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EARTHQUAKE RESISTANT DESIGN OF LIQUID STORAGE TANKS

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ABSTRACT

The seismic performance and safety of liquid storage tanks located in areas of high seismic activity are major concerns of tank designers and engineers. Experience of tank performance in recent earthquakes indicates that the seismic design provisions in the current design standards and procedures may not be adequate. In this paper, the response behaviour of thin-walled metal ground supported flat bottom cylindrical liquid stroage tanks are briefly discussed. Aspects in the earthquake resistant design of tanks, and the basis and approach adopted by several currently available design standards and procedures are examined. In particular, the difference in the design requirements and current status in the design practice for anchored and unanchored tanks are discussed. The design loadings for tanks of typical dimensions are calculated from the various design procedures, and these are compared in a parameter study. The validity and accuracy of the specified design loadings are compared with the results obtained by a time history analysis procedure.

KEYWORDS

Buckling; cylindrical shell; design loads; earthquakes; liquid storage tanks; seismic damage; steel.

INTRODUCTION

In recent years, the seismic performance and safety of ground supported flat base steel cylindrical liquid storage tanks has been the subject of many studies in the field of lifeline earthquake engineering. The motivations of these studies are the observed poor performance and inadequacy of many tank facilities in withstanding the shaking caused by severe earthquakes, and the hazards and risks posed by the failure of these facilities. Unlike other civil engineering structures, the seismic risk of a liquid storage tank is not limited to the vulnerability of the tank structure itself and the immediate danger to nearby human lives, but also to a large extent the serious consequence and long-term effect the failure of the tank may cause to the environment. The loss of the liquid content from a tank containing highly inflammable and toxic petrochemical product may lead to fire and contamination of the surrounding environment. Flooding and interruption to essential water service may result from the failure of large water reservoir.

With the objective of improving the seismic safety and reducing the risk of thin walled cylindrical liquid storage tanks, numerous experimental studies and theoretical research have been carried out in recent years to better understand the behaviour of liquid storage tanks under seismic loads. Among these efforts, early investigations have focused mainly on the simpler problem of anchored tanks. Significant insight to the hydrodynamic fluid-structure interaction effect between the vibrating liquid content and the cylindrical tank shell has been gained from these studies. As a result, accurate analysis and design procedures have been developed for liquid storage tanks anchored at the base (Veletsos, 1984, Haroun and Housner, 1981). More recently, the research focus has been shifted to the more complex problem concerning the behaviour of unanchored tanks. This is because most medium to large capacity tanks are unanchored. An unanchored tank is free to uplift during dynamic response to the strong ground motions of a severe earthquake, and therefore more vulnerable to seismic damage precipitated by the uplift phenomenon which includes overturning. The uplift mechanism in an unanchored tank is a very complex and highly nonlinear phenomenon. Based on the analytical results obtained from approximate beam models, simplified design provisions for seismic uplift of unanchored tanks have been developed, such as those specified in the design standards API-650 (1988) and AWWA-D100 (1984). Although these design provisions represent significant advance in the design of tanks, experience in recent earthquakes seems to indicate that these provisions may not be adequate to accurately predict the seismic response of unanchored tanks, especially when significant uplift occurs during strong ground shaking.

The objective of this paper is to examine the degree of applicability and accuracy of the various design methods and procedures currently available for the design of ground-supported flat bottom thin-walled cylindrical metal liquid storage tanks. Results obtained from a parameter study on the design forces of both anchored and unanchored tanks are discussed. The accuracy of the code specified design forces is examined by comparing them with those obtained from a time-history analysis procedure. The nonlinear time-history analysis procedure is based on a Ritz-type formulation of the liquid tank system capable of modelling the uplift behaviour of unanchored tanks in detail.

