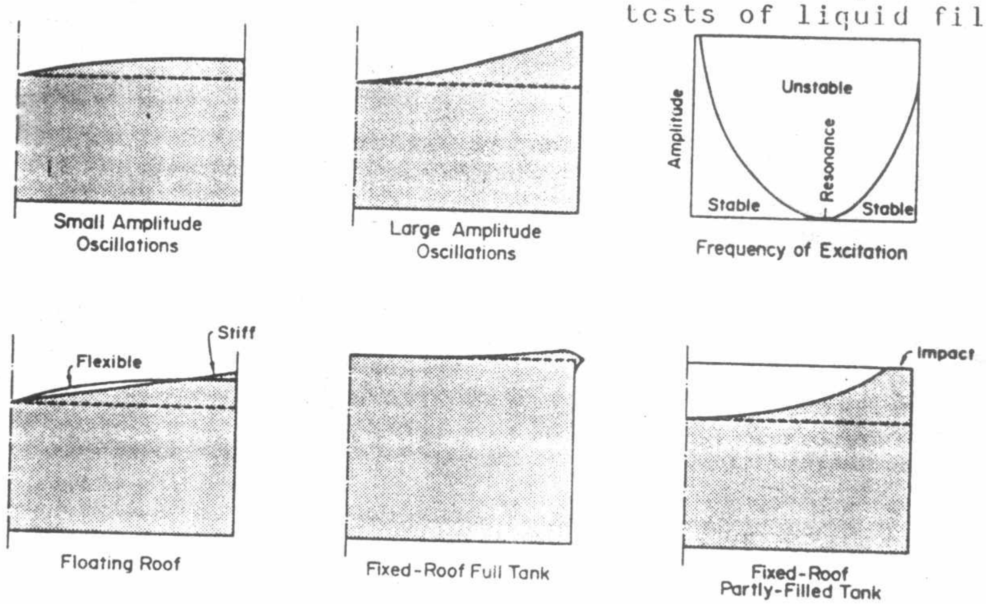

Fig. (4). Problems associated with liquid sloshing

Fig. (5). Typical loads on the walls of a rectangular tank due to a dynamic loading