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Review of seismic studies of liquid storage tanks

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Abstract. The academic research works about liquid storage tanks are reviewed for the purpose of providing valuable reference to the engineering practice on their aseismic design. A summary of the performance of tanks during past earthquakes is described in this paper. Next, the seismic response of tanks under unidirectional earthquake is reported, supplemented with the dynamic response under multidirectional motions. Then, researches on the influence of soil-structure interaction are brought out to help modify the seismic design approach of tanks in different areas with variable properties of soils. Afterwards, base isolation systems are reported to demonstrate their effectiveness for the earthquake-resistant design of liquid storage tanks. Further, researches about the liquid-structure interaction are reviewed with description of simplified models and numerical analytical methods, some of which consider the elastic effect of tank walls. Moreover, the liquid sloshing phenomenon on the hydrodynamic behaviors of tanks is presented by various algorithms including grid-based and meshfree method. And then the impact of baffles in changing the dynamic characteristics of the liquid-structure system is raised, which shows the energy dissipation by the vortex motion of liquid. In addition, uplifting effect is given to enhance the understanding on the capacity of unanchored tanks and some assessment of their development. At last, the concluding remarks and the aspects of extended research in the field of liquid storage tanks under seismic loads are provided, emphasizing the thermal stress analysis, the replaceable system for base isolation, the liquid-solid interaction and dynamic responses with stochastic excitations.

Keywords: liquid storage tank; seismic response; soil-structure interaction; fluid-structure interaction; liquid sloshing

1. Introduction

As an effective storage infrastructure, LNG (Liquefied Natural Gas) tanks as shown in Fig. 1 are widely used all over the world. According to the engineering practice, there are three types of tank, namely ground-supported tanks, elevated tanks and underground tanks which may be made of reinforced concrete, prestressed concrete or steel. The construction of liquid storage tanks began in early 20th century. The first LNG factory was built in West Virginia in 1939 and three spherical tanks were completed one year later. In 1958, the first low-temperature liquid storage tank was built in Louisiana with the volume of 50,000 m^3. From the mid-20th century, it pretends to build huge tanks for the efficient operation, and the largest volume of underground LNG storage tank exceeds 200,000 m^3 in Tokyo. Such a huge tank leads the challenge in the engineering practice. Unlike buildings, liquid storage tanks are lifeline structures with less ductility, suffered from varying hydrodynamic pressures on tank walls. The strict design and the fabrication of tanks should consider low-temperature or corrosive characteristics of substances.

The seismic analysis of liquid storage tanks has become a significant issue because heavy damage occurs due to severe seismic events such as the 1999 Turkey earthquake (Sezen and Whittaker 2006) and 2012 Emilia Italy earthquake (Brunesi *et al.* 2015). The failure of tanks may cause collapse of the infrastructure, explosion, fire and environmental pollution which leads to great economic losses and casualties. However, the safety of liquid storage tanks under seismic loads has become a crucial concern, and has been studied by lots of researchers in engineering and academic field over recent years. A review on the behaviors of liquid storage tanks under earthquake motions is presented in order to provide an effective and valuable reference to current studies and engineering practice on its aseismic design.

A summary of the performance of tanks during past earthquakes is described in this paper. Next, the seismic response of tanks under unidirectional earthquake is reported as well as under multidirectional motions. Then, researches on the influence of soil-structure interaction are brought out to help modify the seismic design approach of tanks in different areas. Afterwards, the isolation effect on dynamic characteristics is carried out. Further, the liquid-structure interaction is reviewed, followed by the liquid sloshing phenomenon. The impact of baffles is also provided, emphasizing on changing the dynamic characteristics of the liquid-structure system. In addition, uplifting effect is given to enhance the understanding on the capacity of unanchored tanks and some assessment of their development. The last section provides concluding remarks and extended works oriented in this area.

2. Failure modes of liquid storage tank

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(a) ground-supported tank

(b) elevated tank

Fig. 1 LNG storage tank

(a) elephant foot buckling

(b) diamond shape buckling

Fig. 2 Buckling of liquid storage tank (Brunesi *et al.* 2015)

Liquid storage tanks may suffer structural damage seriously under seismic loads. From the retrospect of the performance of tanks during past earthquakes, the failure modes of liquid storage tanks are always shown nonlinearity.

2.1 Buckling

Tanks always have two types of buckling under earthquakes. The EFB (Elephant Foot Buckling) is an outward bulge at the bottom of tank walls near the tank base, normally occurring in squat tanks with lower height to radius ratio, which easily leads to the leakage of inner contents due to the cracking of tank walls. Another typical failure mode is the diamond shape buckling, an elastic buckling form due to high axial compressive stress, usually appearing in slender tanks with larger height to radius ratio. Fig. 2 shows the buckling phenomenon of the liquid storage tank (Brunesi *et al.* 2015).

An experiment by Niwa and Clough (1982) concluded that the EFB is rooted in the combination of the vertical compressive stress exceeding the critical stress and the hoop tensile stress approaching to the yield limit of materials. It also demonstrated that the diamond shape buckling occurring at upper tank walls results from the high axial compressive stress approximate to 60 percent of the critical stress in theory.

Tazuke *et al.* (2002) verified the earthquake-resistant property of liquid storage tanks by shaking table test with the evaluation of FEM (Finite Element Method) analysis considering nonlinearity and uplifting of side walls. The model tank was used for slip test, static and dynamic elephant foot bulge test to study the buckling phenomenon and the lateral slip of the structure. The tank suffered liquid pressure and overturning moment under earthquakes. It indicated that the circumferential tensile stress and the vertical compressive stress were generated, leading to EFB, a large plastic deformation of tank walls.

2.2 Damage of tank roof

The damage of tank roofs usually occurs under seismic loads with high intensity, especially when the frequency of the earthquake is close to the fundamental one of liquid sloshing. Tank roof generally has two types. The fixed one always bears the impact caused by the liquid sloshing wave which leads to buckling or the crack of the connection between tank walls and roofs. The floating one can be stuck and unserviceable to lift due to liquid sloshing pressure. The upper members are also broken. When the sloshing wave height exceeds the design limit, liquid may spill over the roof resulting in fire and environmental contamination.