SEISMIC RESPONSE BEHAVIOUR OF LIQUID STORAGE TANKS

When a flexible anchored storage tank is subjected to horizontal base support excitation during an earthquake, the inertia effects of the vibrating tank and fluid cause a change in the magnitude and distribution of the pressure loading exerted by the liquid on the tank wall and bottom. The hydrodynamic pressure loading depends on the characteristics of the ground motion, the properties of the liquid, the geometric configuration and properties of the tank structure, and the underlying supporting foundation-soil characteristics. During dynamic response, the vibrating liquid exerts a resultant lateral force and an overturning moment at the base. In response to the overturning moment, part of the tank shell is under axial compression while the remaining part of the shell is under tension. The resulting compressive axial stress in the tank shell tends to buckle the tank wall resulting in the failure of the tank, as observed in many cases of tank damage in past earthquakes. The earthquake forces in a vibrating flexible liquid storage tank can be separated into two components: the impulsive component and the convective component. The impulsive component is associated with the part of the liquid that moves in unison with the tank wall, whereas the convective component of the earthquake force arises from the sloshing part of the liquid that oscillates in response to the input support excitation.

In addition to the fluid-structure interaction behaviour as in an anchored tank, the dynamic response of an unanchored tank is further complicated by the tendency that part of the tank bottom near the base rim may uplift as a result of the overturning moment. The resistance to the overturning is provided by the weight of the uplifted liquid, tank shell and roof. The dynamic uplift of an unanchored tank is a highly nonlinear mechanism. The dynamic characteristics of an uplifting fluid-tank system is significantly affected due to the partial loss of base support and the change in the stiffness properties of the tank. As a result, the distribution of the axial compressive stress in an unanchored tank concentrates more around the excitation or uplift axis, and thus the tank wall is subjected to a greater risk of buckling failure. Furthermore, the variation in the extent of bottom uplift and the vertical uplift displacements can significantly exceed the limit of linear small displacement theory, requiring the use of nonlinear large displacement theory to model the uplifting tank with possible inelastic behaviour in the shell plates.

EARTHQUAKE RESISTANT DESIGN OF LIQUID STORAGE TANKS

The main objective in earthquake resistant design of a typical civil engineering structure is to ensure the reserve capacity of the design system, either in strength or in its ability to sustain large deformation without significant loss of load carrying capacity, exceeds the demand imposed by the seismic actions on the system. For the case of design of liquid storage tanks, the seismic design loads are generally prescribed in design standards or procedures in terms of maximum design resultant lateral force and overturning moment at the base of the tank. The primary failure mode considered in the design process is instability failure related to buckling of the shell wall or overturning of the tank system. In the following, the approaches adopted by the commonly used design standards and procedures in determining the seismic design loads for anchored and unanchored tanks are briefly discussed. The design loads obtained from the different design models and procedures are compared in a parameter study.

Design of Rigid Anchored Tanks

The analysis and design model developed by Housner (1957) is one of the pioneering procedures to predict the dynamic response of rigid anchored tanks on rigid foundations during earthquakes. In the model, Housner introduced the concept of impulsive and convective pressure in the modelling of the hydrodynamic effect of the vibrating incompressible and inviscid fluid. Equivalent mechanical spring-mass oscillator models were developed to simulate the base shear and overturning moment generated by the impulsive and convective sloshing modes of the fluid-tank system for design purposes. Based on the Housner model, Epstein (1976) generated equations and design charts to obtain the maximum effects for design by assuming that the fluid convective response occurs only in the upper part of the liquid to a depth of 1.5 times the tank radius from the liquid free surface. The Housner model was adopted as the basis for the seismic design provisions in the commonly used design standards API (1988) for oil storage tanks and AWWA (1984) for water reservoirs.

