

ROCKING BEHAVIOUR OF CYLINDRICAL LIQUID STORAGE TANKS

by

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SUMMARY

To investigate rocking behaviour of cylindrical liquid storage tanks, and those "lifting off" phenomena in particular during strong earthquakes, forced excitation experiments were conducted with small tank models mounted on a shaking table. The results of steady-state sinusoidal wave experiments have demonstrated that rocking response of liquid storage tanks has soft-spring type non-linearity; that "lifting off" motions occur at smaller acceleration than the one calculated by the rigid body theorem.

1. INTRODUCTION

Experience has taught us that failures such as "lifting off" of un-anchored storage tanks simply resting on foundations; outward bulges at the bottom belts of tank shells; and fractures of the bottom annular plates were caused by the seismic forces exerted during strong earthquakes.⁽¹⁾

One of the causes which bring about these failures can be identified in rocking behaviour due to earthquake-originated overturning moment. The author of this paper carried out vibrational test by small storage tank models (mainly, steady-state sinusoidal wave excitation experiment) to investigate rocking behaviour associated with "lifting off", and assessed several patterns of rocking motions and the critical lifting off acceleration.⁽²⁾ Although the rocking patterns of tanks are supposed to be dependent on their scale, rigidity, levels of seismic potential, etc., they were considered classifiable into the patterns as given in Table 1, and attempts were made to correlate the classified patterns of rocking behaviour to the experimental results.

2. EXPERIMENTS

2.1 Method of Experiments The shapes and dimensions of the small storage tank models are as shown in Fig. 1. A steel mount or rubber sheet was fixed on a shaking table designed to undergo single horizontal axial motions, and a small storage tank model made of steel plates was placed thereon. To check undue swaying motions, knife-edged metal stoppers were arranged afore and aft of the model at few millimeters intervals. To simulate slightly elastic foundation, a rubber sheet was used as surface material of the mount. The force exerted on the model was of horizontal sinusoidal oscillations with an amplitude of excited displacement confined to a range between 0.25 and 9.6 mm where frequency was swept up and down under a fixed dynamic displacement amplitude.

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2.2 Experimental Results (1) Shown in Fig. 2 are the measured oscillatory waves; Fig. 3 the measured position of response displacement y and patternized response curves of rocking angle versus frequency and Fig. 4 the measured results of rocking angle versus frequency respectively. In low frequency region (the region between points ① and ③ in Fig. 3), the tank bottom of the model was left in contact with the foundation thus representing type a. When excitation was intensified to a range ③ to ④, leaps and bounds occurred at point ④, thence in a range ⑤ to ⑥, intense vibrations involving "lifting off" phenomena continued (representing type c). When a thin rectangular shape tank was excited on the shaking steel mount, irregular occurrences of small-amplitude lifting off motions were observed right before point ④. This can be regarded as rocking behaviour similar to type b. Except small and tall storage tanks, those real cylindrical liquid storage tanks never assume rocking behaviour of type c. In storage tanks of medium size, type b rocking is considered important.

(2) Acceleration at the onset of lifting off vibration When α_0 denotes the amplitude of horizontal acceleration of the shaking table right before the onset of lifting off of tank models, and "a" denotes the displacement amplitude of excitation, the relationship between α_0/α_S and a/B (or a/D) is as shown in Fig. 5,

where,

α_S : acceleration at static overturning onset when the storage tank and the liquid contained therein are taken as a rigid body,

B (or D): length of the model in the direction of excitation.

It may be realized that the horizontal acceleration of the foundation at the start of lifting off in excitation experiments tends to assume smaller value than the overturning acceleration determined by the static condition of equilibrium; and, that it is dependent on the displacement amplitude of the input.

3. COMPARISON OF EXPERIMENTAL RESULTS WITH ROCKING THEORY OF APPROXIMATION

Sonobe, Umemura et al.'s work⁽³⁾ on forced excitation of lifting off rocking structures is available, and an approach using numerical integration has been reported on rocking of a rigid block.⁽⁴⁾ However, very few theoretical studies have been reported on lifting off vibration of a liquid-containing storage tank. As an approach to deal with the liquid storage tank statically, studies⁽⁵⁾ of Appendix E of API 650 and D.P. Clough's work⁽⁶⁾ have been publicized. Here, the entire mass of the liquid contained in the storage tank was regarded as fixed liquid; the storage tank structure and foundation were taken as a rigid body whereby the relationship between angular amplitude θ_{max} and angular frequency p was calculated by using Sonobe, Umemura et al.'s approximate formula (1) to plot curves as shown in Fig. 4.

$$\theta_{max} = \alpha \left(1 - \frac{1}{\cosh \frac{\pi}{2} \varphi} \right) \pm \frac{ra}{r^2 + k^2} \frac{1}{1 + \varphi^2} \dots \dots \dots (1)$$

where α : angle GAB, $\varphi = n/P$, $n^2 = rg/(r^2 + k^2)$, $r = \overline{AG}$, k : radius of gyration around center of gravity G, g : gravitational acceleration, sign (+) signifies out-of-phase response (Fig. 6-1), and sign (-) signifies in-phase response respectively (Fig. 6-2).