2.3 Connection and other damage

When the magnitude of overturning moment exceeds the restoring moment, the tank base may uplift from foundation or even experience rocking motion. The axial stress of tank walls may undergo a significant increase due to the great impact effect. Earthquake can also cause

Table 1 Summary of tanks with dynamic analysis

Reference	Tank type	Liquid	Method	Ground motion	Remarks
Nachtigall *et al.* (2003)	Cylindrical steel tank	Effective density of wall	Shell form based numerical method	Horizontal motion	Fundamental frequencies
Barton and Parker (1987)	Cylindrical tank	Added mass	FEM	Horizontal motion	Cantilever beam and bending mode
Virella *et al.* (2006)	Cylindrical tank	Added mass and acoustic element	FEM	Horizontal motion	Cantilever beam and bending mode
Dieterman (1986)	Elevated tank	Spring-mass model	Numerical method	Horizontal motion	Continuous model, equivalent model
Curadelli *et al.* (2010)	Elevated spherical tank	Water and rigid solid block	Vibration test and FEM	Horizontal motion	Pendular, sloshing and translation mode
Maekawa *et al.* (2010)	Cylindrical tank	Water	Vibration test and linear theory	Horizontal motion	Beam-type and oval-type vibration
Bayraktar *et al.* (2010)	Cylindrical steel tank	Fuel oil	Ambient vibration test and FEM	Natural excitation	Bending mode
Amiri and Sabbagh-Yazdi (2011)	Welded steel tank	Fuel oil, MTBE and water	Ambient vibration test and FEM	Natural excitation	Axial mode and circumferential mode
Razzaghi and Eshghi (2015)	Cylindrical steel tank	Oil	Numerical method	Earthquake	Height to diameter
Wunderlich and Seiler (2000)	Cylindrical tank	Pressure	Quasistatic approach	Horizontal and vertical motion	EFB and buckling in the tank wall
Kianoush and Chen (2006)	Rectangular concrete tank	Hydrodynamic pressure	FEM	Horizontal and vertical motion	Tank flexibility and combined response
Ghaemmaghami and Kianoush (2010)	Rectangular concrete tank	Hydrodynamic pressure	FEM	Horizontal and vertical motion	Impulsive and convective response
Moslemi and Kianoush (2012)	Cylindrical concrete tank	Water	FEM	Horizontal and vertical motion	Impulsive and convective response
Mirzabozorg *et al.* (2012)	Rectangular concrete tank	Water	Numerical method and FEM	Motion of three components	Impulsive and convective response
Ozdemir *et al.* (2012)	Cylindrical steel tank	Water	Nonlinear FSI algorithm of FEM	Horizontal and vertical motion	Fixity condition and uplift response
Alembagheri (2014)	Cylindrical steel tank	Water	Endurance Time Method	Motion of three components	Fixity condition and correlation diagram
Cho *et al.* (2004)	Cylindrical steel tank	Water	Numerical method	Horizontal motion	Soil condition and isolation system
Livaoglu (2008)	Rectangular concrete tank	Spring-mass model	Numerical method	Horizontal motion	Idealized FSI and SSI model
Larkin (2008)	Steel and concrete tank	None	Frequency domain method	Translation and rotation	Shear Strain and layered site
Kianoush and Ghaemmaghami (2011)	Rectangular concrete tank	Water	FEM	Horizontal motion	Foundation deformability and soil stiffness
Chaduvula *et al.* (2013)	Elevated steel tank	Water	Experiment	Combined motion	Rocking motion as SSI
Peña and Guzmán (2015)	Cylindrical concrete tank	Lumped mass	FEM	Horizontal motion	Soil properties and equivalent damping
Taniguchi (2004)	Cylindrical tank	Effective mass	Numerical method	Horizontal motion	Uplift angle and rocking behavior
Malhotra and Veletsos (1994a, b)	Cylindrical tank	Liquid pressure	Beam model	Uplift	Plastic rotation and plate thickness
Malhotra and Veletsos (1994c)	Cylindrical tank	Liquid pressure	Numerical method	Horizontal motion	Plastic rotation and plate thickness
Ahari *et al.* (2009)	Cylindrical steel tank	Hydrostatic pressure	Numerical method	Uplift	Hydrostatic pressure and plate thickness
Malhotra (1997)	Cylindrical tank	Liquid pressure	Numerical method	Horizontal motion	Flexible foundation and thickness
Ozdemir *et al.* (2010)	Cylindrical steel tank	Water	FEM	Horizontal motion	Base uplift and pressure distribution
Alembagheri and Estekanchi (2011)	Cylindrical steel tank	Water	Endurance time method	Horizontal motion	Flexible foundation and uplift height
Vathi and Karamanos (2015)	Cylindrical steel tank	Spring-mass model	FEM and numerical method	Horizontal motion	Rotation, uplift height and fatigue
Ormeño *et al.* (2015)	PVC tank	Water	Experiment	Horizontal motion	Rotation and stress
Wang *et al.* (2001)	Cylindrical tank	Spring-mass model	Non-linear dynamic analysis	Horizontal motion	Friction pendulum seismic bearing
Shrimali and Jangid (2004)	Cylindrical tank	Lumped mass	Numerical method	Horizontal motion	Linear elastomeric bearing
Panchal and Jangid (2008)	Cylindrical steel tank	Lumped mass	Numerical method	Horizontal motion	Variable friction pendulum system
Seleemah and El-Sharkawy (2011)	Cylindrical steel tank	Lumped mass	Numerical method	Horizontal motion	Elastomeric or sliding bearing

Table 1 Continued

Reference	Tank type	Liquid	Method	Ground motion	Remarks
Soni *et al.* (2011)	Circular steel tank	Lumped mass	Numerical method	Horizontal motion	DVFPI
Curadelli (2013)	Circular steel tank	Lumped mass	Numerical method	Horizontal motion	Lead–rubber bearing
Colombo and Almazán (2015)	Cylindrical steel tank	Lumped mass	Numerical method and FEM	Horizontal motion	U-shaped steel damper
Ormeño *et al.* (2015)	PVC tank	Water	Shaking table test	Horizontal motion	Sip-friction connector
Saha *et al.* (2016)	Cylindrical tank	Lumped mass	Numerical method	Horizontal motion	Lead–rubber bearing
Chalhoub and Kelly (1990)	Cylindrical steel tank	Water	Shake table test	Horizontal motion	Scaled nine-story steel structure

differential settlement of the foundation and soil liquefaction, leading to incline even collapse of tanks. In addition, the welding joint of tank walls and the base plate, the piping system and anchor bolts may suffer serious damage.

3. Seismic response under earthquake

3.1 Unidirectional ground motion

Since the seismic safety of a large liquid storage tank is crucial and has a great effect on its economic performance, reliability and service life, studies on hydrodynamic characteristics of tanks under earthquake loads tend to be a very important issue. The dynamic analysis by FEM and seismic experiment is always utilized to obtain the base shear, the overturning moment, the distribution of hydrodynamic liquid pressure, the displacement of the structure and the stress of tank walls. A brief summary is presented in Table 1. In the view of the effect of field condition and earthquake parameters including intensity and frequency, the fundamental frequency and the damping of the structure incorporating liquid coupled vibration are also important objects which deserve to be investigated.