Design of Flexible Anchored Tanks

Investigations of tank damage due to earthquakes in the field and laboratory experimental studies have shown that flexibility of the thin-walled cylindrical tank shell has a significant effect on the distribution of the hydrodynamic pressure loading and thus the overall response of the tank. Procedures were developed by a number of researchers to account for the effect of tank wall flexibility on the seismic design loading. Using a variational approach, Veletsos (1984) included the tank wall flexibility effect on the impulsive pressure component by replacing the ground acceleration in the relevant response equations with the pseudoacceleration function corresponding to the fundamental natural frequency of the fluid-tank system. The effect of the tank wall flexibility on the convective pressure was ignored by the reason that the short period vibrational response of the tank wall is not significantly coupled to the relatively long period response of the sloshing liquid, and thus the convective effect cannot significantly be affected by the tank wall flexibility. This is the approach adopted by the API (1988) and AWWA (1984) design standards for the design of flexible anchored tanks. A similar tank design model for flexible anchored tank was also developed by Haroun and Housner (1981) using the boundary integral techniques. Other researchers have included the tank wall flexibility effects in their studies by using the finite element approach (Balendra et al., 1982). Design recommendations were developed based on the results obtained from these analytical models (Priestley et al., 1986, Adams, 1990). In the New

Zealand design recommendations (Priestley et al., 1986) modifications were introduced to include the effect of flexible foundation on the design forces.

As in a typical design process, after determining the design loadings, it is necessary to evaluate the relevant design actions, such as deformations, stresses and other response parameters, due to the determined loadings. In the design of liquid storage tanks, the axial stress in the tank shell is an important parameter for consideration. For anchored tanks, the distribution and magnitude of the shell axial stress around the tank circumference due to the overturning moment are generally considered acceptable to be described by the simple theory.

Design of Flexible Unanchored Tanks

As discussed earlier, the dynamic response of an uplifting unanchored tanks is very complex and there is no reliable and yet simple to use acceptable design procedures for their design. In the API (1988) and AWWA (1984) design standards, essentially the same procedures are used to determine the design loadings for anchored and unanchored tanks. Previous studies on the dynamic behaviour of unanchored tanks have demonstrated that the design loadings and design actions may be significantly underestimated by the anchored tank assumptions, thus resulting in unconservative design. The earthquake damage suffered by many unanchored tanks in recent earthquakes seems to confirm this observation. In the API and AWWA standards, Wozniak and Mitchell (1978) used a quasi-static beam model with two plastic hinges to model the uplift mechanism. In another approach, the New Zealand recommendations adopted the uplift model developed by Clough (1977) in the evaluation of the seismic uplift design actions. In this model, a circular contact area between the partially uplifted bottom plate and the supporting foundation is assumed. The axial compressive stress in the part of the tank shell that remains in contact with the foundation is assumed to vary linearly from its maximum value on the excitation axis at the center to zero at the edge of the contact shell base.

Recently, Scharf et al. (1989) developed design procedures from which design curves were presented for the design of unanchored tanks. This design method is based on finite element approach which makes use of an appropriate nonlinear spring model to represent the tank resistance to uplift.

Dynamic Buckling of Tanks

The design criterion that is particularly important in the design of liquid storage tanks is the dynamic buckling capacity of the tank shell. The dynamic buckling capacity is substantially influenced by the presence of the internal pressure, the geometric imperfections of the shell, and the degree of concentration in the circumferential distribution of the compressive axial stress from the overturning moment. At present, there is no reliable method that can give an accurate estimate on the dynamic buckling strength of thin-walled liquid storage tanks during dynamic response. The design standards API and AWWA give a buckling capacity based on test results of cylindrical thin shell subjected to uniform compression, which is clearly different from the case in the actual condition. Improved estimates on the dynamic buckling capacity were proposed by Priesley et al. (1986) and Rotter (1985) which take into consideration the effects of internal pressure, the circumferential variation of axial stress, the tank wall imperfections, and the difference in buckling capacity of the two buckling modes: the elastic buckling failure mode (shell crippling) and the elastic-buckling failure mode (elephant's foot bulge).

NUMERICAL EXAMPLES AND PARAMETER STUDY

To compare the different design models and procedures, the design loadings, specifically the base shear and overturning moments, are determined for tanks of typical dimensions. The tank considered is a ground supported, flat bottom, open top, cylindrical steel tank, as shown in Fig. 1. It is fully filled with water with a weight of 3500 kN. The tank bottom plate is 9.5 mm thick and the shell thickness to tank radius ratio is 0.001. In the parameter study, the liquid height to tank radius ratio, h/r, varies from 0.6 to 3.0, while volume of the liquid content, the shell thickness to tank radius ratio, and the bottom plate thickness are kept constant. The design loadings are compared with the numerical results obtained from a dynamic time-history analysis procedures (Zeng, 1993, Lau et al., 1992) for a broad tank and a tall tank. Characteristics of the input ground motion for the time history analysis are shown in Figs. 2 and 3.