When a storage tank contains no liquid, the calculated curves of out-of-phase response show fair agreement with the measured results, but the measured results on a tank filled with liquid assume lower values than the calculated curves of out-of-phase response. For the specific portion of the in-phase response right before the start of lifting off, it is not recommendable to apply this approximation, and thus considerations on elastic deformations of the tank structure and foundation may be called for. The forementioned method of API considers the deformation of the tank bottom statically, but in recognition of the existence of the point of resonance verified through the experiments, discussions on the subject of resonance taking the deformation of tank bottom into account must be digged further.

4. CONCLUSIVE NOTES

The results of experiments on small storage tanks have shown that the rocking response of cylindrical liquid storage tanks is featured by its strong non-linearity, and its natural frequency comes down as displacement amplitude grows; that the critical lifting off horizontal acceleration tends to assume smaller value than the overturning acceleration determined by the rigid body theorem as applied to an object on a rigid foundation. In view of the small models employed in the experiments, deformation of a real storage tank was hardly simulated, and thus any proposal from a viewpoint of structural design on lifting off conditions is hardly made. It is therefore considered necessary to investigate such lifting off conditions as a problem of resonance by applying the principle of similitude of rigidity in the future.

ACKNOWLEDGEMENTS

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Table. 1 Rocking Patterns of Cylindrical Storage Tanks

| Rocking Pattern of Cylindrical Storage Tank | | | |
|---|----------------------------------|--|---------------|
| Type | a | b | c |
| Deformation pattern | Contact area | Contact area | Contact area |
| Typical failure mode | ① Local settlement of foundation | ② Failure of annular bottom plate ③ Rocking of bottom shell | ④ Overturning |
| Tank shape | Large | Small | Shell Tall |
| Earthquake force | Small | Large | Large |

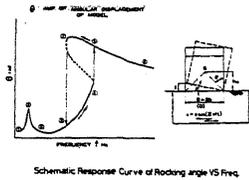


Fig. 3 Schematic Response Curve of Rocking Angle VS Frequency

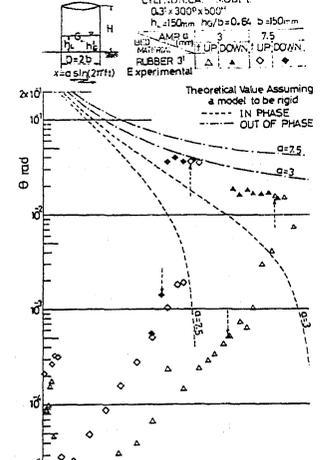
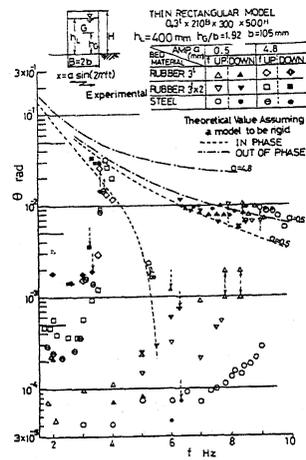
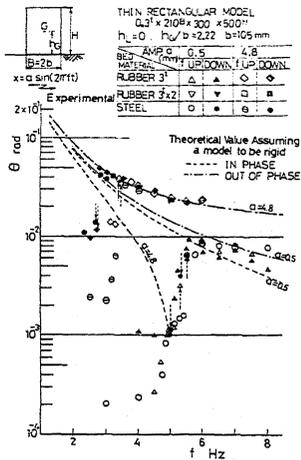


Fig. 4 Rocking Angle (θ) VS Frequency

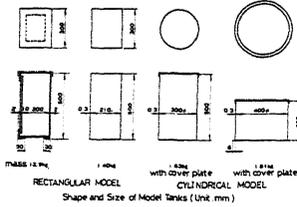


Fig. 1 Shape and Size of Model Tanks

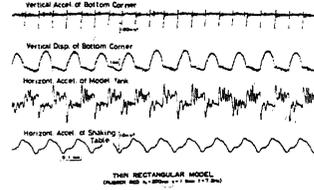


Fig. 2 Typical Experimental Results of Response to Sinusoidal Input

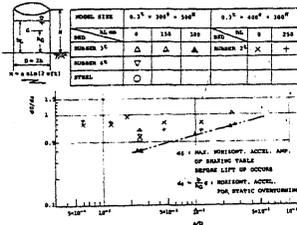


Fig. 5 Critical Accel. of Table Causing Lift-up VS Displacement Amp.