With a brief comment about API Standard 650 (1980) and EC 8 (1998), Nachtigall *et al.* (2003) proposed the basic assumption of current design provisions that cylindrical storage tank behaves like a cantilever beam without deformation of its cross-section. Based on Galerkin's approximation (Soedel W 1981), a method was presented out to study fundamental frequencies and failure modes with introduction of a deformability parameter, the applicability of which was justified in the fields of stress. According to the recent investigation, most damage of tanks was caused by resonant effect.

Barton and Parker (1987) studied the seismic response of the cylindrical tank by finite element models and asserted that with the tank height/diameter larger than 0.5, the cantilever beam mode is fundamental in tanks under horizontal accelerations. The $\cos\theta$ type with higher mode in particular has very small participation factor in predicting the dynamic behavior of tanks. It can be seen from Virella *et al.* (2006) who used finite element program to study the fundamental impulsive vibration modes of anchored cylindrical storage tanks under unidirectional ground motion. The structure was modeled by shell element and the liquid was modeled by two forms, added mass or acoustic element. The hydrostatic pressure and the self-weight were considered. The natural period and modes were identified with respect to different aspect ratios (height to radius ratios) from free vibration and harmonic response analysis. It showed that the response of liquid-tank system can be assessed with the fundamental mode while higher modes have less modal participation factors. And the fundamental modes are related to the aspect ratios H/D. Higher tank with H/D larger than 0.63 seems to behave like a cantilever beam, while the shortest tank (H/D = 0.40) is similar to bending like a bulging form.

The research papers are mainly related to ground-supported liquid containers whereas works concerning the seismic response of elevated tanks are limited. Dieterman (1986) developed a mechanical representation for watertower by a continuous model with liquid specified by lumped mass, which was confirmed by several measurements. Similarly, the dynamic response of an elevated spherical water tank under horizontal motions was investigated by Curadelli *et al.* (2010) with free vibration test, in which the frequency of vibration modes was obtained by response spectrum in terms of different liquid surface height. The results were compared with linear steady-state harmonic analysis of the model tank by FEM. Sloshing effects were also discussed with two cases, the liquid inside considered as real water and rigid solid block respectively. The conclusion was that the frequency of the liquid filling tank decreases with increase of fluid level, and the liquid sloshing has a great effect on dynamic properties of tanks.

Maekawa *et al.* (2010) performed a shaking table test of a 1/10 scaled model tank under sinusoidal excitation with different amplitudes and seismic loads. The axial distribution of hydrodynamic pressures, the acceleration on the top tank and the strain on the bottom wallboard were obtained and compared with those calculated by linear theory. The beam-type vibration and the oval-type vibration were identified. The latter one influenced the pressure distribution and magnitude. However, it played a small role in the seismic safety evaluation such as the shearing force and bending moment.

Using finite element software accompanying with ambient vibration test, modal analysis was presented by Bayraktar *et al.* (2010) to clarify dynamic characteristics of the cylindrical storage tank. Through updating the finite element model with changing material properties, the difference between natural frequencies of analytical and experimental results reduced. The updating model was then used for analyzing the earthquake behavior of liquid fuel storage tank. It showed that the first ten mode shapes are bending modes related to side walls of tank on horizontal direction.

Amiri and Sabbagh-Yazdi (2011) investigated the dynamic response of liquid storage tanks with aspect ratios larger than 1 under microseismic and wind load by ambient vibration test. The natural frequencies and mode shapes were obtained by using peak picking spectral method as shown in Fig. 3. Utilizing finite element method, the dynamic parameters were derived from free vibration analysis, and the influence of the roof was discussed. The cylindrical storage tank can vibrate in axial mode like cantilever beam along with circumferential bulging mode, and the tank roof restricted the radial deformation of the tank top.

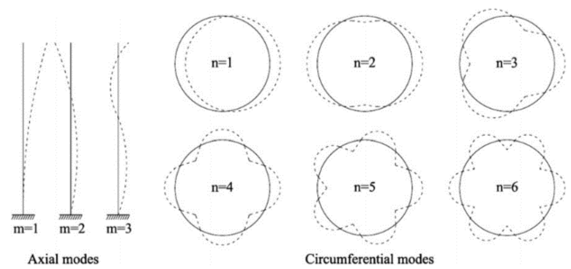

Fig. 3 Vibration modes of a circular cylindrical tank (Amiri and Sabbagh-Yazdi 2011)

Razzaghi and Eshghi (2015) studied cylindrical steel tanks built earlier and presented seismic fragility curves. Probabilistic seismic safety analysis was performed with tanks of different aspect ratios and liquid levels, which calculated the probability of exceeding a particular damage state. Empirical probabilistic evaluation of seismic performances of tanks during major earthquake in Iran was performed with comparison of analytical one. The results of fragility curves showed that the tank aspect ratio is a very important source of uncertainty in the probabilistic seismic safety analysis of tanks while the liquid level has obvious changes in fragility curves of tanks.

3.2 Multidirectional ground motion

Seismic responses of the liquid storage tank under horizontal ground motion have been studied by lots of academic researchers. The impulsive response is dominant and $\cos\theta$ type vibration contributes more to the seismic performance of tanks. However, earthquake motions are complicated in the field with different wave velocity, period and phase. Multidirectional components may have a vital effect on the dynamic characteristics, particularly base shear and overturning moment. For example, vertical earthquake motion may increase the height and probability of uplifting especially for slender tanks and also has an obvious effect on convective response.

Wunderlich and Seiler (2000) studied the elephant foot buckling and the failure of the upper tank wall by a quasistatic method. In order to simplify the dynamic problem into a static load case, different equivalent loading conditions on the tank wall were obtained by superposition of linear modal pressure eigenforms. The maximum response was approximated employing the response spectrum method. The load capacity and failure mechanism of tank on rigid foundation were proposed with different height to radius ratios under horizontal and vertical earthquake motions. As a consequence, the influence of the vertical earthquake component is drastical on the load capacity, tank wall inclined to buckling.

Based on the potential flow theory, the kinematic equation of liquid storage tank under vertical earthquake load was established by Kianoush and Chen (2006) to analyze the overall seismic performance of tanks with consideration of the flexibility of the tank wall by the sequential method. The combined response due to horizontal and vertical motions was calculated by SRSS (square root of the sum of squares) method. The results showed that the hydrodynamic pressure induced by horizontal motion is more significant than that due to vertical motion. However, the vertical acceleration cannot be neglected in the dynamic analysis.

By using FEM model of the tank anchored on rigid foundation, and taking wall flexibility and damping characteristics of liquid into account, Ghaemmaghami and Kianoush (2010) studied the dynamic behavior of concrete rectangular tanks subjected to both horizontal and vertical earthquake. Shallow and tall tanks were investigated in 2D space including impulsive and convective response. The impulsive pressure distribution of rigid tank was compared with analytical solutions. It can be seen that the flexibility of tank walls results in amplification of the maximum impulsive response and the vertical excitation leads to an increase of convective response.