Numerical Results

Time histories of the lateral resultant force and overturning moment, normalized by the total weight of the system, are presented in Figs. 4 and 5 respectively. In general, the results show that the response of the tall tank is significantly different from that of the broad tank. The results also show that the sloshing response gradually becomes the dominant response in the broad tank.

Figure 6 presents the time history of the vertical uplift. When the overturning moment is lower than a critical threshold level, no uplift occurs; otherwise, the value of uplift is approximately proportional to the magnitude of the overturning moment exceeding the critical value. The amount of uplift is several times that of the tank base thickness.

The uplift will greatly change the characteristic of the structure and the dynamic behaviour will become highly nonlinear.

Parameter Study

Figures 7 and 8 present the calculated design loadings in terms of the base lateral resultant force and overturning moment obtained from the different design methods and the time history analysis results. The analysis show that the results obtained from the procedures considering tank flexibility (curves (b), (c), (d), (e)) are generally greater than those obtained from procedures which assume the tanks are rigid (curve (a), (f), (g), (h)). The results presented in figs. 7 and 8 show that both the base shear and overturning moment generally increase with liquid height to tank radius ratio. Furthermore, it is somewhat surprising to find that the dynamic time history results do not give the critical design loads for the cases considered. One reason for this observation may be due to the input ground motion selected for the study. Consequently, further and more detailed investigations are needed to draw proper conclusion on the validity of the design procedures in determining the seismic design loadings for liquid storage tanks.

CONCLUSION

The seismic response behaviour of anchored and unanchored cylindrical liquid storage tanks are briefly discussed. Aspects in several design standards and procedures relevant to the seismic design of thin-walled ground supported metal tanks are examined. In a parameter study, results on the design loadings obtained from the different design procedures shows that there is significant difference and variations between the specified seismic loads, dependent on the assumptions adopted in the design procedures. Further and more detailed investigations are needed to determine the proper design loads for flexible liquid storage tanks, especially for the unanchored ones.

REFERENCES

Adams, N. J. J. (1992). Seismic design rules for flat bottom cylindrical liquid storage tanks. *Int. J. of*

Pressure Vessel and Piping, **49**, 61-96.

API-650 (1988). Seismic design of storage tanks. In: *Welded Steel Tanks for Oil Storage*, Appendix E, American Petroleum Institute, Washington, D. C.

AWWA-D100 (1984). *AWWA Standard for Welded Steel Tanks for Water Storage.* American Waterworks Association, Denver Colorado.

Balendra, T., Ang, K. K., Paramasivam, P. and S. L. Lee (1982). Seismic design of flexible cylindrical liquid storage tanks. *Earthquake Eng. and Structural Dynamics*, **10**, 477-496.

Clough, D. P. (1977). *Experimental evaluation of seismic design methods for broad cylindrical tanks.* EERC-77/10, Earthquake Engineering Research Center, University of California Berkely.

Epstein, H. I. (1976). Seismic design of liquid storage tanks. *J. of the Structural Div. ASCE*, **102**, 1659-1673.

Haroun, M. A. and G. W. Housner (1981). Seismic design of liquid storage tanks. *J. of the Technical Councils of ASCE*, **107**, 191-207.

Housner, G. W. (1957). Dynamic pressures on accelerated fluid containers. *Bulletin of the Seismological Soc. of Am.*, **53**, 381-387.

Lau, D. T., X. Zeng and R. W. Clough (1992). Dynamic uplift analysis of unanchored cylindrical tanks. In: *Tenth World Conference on Earthquake Engineering*, pp. 5011-5016 , Balkema, Rotterdam.