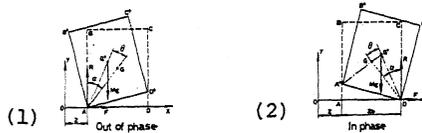


Fig. 6 Model for Rocking Phenomenon

SUSPENDED CEILING SYSTEMS

(The Seismic hazard and damage problem and some practical solutions)

BY: ¹O A Glogau and ²W D Clark

SYNOPSIS

Substantial evidence from earthquake damage indicates that modern, gravity design only, suspended ceilings with light metal grids and lay-in tiles or light fittings, may result in life hazards, costly damage and disruption of function of buildings in severe or even moderately intense earthquakes.

The authors discuss the theoretical problem of seismic ceiling design and give a number of professionally engineered solutions suitable for both rigid and flexible structures.

Suggestions are made for further study of some aspects not fully investigated at present.

1.0 INTRODUCTION

Traditional structures usually were low and had many walls. Thus they were much stiffer than modern buildings and the problem of hazards due to ceilings was not evident prior to about 1964. Since then however, as a result of damage in several earthquakes, the profession became alerted to the seriousness of the problem. Of particular concern was that damage to integrated ceilings was experienced in events of only moderate intensity eg Gisborne earthquake, New Zealand 1966 (MM7)¹. An important economic point of consideration is that ceiling damage, together with the usually associated extensive partition damage, often occurred in buildings structurally little affected. In addition to the direct costs, very high losses due to the disruption of function of a building result. A most graphic example is the damage to the Banco Central, during the Managua earthquake of 1972. (Fig. 1). Ceiling tiles are often made of heavy materials such as gypsum, hence together with the support rails and integrated associated light fittings they present a significant life hazard and have a tremendous potential for panic.

2.0 TRADITIONAL SUSPENDED CEILINGS

Suspended ceilings have come into wide-spread use in many countries during the last 20 years, primarily to provide a rapid means of erecting a ceiling to meet a wide range of architectural and services requirements. Design considerations were gravity forces and the provision of just sufficient stiffness to ensure good appearance.

A typical system is shown in Figure 2. In some arrangements the cross members are carrying channels above the main runners. Older systems had no cross members.

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3.0 PRINCIPAL SEISMIC EFFECTS AND COUNTER MEASURES

Hazardous ceiling damage may be the result of either the dynamic response of the ceiling itself or due to stresses induced by the building and/or partitions deformations². The motions causing excitation of the ceiling are those transmitted by the floor above and may reach accelerations in excess of $1g$ ³.

The earliest observed ceiling failures were the result of lack of positive positioning of the T-rails relative to each other. Although the clearance between tiles and supporting rails in any one row is too small to allow tiles to drop, a "compression wave" due to horizontal earthquake effects (at right angle to the T-rails) may aggregate the clearance between tiles and rails until in one row the space is sufficient for the tiles to drop. The rest follow.

In regions of low seismicity the above shortcoming can be overcome by the use of spreaders holding the T-rails in position relative to each other. To provide adequate seismic resistance against moderate or intense responses a number of other more complex effects must be considered.

In truly rigid buildings such as those with adequate shear walls, ceilings may be braced off the building, provided all ceiling members, splices and connections in the load path are designed for the real forces. Because mass production requires fabrication methods that are detrimental to ductile behaviour (Fig.5) the possibilities of departure from the intended load path should be examined otherwise local failure may occur (Fig. 4) before redistribution takes place.

In modern buildings ceiling systems must usually be considered in conjunction with the associated removable partitioning. The approach is as a rule to independently brace the ceiling from the floor above. A good way of doing this is by means of inclined wire braces together with adjustable vertical struts (Fig. 3). The latter have an important function: simple statics indicates that at a bracing point the horizontal seismic load, and the inclined tension of the brace require a vertical component for balance. Except where response is low and/or bracing points very frequent, gravity loads that can be locally materialised are inadequate to furnish this component, and struts are required. Fig. 3 is an arrangement suggested by J F Meehan.

In flexible buildings, clearances must be provided at the junction of ceilings and partitions. Ceilings are designed to move with the floor above, partitions usually with the floor below. Figure 7 shows a suitable detail. An edge member independent of the wall, to tie ends of cross members and support end tiles, should be used to avoid the danger of loss of end tiles.