Based on the theory of velocity potential, a wide range of parameters were examined by Moslemi and Kianoush (2012), including base fixity and higher modes. FE model was employed for tanks with different aspect ratios. Free vibration analysis was carried out on the rigid tank with fixed base station and time history analysis was presented to study the effect of wall flexibility and vertical excitation. The conclusion was that the vertical ground acceleration has a greater impact on convective response, the overall effect of which is found to be more significant in tall tank.

Mirzabozorg *et al.* (2012) researched on the seismic response of the rectangular liquid storage tank subjected to three directional earthquake motions applying staggered displacement method. The liquid was described in Euler form in order for simpler boundary conditions with the consideration of surface sloshing. The base shear and the overturning moment were obtained in different load combinations and compared with the results of FE model as well as the convective term. Generally, the convective component performs an important part of responses extensively in the horizontal excitation of the system, but almost no effect on tanks in the vertical excitation.

Utilizing central difference method, Ozdemir *et al.* (2012) solved the coupled liquid-structure problem in ALE formulation. The dynamic responses of anchored and unanchored tanks were discussed under real earthquake loads, considering both geometric and material nonlinearities. The successive contact and separate between the base plate and the foundation were simulated by face to face contact principle. The seismic response of tanks under unidirectional horizontal earthquake was calculated by simplified method, the numerical results of which under multidirectional earthquake were compared with those carried out by API 650 (2005), Eurocode 8 (2006) and NZSEE (1986). It indicated that the maximum base shear and the overturning moment of anchored tanks are obtained in one horizontal ground motion with the vertical component affecting slightly. On the other hand, those of unanchored tanks can be substantially magnified by the second horizontal excitation.

With a new Endurance Time method, Alembagheri (2014) studied the seismic safety of liquid storage tanks under multidirectional earthquake excitations selected from seven real earthquake records and three artificial intensifying records. The correlation diagrams were presented to investigate the maximum von-Mises stress with the comparison of anchored and unanchored tanks in two- and three-directional excitations states. As a result, the vertical earthquake load leads to an increase in the stress of side walls of the anchored tank.

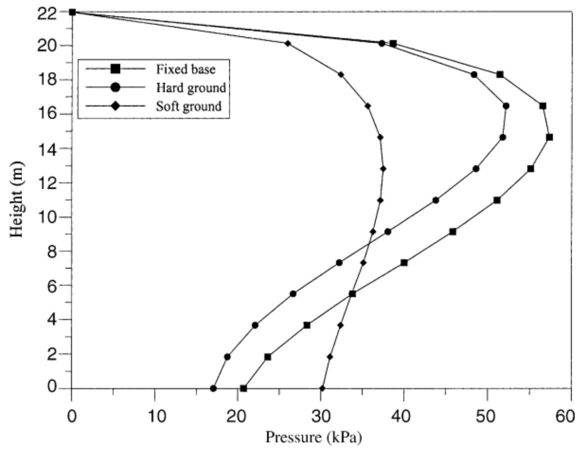

Fig. 4 Distributions of hydrodynamic pressure for various soil properties (Cho *et al.* 2004)

The dynamic analysis of tanks is first conducted by harmonic vibration. Then one- and three-dimentional ground motions are applied to obtain the dynamic response of the structure. Further, the probabilistic seismic safety analysis is put forward to get fragility curves, which gives an insight into uncertain evaluation of the seismic performance of tanks. The ambient vibration test with updating model and shaking table test are also provided for more accurate estimation with the help of time domain and frequency domain algorithm.

4. Soil-structure interaction

The design of the liquid storage tank nowadays is based on simplification of boundary conditions. However, the natural frequency and vibration modes of the liquid-structure system depend on the complex foundation state because of the soil-structure interaction. The earthquake load acts on the structure through ground soil and the oscillation of structure leads to a new hypocenter as a fresh input load. The interaction effects are induced by different material properties such as elastic modulus and shear wave velocity. The dynamic characteristics of the structure can be changed due to the deformability of the supporting medium which is taken as a sort of energy dissipation system by radiation of waves and its hysteretic action. Tanks containing LNG or other liquid are commonly cited on marginal ground in the vicinity of seashores with soft or loose soil and uneven displacement of the foundation may be seriously considered. Hence, the soil types and features need to be deliberated for the seismic safety of tanks.

Cho *et al.* (2004) studied the seismic response of base-isolated liquid storage tank rested on flexible foundation using the coupled boundary element and finite element method. The homogeneous half-space, base isolation and tank flexibility were idealized by spring-dashpot model, biaxial hysteretic element and degenerated shell element respectively. The responses of tanks with different boundary conditions were investigated to show the effect of base isolation and flexible soil, by which the distribution of hydrodynamic pressure was illustrated in Fig. 4. The maximum hydrodynamic pressure decreased with the soil stiffness deceasing. The results demonstrated that the soft soil condition generally reduced the seismic responses of tanks such as radial displacements and resultant forces, but has no effect on liquid sloshing.

By using Housner model to simplify the liquid and the cone model to simulate the foundation interaction effect, Livaoglu (2008) completed a seismic analysis of the liquid storage tank on different soil conditions under two different earthquakes separately. The displacement at the height of the impulsive mass, the sloshing elevation and base shear forces were obtained with the consideration of wall flexibility and foundation embedment effect. For the evaluation of soil-structure interaction, it concluded that the displacement responses change with decrease of the soil stiffness especially in flexible tanks and the base shear of the structure increases with the embedment.

Larkin (2002) studied the seismic response of a squat concrete tank sited on competent ground and a slender thin walled steel tank founded on soft soil. The dynamic impedance functions to account for the translation and rotation of the foundation were utilized (Gazetas 1991) in the frequency domain. It showed that the foundation compliance effect displays greater in the latter case. This conclusion was also founded in Larkin (2008) with the frequency dependent dynamic impedance function calculated by Wolf and Deeks (2004). The concept of near field and far field was introduced, considering the strain compatible shear stiffness and the material damping of near field and the radiation damping of far field. The consequence of the effect of the soil stiffness on seismic responses of tanks demonstrated that higher shear strain exists in tall tank on soft soil. Soil-structure interaction (SSI) is shown to be significant in establishing seismic load. Six soil types were adopted by Kianoush and Ghaemmaghami (2011) for analysis of the dynamic behaviors of liquid storage tanks incorporating deformable foundation effects with emphasis on the effect of frequency content of earthquake. The shallow and tall tank models with viscous boundary by finite element method were applied for spectrum and time history analysis. As for high frequency earthquake motion, the maximum response of the structure reduces with decrease of soil stiffness. And it can be magnified when the frequency characteristics close to those of liquid tanks.