Priestley, M. J. N., B. J. Davidson, G. D. Honey, D. C. Hopkins, R. J. Martin, G. Ramsey, J. V. Vessey and J. H. Wood (1986). *Seismic Design of Storage Tanks.* New Zealand National Society for Earthquake Engineering, Wellington.

Rotter, J. M. (1985). *Local inelastic collapse of pressurised thin cylindrical steel shells under axial compression.* Research report, School of Civil and Mining Engineering, University of Sydney.

Scharf, K., F. G. Rammerstorfer and F. D. Fischer (1989). The scientific background of the Austrian recommendation for earthquake resistant liquid storage tank design. In: *Structural Dynamics and Soil-Structure Interaction* (Cakmak, A. S. and I. Herrera, eds.), pp. 281-313.

Veletsos, A. S. (1984). Seismic response and design of liquid storage tanks. In: *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*, pp. 255-365, ASCE, New York.

Wozniak, R. S. and W. W. Mitchell (1978). Basis of seismic design provisions for welded steel oil storage tanks. In: *Proceedings-Refining Department of American Petroleum Institute*, Vol. 57, pp. 485-501. Washington, D. C.

Zeng, X. (1993). *Earthquake Response Analysis of Unanchored Cylindrical Liquid Storage Tanks.* Ph. D. Thesis, Carleton University, Ottawa, Canada.

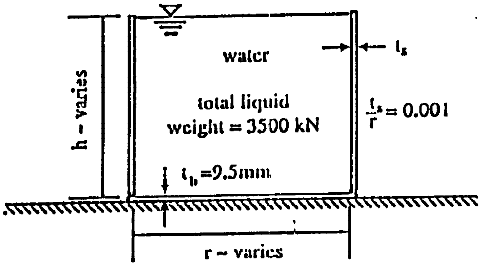


Fig. 1. Tank configuration

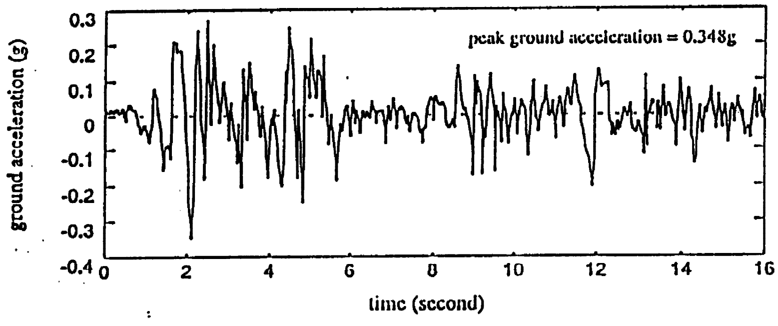
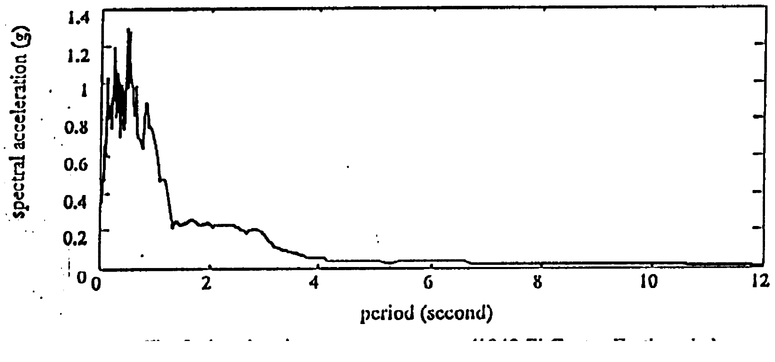


Fig. 2. Input ground acceleration (1940 El Centro earthquake N-S component)