In regions of higher seismicity ceiling tiles should be positively held down to prevent them from dropping due to upward vertical effects. The design of the holding devices must allow easy removal and replacement of tiles from below for services access to the ceiling. Figure 6 shows an adequate device.

4.0 CODE PROVISIONS

A number of codes have provisions for seismic design of ceilings including NZS 4203:1976⁴, which requires heavier ceilings to be designed for loading of 0.6 g to 1.0 g in the zone of highest seismicity. ATC-3, 1978⁵ specifies loadings of 0.24g to 0.54 g. These values are by no means excessively conservative³.

5.0 ECONOMIC CONSIDERATIONS

In the case of light weight ceilings which do not provide significant life hazards, and provided light fittings have independent attachments to the floor above, a decision to provide seismic protection must be made on economic grounds. A particular study appropriate for a area of intermediate seismicity indicated that about 15% of the cost of a ceiling could be spent on protection to avoid direct losses.¹

6.0 FUTURE WORK

The formation of wave motions in ceilings under combined vertical and horizontal effects is difficult to predict and would best be resolved by tests on large size models.

7.0 CONCLUSION

Integrated suspended ceiling systems subjected to earthquake motions, have been shown to have a high potential for both life risk and economic losses unless very carefully engineered.

Notwithstanding the improvements that have been made in recent years, for any particular ceiling-partition system to perform adequately in a given building, requires a good basic understanding of its intended performance by the designer, field supervisor and erector.

The dynamic response of large ceilings should be further investigated.

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Fig.1 Managua 1972, Bauco Central

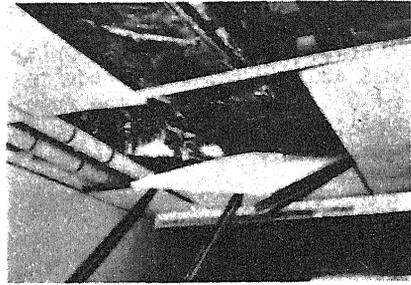


Fig.4 San Fernando
Failure of Cross Runner Joints

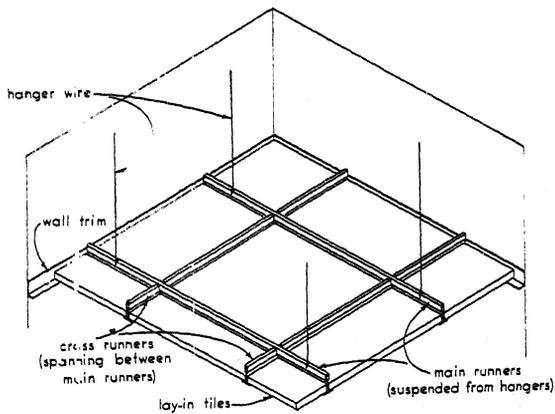


Fig.2 Two-way Inplane Suspended Ceiling Grid System

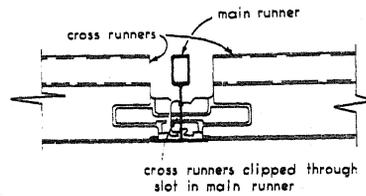


Fig.5 Cross Runner Joint

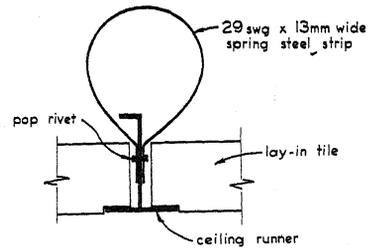


Fig.6 Balloon Spring Tile Clip

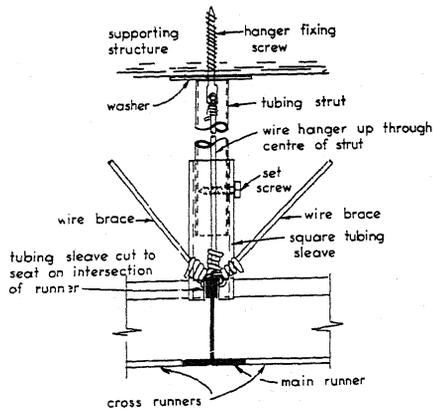


Fig.3 Bracing & Strut

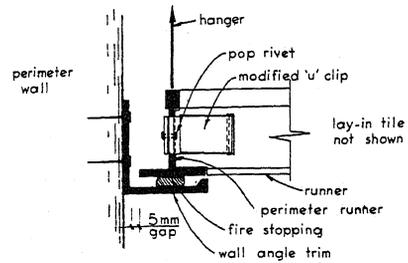


Fig.7 Ceiling Perimeter Detail