Chaduvula *et al.* (2013) presented a shaking table test of a 1/4 scaled elevated cylindrical liquid storage tank under horizontal ground motion and rotation, with the soil-structure interaction simulated by rocking motion. The impulsive and convective base shear, the overturning moment and the pressure distribution with different horizontal acceleration and rocking angle were analyzed respectively by filtering of the frequency from the response recorded. It can be observed that rocking motion leads to an increase of impulsive response, the larger angle of which results in a reduction of convective response.

The seismic responses of liquid storage tank supported on elastic medium subjected to horizontal excitation were investigated by Peña and Guzmán (2015). The foundation soil was simulated by elastic half-space. The impedance function was introduced to extract the radiation damping and stiffness (Gazetas 1983, 1991). The distribution of pressure was simplified by impulsive mass changing along with tank height. The eigenvalues were detected for modal analysis and the displacement of the structure under unit harmonic excitation was discussed. The observation of the composite modal damping obtained by weighted mean method and the fundamental period for impulsive mode reveals an increase for softer soils.

The soil-structure interaction is one of the influential factors in seismic analysis of liquid storage tanks. Instead of the simplified approach in fixed-base analysis, the local soil characteristics are carried out to take into account the site effect. The soil is represented simply by static springs or even linear elastic medium considering the material damping using finite element-based methodology. In addition, the experiment is employed to study the performance of tanks, using rocking motion to consider the soil effects.

5. Uplifting effect

Uplifting of tanks is a complicated nonlinear behavior conducted by overturning moments which are induced by the liquid force of inertia especially for unanchored tanks subjected to strong earthquake motions. Studies of the performance of tanks with uplifting behaviors during earthquake (Mano and Clough 1985) have shown such tanks to be prone to damage. The localized elevation of the tank plate results in the liquid moving to the other side walls, whose axial compressive stress may significantly increase. As a consequence, the buckling of tank walls may occur with the fracture of the connection between the plate and the shell. In another words, uplifting effects possibly cause the strength failure or serious plastic deformation of the structure, which need to be considered well in the seismic design of liquid storage tanks.

Taniguchi (2004) studied the rocking response of the tank with rigid bottom plate by the established kinematic equation considering the rock-translation interaction. Assuming the effective mass and the moment inertia of liquid, the rocking response and the friction coefficient of the tank with flexible bottom plate were presented that the translational response of liquid storage tanks without the rock-translation interaction may be overestimated during uplift. Tall tanks are easier to uplift.

Malhotra and Veletsos (1994a, b) used an infinitely long uniformly loaded prismatic beam to model the uplift effect of the tank plate and concluded that the plastic hinge is formed along the bottom plate boundary when the end moment attains the yield moment. The uplift nonlinearity is related to the bottom plate thickness, axial force and plastic yielding. In addition, the cylindrical tank under horizontal motion was studied by Malhotra and Veletsos (1994c) to show that the uplifting reduces hydrodynamic pressures but increases compressive stresses in tank walls. Then a more realistic result was obtained by Ahari *et al.* (2009) with a tapered beam model. It's more compatible with the shape of the tank bottom plate because of the adjacent overlapped constant beam. The evaluation of the uplift response was completed by the unanchored liquid storage tank on rigid foundation. The result was compared with that of a uniform beam model in terms of the load reversal, the hydrostatic pressure and the normalized thickness of walls and the bottom plate. The second order shortening effect on the solution at small uplift length values was discussed. It showed that the hydrostatic pressure only influences the initial uplift and the axial force of the beam and the increase in the thickness of the bottom plate boosts its plastic deformation capacity. Malhotra (1997) also asserted that the uplifting resistance increases with thicker base plate and tank walls. And the flexibility of the foundation reduces the base overturning moment and the wall axial compressive stress but raises the base uplift and plastic rotation.

Ozdemir *et al.* (2010) studied the dynamic behaviors of anchored and unanchored tanks by finite element method with the results compared with those of API 650 (2005), EC 8 (2006) and NZSEE (1986). The contact algorithm with friction forces was taken into account. The results of the liquid sloshing displacement, the pressure distribution, the base uplift and the base shear demonstrated that uplift effects lead to an increase in the pressure response. High compressive hoop membrane and axial bending stresses are developed near the bottom of the uplifted wall for the unanchored case. The uplift displacement can be computed with the formula employed by NZSEE whereas API 650 recommends an allowable value. However, the uplift height according to Eurocode 8 cannot be evaluated because of the normalized overturning moment outside the range by such code.

The seismic response of liquid storage tanks in ground motions and the endure time analysis were investigated by Alembagheri and Estekanchi (2011). The contact between the bottom plate and the foundation was defined as friction interaction and the explicit dynamic analysis of tanks was done by the direct time integration. The maximum response was predicted and the floor flexibility was discussed. The correlation diagrams showed that the uplifting phenomenon leads to scattering of results in the unanchored state with higher von-Misses stress.

The nonlinear incremental static analysis was present by Vathi and Karamanos (2015) with the distribution of hydrodynamic pressure acted on. The overturning moment with different uplift angles, the uplift parameter and the equivalent plastic strain of the base plate were obtained. The simplified model incorporating the uplift effect was proposed out to calculate the local strain and the fatigue strength of the plate-shell connection which illustrated that uplift effect may cause the fatigue fracture of the connection.

Ormeño *et al.* (2015) studied the axial and hoop stress of side walls of unanchored liquid storage tanks with uplift by shaking table experiment. The seismic response of tanks with different liquid depths under stochastically generated ground motions was carried out with derived evaluation indexes. It can be seen that the uplift effect results in an

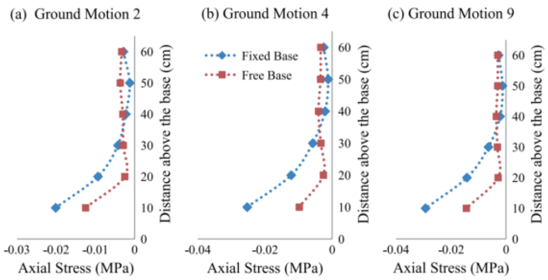

Fig. 5 Vertical distribution of maximum compressive stresses with H/R equal to 1 (Ormeño *et al.* 2015)

increase in the displacement of tank roofs and the acceleration of tank walls but a reduction in the axial compressive stress as shown in Fig. 5. The effect of uplift on the maximum hoop stress is related to the liquid height to tank radius ratio.

The rocking motion is applied for dynamic analysis of the uplift effect of tanks as an approximation method. And the beam model is adopted to evaluate the uplift deformation of unanchored liquid storage tanks. Moreover, the endurance time method is presented out as a new dynamic analysis method based on time history algorithm for the seismic performance assessment of the structure. Otherwise, the FEM based method like nonlinear incremental static analysis is always used for estimation of uplift responses.