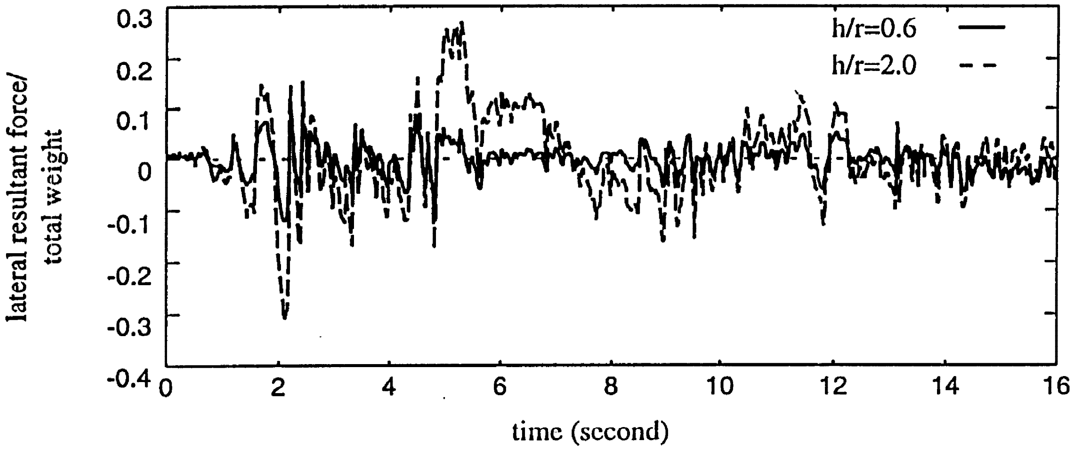


Fig. 4. Normalized lateral resultant force

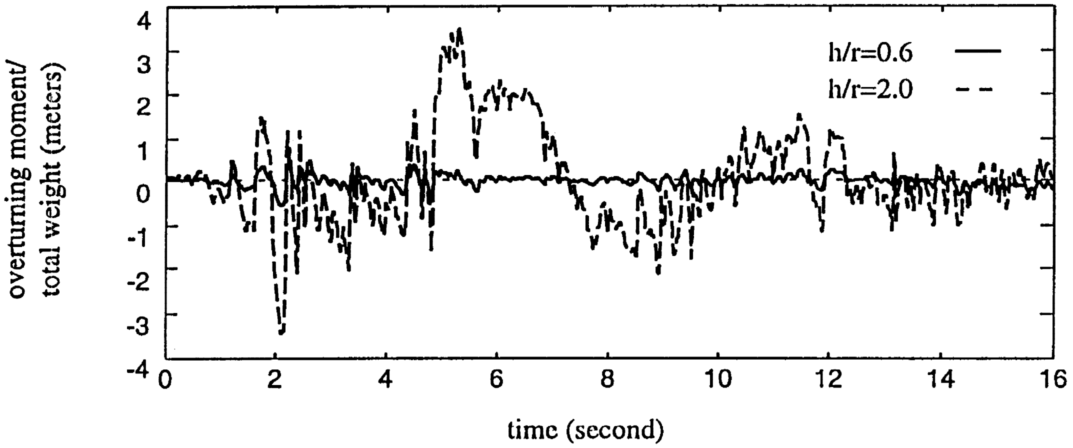


Fig. 5. Normalized overturning moment

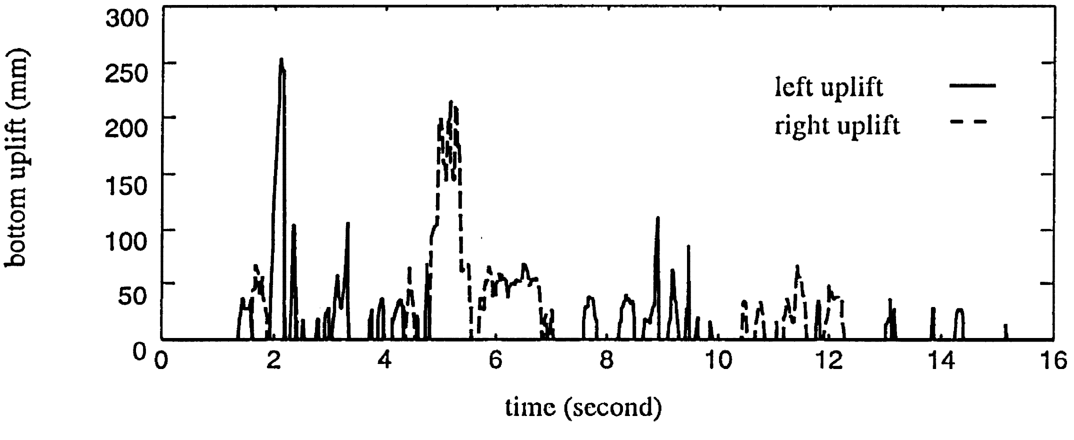


Fig. 6. Bottom uplift time-history (h/r=2.0)