6. Isolation of tanks

To guarantee the seismic safety of liquid storage tanks, the conventional approach is to enhance the structure members with size and material strength in order for higher load capacity. And the alternative method is to reduce the response of the structure by energy dissipation. Hence, base isolation introduced between the foundation and the superstructure is applying for separating the upper liquid-tank system and foundation to alleviate the strong earthquake wave transformed to the structure. The isolation system can change the fundamental frequency of tanks away from the dominant frequencies of earthquake ground motion. Base isolation technique is used in practical design of liquid storage tanks.

Wang *et al.* (2001) studied the effect of sliding-type friction pendulum seismic (FPS) bearings on liquid storage tank under earthquake motion with the hybrid structure-hydrodynamic numerical model. The parametric analysis was presented in terms of the aspect ratio, earthquake intensity and friction coefficient of base isolation. And the empirical formulation was devised for evaluation of the peak dynamic response reduction. It was shown that seismic isolation can significantly reduce the impulsive pressure while scarcely influence the convective pressure, the effect of which becomes better with its friction coefficient declines.

The modal superposition method was used to assess the seismic responses of base-isolated liquid storage tank by Shrimali and Jangid (2004). The peak response of different modes was obtained by response spectrum method and combined to be compared with exact values. The effects of non-classical damping were investigated under different tank aspect ratios, stiffness and damping of bearings. The closed-form expressions of modal parameters of isolated tank and simplified approximate formulations were developed to evaluate various response quantities. It implied that the response of the isolated system decreases with the increase of bearings damping and it can be predicted by the modal analysis with classical damping approximation.

Using Newmark method with the assumption of lumped masses replacing liquid, Panchal and Jangid (2008) solved the kinematic equation of the variable friction pendulum isolated liquid storage tanks. The seismic behavior of the system was researched under normal component of near field earthquake and trigonometric cycloidal pulse. As for tank aspect ratio, the period of isolator and initial time period, the parametric study was carried out and compared with conventional one. It observed that the base shear, sloshing wave height and isolator displacement can be controlled in a desirable level with the introduced variable friction pendulum isolator, whose flexibility has an obvious effect.

The simplified coupled liquid-solid model was adopted to examine the seismic performance of liquid storage tank isolated with rubber and friction pendulum bearings by Seleemah and El-Sharkawy (2011), the results of which were compared with non-isolated tanks. The tank aspect ratio, isolation period, friction coefficient of sliding bearings and damping of rubber bearings were discussed. It demonstrated that base isolation is quite useful in reducing the base shear and the impulsive displacement while increasing the convective displacement especially for slender tank. The effect of the friction pendulum isolation system is better than rubber bearings.

Soni *et al.* (2011) built a numerical model of liquid storage tank with the double variable frequency pendulum isolator (DVFPI) for calculating its bidirectional earthquake response under different far-field ground motions. The performance optimization method was presented with analysis of the properties of isolator in different geometry and friction coefficients. The isolator with higher initial stiffness from top to bottom sliding surface performs better for slender tank, while the one with the same initial stiffness and friction coefficient does better for shallow tank.

Based on random vibration theory, the ground motion was expressed as stationary random process using the power spectral density function by Curadelli (2013), who calculated the root mean square values of the stochastic response of liquid storage tank isolated by bilinear bearings with a statistical linearization scheme. The effect of isolation period, yield strength and viscous damping ratio on seismic isolation was proposed with different soil conditions. It indicated that the sloshing elevation is amplified by the post-yield stiffness. And the base isolation system decreases the base shear force but leads to a significant base displacement.

Colombo and Almazán (2015) completed a nonlinear dynamic analysis of liquid storage tank utilizing numerical method with the consideration of liquid-structure-soil interaction. The seismic reliability of tall and shallow tanks was studied with different anchored conditions under several ground motions. The limit state probability was calculated to evaluate the effectiveness of the energy dissipation system. As a result, the steel damper reduces the probability of the structure reaching the limit state.

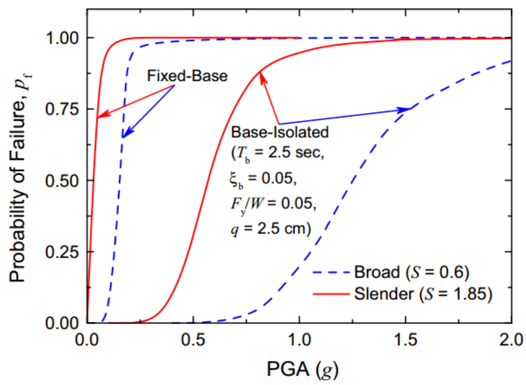

Fig. 6 Comparison of seismic fragility for fixed-base and base-isolated liquid storage tanks (Saha *et al.* 2016)

The mechanical properties of the slip-friction connector were studied by Ormeño *et al.* (2015). Considering the liquid storage tank with fully fixed, partially fixed and free to uplift conditions, the uplift height of tank base and the axial compressive stress of side walls were gained by cyclic experiment and shaking table test. It provided an insight into the feasibility of the slip-friction connector which can reduce the maximum axial stresses in the tank wall and the maximum vertical displacement of the tank base due to energy dissipation.

Saha *et al.* (2016) developed the seismic fragility curves for base-isolated liquid storage tanks under non-stationary ground motion generated by Monte Carlo method. The results were compared with the ones of fixed-base tanks, as shown in Fig. 6. The connection of earthquake intensity measure parameters and the peak response was studied with analysis of the effect on the isolation period, damping, yield strength and yield displacement. As a result, PGA of the earthquake motion is largely relevant. And the base isolation system with higher isolation period and damping can reduce the failure probability of tanks more. It can also be observed by Saha *et al.* (2016) who investigated the seismic response of liquid storage tank isolated with lead-rubber bearings using response surface model. The yield strength has a greatest influence on the probability distribution of peak response.

In the dynamic analysis of liquid storage tanks, the ground motion is always adopted from real seismic records. In order to predict the true dynamic response, non-stationary vibration generated by Monte Carlo method and stationary random process using the power spectral density function are employed for stochastic analysis of tanks. The correlation between different earthquake intensity measure parameters and seismic fragility tends to be investigated more for better design of base-isolated tanks than the conventional time-history analysis.

7. Liquid-structure interaction

Table 2 Summary of research papers about the liquid-solid interaction

Reference	Tank type	Liquid	Method	Ground motion	Remarks
Housner (1957)	Variable tank	Lumped mass	Numerical method	Horizontal motion	Spring-mass model and rigid wall
Veletsos (1974)	Cylindrical tank	Hydrodynamic pressure	Numerical method	Horizontal motion	SDOF system and wall flexibility
Haroun (1983)	Cylindrical tank	Hydrodynamic pressure	Numerical method	Horizontal motion	Spring-mass model and flexible wall
Sezen *et al.* (2008)	Elevated steel tank	Liquid oxygen and nitrogen	FEM	Horizontal motion	FE and three lumped mass model
Drosos *et al.* (2008)	Arbitrary tank	Water	FEM	Horizontal motion	Hybrid and full FE model
Chen and Kianoush (2015)	Rectangular concrete tank	Consistent mass	Numerical method	Horizontal motion	Single degree of freedom system
Hashemi *et al.* (2013)	Rectangular tank	Hydrodynamic pressure	Numerical method	Horizontal motion	Spring-mass model and flexible wall
Elkholy *et al.* (2014)	Cylindrical steel tank	Water	FEM	Natural frequency	Finite element and densitiy
Yue and Wang (2006)	Cylindrical tank	Water	ALE FEM	Horizontal motion, rotation	Free surface and wave height
Elahi *et al.* (2015)	2D container	Water	VOF method	Linear, complex motion, rotation	Free surface and wave height
Močilan *et al.* (2016)	Fuel tank	Fuel	VOF method	Horizontal motion	Free surface
Liu *et al.* (2014)	2D tank	Water	ISPH model	Prescribed and free motion	Free surface and wave height
Lee *et al.* (2007)	2D tank	Water	MPS method	Sloshing, water breakdown	Free surface and wall flexibility
Lee *et al.* (1997, 2007)	Rectangular tank	LNG	VOF method	Rotation	Free surface and wave height
Virella *et al.* (2008)	2D tank	Water	FEM	Sloshing	Free surface and liquid pressure
Firouz-Abadi *et al.* (2009)	3D tank	Water	Reduced order model	Lateral and angular excitation	Free surface and wave height
Nicolici and Bilegan (2013)	Cylindrical steel tank	Water	CFD/FEA model	Horizontal motion	Wave height and wall flexibility
Ruiz *et al.* (2015)	2D tank	Water	FEM	Horizontal motion	Sloshing period
Bochkarev *et al.* (2016)	Cylindrical steel reservoir	Water	FEM	Harmonic excitation	Eigenfrequency and liquid pressure
Saghi and Ketabdari (2012), Saghi (2016)	2D tank	Water	FEM-BEM	Horizontal periodic sway motion	Free surface and pressure distribution
Celebi and Akyildiz (2002)	2D tank	Water	VOF method	Moving and rolling	Vertical baffle
Akyildiz and ünal (2005)	Rectangular tank	Water	Experiment	Rotation	Horizontal and vertical baffle
Panigrahy *et al.* (2009)	Rectangular tank	Water	Experiment	Horizontal motion	Horizontal, vertical and ring baffle
Akyildiz (2012)	2D tank	Water	VOF method	Rotation	Vertical baffle
Nayak and Biswal (2015)	Rectangular tank	Water	Experiment	Harmonic excitation	Vertical baffle and block
Lu *et al.* (2015)	2D tank	Water	VOF method	Sinusoidal excitation	Horizontal baffle
Goudarzi and Danesh (2016)	Rectangular tank	Water	Finite volume method	Horizontal motion	Vertical baffle
Sanapala *et al.* (2016)	2D tank	Water	CFD method	Harmonic and horizontal motion	Vertical and ring baffle

In liquid containers, the hydrodynamic pressure leads to the deformation of the structure while the structure motion results in the variation of flow field. The dynamic characteristics of the structure change with different liquid levels. Hence, based on fluid mechanics and solid mechanics, the liquid-structure interaction problem is derived as a new branch of research with the emphasis on the correlation of two totally different mediums. However, to solve this kind of problem, coupled liquid-structure equations need to be developed incorporating both the fluid domain and the solid domain with the description of representative quantities respectively. Generally speaking, the liquid-structure problem is of two typical types, one of which is that both regions are partially or entirely overlapped and expressed by differential equations with specific physical quantities. The other one is that the interaction effects only exist on the interface by mechanical equilibrium and deformation compatibility conditions. The

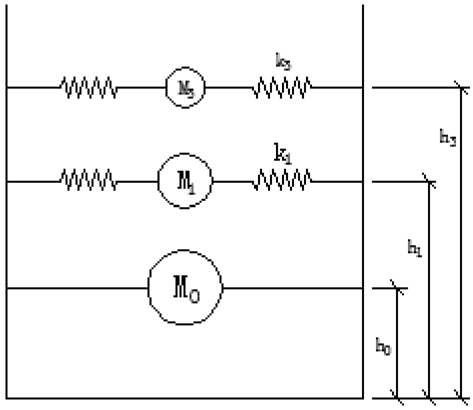

Fig. 7 Housner model for rectangular tanks

seismic studies of liquid storage tank belong to the second category. The analysis methods are mainly simplified model, assumed mode and finite element method. A brief summary of some important research papers about the liquid-solid interaction is presented in Table 2.

Assuming that the liquid was inviscid, irrotational and incompressible, a mass-spring simplified model was proposed by Housner (1957, 1963) as shown in Fig. 7. The hydrodynamic pressure on the structure induced by liquid was divided into impulsive pressure, associated with the forces of inertia from the liquid component rigidly attached to the tank wall and convective pressure, produced by oscillation of the liquid. The equivalent liquid masses and the height of bisymmetrical tanks were presented and the fundamental frequency of liquid sloshing was calculated with the base shear and the overturning moment obtained. However, liquid storage tanks fabricated based on the assumption suffered great damage in 1964 Alaska earthquake because the impulsive response was underestimated without consideration of the wall flexibility. Afterwards, researchers begin to study the liquid-structure coupling interaction including the flexible deflection of wallboards.

Veletsos (1974) devised an assumed mode method giving consideration of the effects of tank flexibility and only impulsive pressure, which regarded the liquid storage tank as a single-freedom system. The base shear, overturning moment and distribution of hydrodynamic pressure were evaluated for several prescribed modes of vibration. As a result, for tanks with realistic flexibility, the impulsive force is considerably higher than those for tanks with rigid walls. It was also concluded by Haroun (1983) using potential flow theory and boundary integral method. With tank walls discretized by shell ring element and fluid simplified by additional masses, the initial hoop stress, the stiffness in the plane of the dome and the foundation rigidity were discussed for their effect on the vibration of tanks. The simplified analytical model was presented with the liquid separated into rigid impulsive component, flexible impulsive component incorporating the tank wall flexibility and convective component.

With the development of the finite element software and numerical simulation, finite element programs are widely used in the research of the liquid-structure interaction of tanks, by which Edwards (1969) was the first one to analyze the seismic response of liquid storage tanks.

The elevated liquid storage tanks in Habas plant were modeled using finite element method by Sezen *et al.* (2008) with a displacement based Lagrangian approach including the effect of liquefied gas–structure interaction. The seismic responses were investigated in terms of sloshing height, lateral displacement, internal forces and column capacities. A modified model with three lumped masses was presented to simplify the calculation which overestimated the response. Ignoring sloshing effects leads to an increase of the lateral displacement of the roof and internal forces of columns.