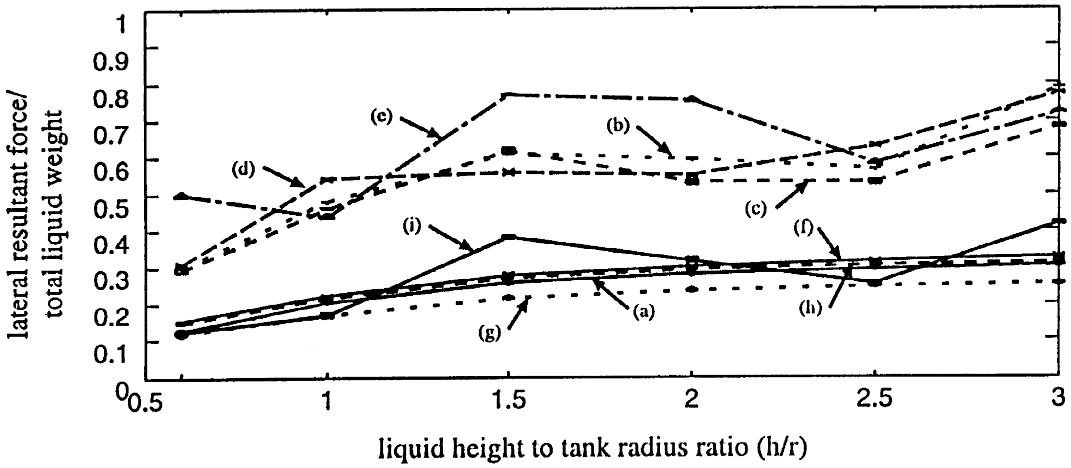


Fig. 7. Normalized lateral resultant force

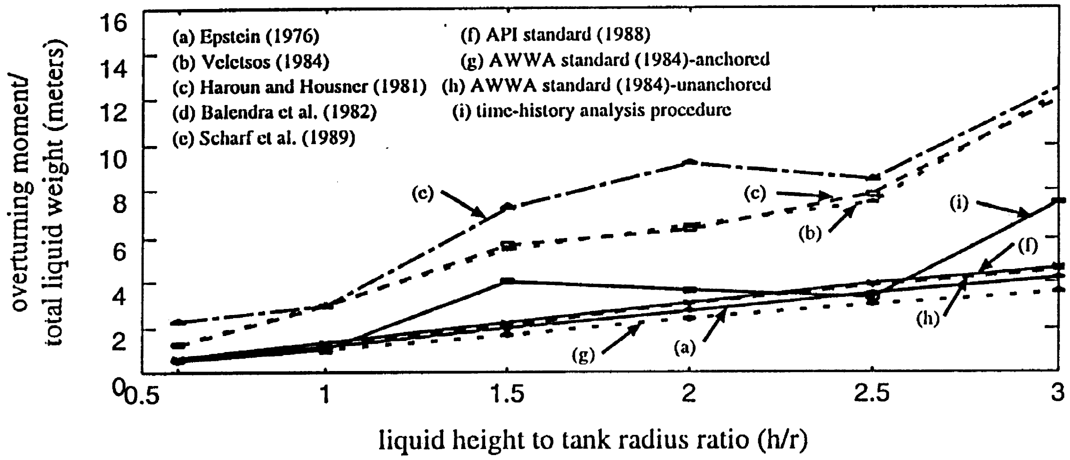


Fig. 8. Normalized overturning moment