The liquid was supposed to be inviscid with linear sloshing and considered by impulsive and convective mass. Drosos *et al.* (2008) developed an available finite element model to study the seismic response of the rigid liquid storage tank with arbitrary geometry and liquid fill height. It can be applied to vertical cylindrical, spherical and conical tanks effectively.

The calculation freedom was reduced by regarding the liquid storage tank as a single-freedom deformable cantilever beam fixed on the foundation by Chen and Kianoush (2009 and 2015). The wall flexibility was considered and the dynamic behaviors of tanks with different aspect ratios were discussed. The vibration modes were carried out to investigate the contribution of higher modes through modal superposition which demonstrated that the first two oscillating modes are enough for dynamic analysis. Otherwise, the seismic design of tanks by ACI 350.3 (2006) is conservative which doesn't take the wall flexibility into account.

Using numerical method, Hashemi *et al.* (2013) studied the seismic characteristics of liquid storage tanks under horizontal earthquake and derived a simplified model. The vibration of tank walls was expressed by Rayleigh-Ritz method and the potential fluid function was solved with three-spring-mass model and boundary conditions to acquire the distribution of hydrodynamic pressure and surface elevation. It showed that the hydrodynamic pressure in the middle of the wall for flexible storage tanks are generally larger than that for rigid storage tanks and those differ from each other in magnitude and shape.

Different finite element models were established with variable element types and densities by Elkholy *et al.* (2014) to conduct an optimal selection of elements to accurately predict the natural frequency and the mode shape of the liquid storage tank. The results in empty and full tanks were available and validated by other experiments and numerical analyses. It showed that the element type and the meshing configuration are important factors in qualified simulation works. SHELL43 seems to be the best and could be recommended for the analysis of filled tank case.

The liquid-structure interaction is studied by simplified method at the beginning with liquid modeled by spring-mass system and hydrodynamic pressure represented by additional mass. However, in order to obtain the seismic response of tanks accurately, FEM is widely used in recent years. The structure and the liquid can be simulated by variable finite elements and their interaction can be easily considered by the contact algorithm. Such method offers an effective way to handle seismic studies of liquid storage tanks even other engineering problems.

8. Liquid sloshing phenomenon

8.1 Unbaffled tanks

The liquid inside the tank is prone to violent sloshing under certain motions, resulting in largely localized impact pressure on higher level of surrounding walls and tank roof which may cause the spillage of the fluid. The analytical liquid sloshing is actually to solve the dynamic problem with moving free surface level. As for small amplitude, linear sloshing theory is always used to predict the movement of liquid with proper description of kinematic parameters and physical quantities. And the nonlinearity needs to be considered when strong sloshing phenomenon occurs with serious broken surface. The numerical method and experiment are mainly utilized to study the liquid sloshing phenomenon.

The liquid motion is generally described by Lagrangian or Eulerian form in fluid mechanics. The former one is based on physical configuration, tracing the moving path of particles, and the mesh element may distort in large liquid sloshing, while the later one is based on special configuration with grid fixed on space which cannot accurately track the free surface displacement. In the view of this, the arbitrary Lagrange-Euler kinematic description is carried out with both advantages of those two forms which can easily express the moving surface with flexible mesh technique. Yue and Wang (2006) developed Navier-Stokes equation in ALE description with the discretization of liquid free surface by quadrilateral element and calculation of its normal vector. The rigid body rotation of fluid and the large-amplitude sloshing in a cylindrical tank were presented that the apparent jump and the swirl mode can be observed in large-scale liquid sloshing. The vortex motion is generated by a force component normal to the excitation direction.

Another technique for tracing the free surface elevation with scalar functions is VOF (volume of fluid) method which can guarantee the conservation of physical quantities and possesses advantages in topology. However, the efficiency depends on the reconfiguration pattern of the interface due to incontinuity of the volume fraction here. With VOF method based free surface, Elahi *et al.* (2015) studied the liquid sloshing of a two-dimensional model in presence of surface deformation, liquid viscosity and surface tension under complex motions. And Močilan *et al.* (2016) using VOF multiphase model examined the free surface shape and stress results which gave an insight into a computer aided methodology for tank design.

Grid based method demands on a certain density of meshing which may be inaccurate due to large deformation. The smoothed particle hydrodynamics method provides a promising application for liquid sloshing analysis as a meshfree and self-adaptive approach with Lagrangian property, which discretizes the continuous medium into a range of random distributed particles with physical quantities described by time history. However, the boundary

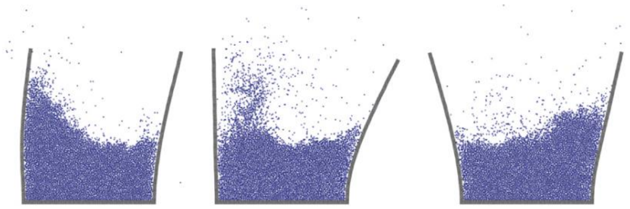

Fig. 8 Elastic wall responses (Lee *et al.* 2007)

needs to be specially handled for the defect of particles at the interface. Liu *et al.* (2014) studied the liquid motion by an incompressible smoothed particle hydrodynamics (ISPH) model with additional free surface criterion. The time history of free surface elevations and the path of the solid block were observed under different free motion simulations and compared with the experiment datum, which showed that the proposed model is effective in handling complicated liquid-solid interaction.

The partitioned coupling scheme and the Neumann–Dirichlet condition were applied by Lee *et al.* (2007) to solve the liquid sloshing problem. The semi-implicit time integration was used for liquid modeled by the moving particle semi-implicit (MPS) method and the symplectic time integration was used for the shell structure motion. The liquid sloshing of rigid and flexible tank was analyzed along with the water column breakdown. The fluid fragmentation and large structural deformations were observed in elastic walled tanks as shown in Fig. 8.

In addition, the liquid sloshing phenomenon is studied by other researchers. Lee *et al.* (2007) investigated the liquid sloshing using a computational program of viscous fluid with the assumption of rigid tank wall and incompressible liquid. The free surface was traced by VOF method and the results were compared with the experiments by Lee (1997). The liquid viscosity, the liquid-gas density ratio, the internal pressure and the compressibility of gas were checked for the influence to the impact pressure with verification of experiment results. It presented that the impact pressure is almost independent on fluid viscosity and liquid-gas density ratio, and the peak pressure of totally compressible gas model is higher than that of incompressible gas model with a sudden increase in lower pressure level.

The linear and nonlinear liquid sloshing phenomenon of rectangular tanks with different liquid heights and aspect ratios were proposed by Virella *et al.* (2008) with the comparison of natural periods, mode shapes and the sloshing pressure distribution. The acoustic model was used in the work of linear wave theory analysis while the plane strain problem with geometric nonlinearity was applied for nonlinear wave theory analysis. It was seen that the liquid sloshing is dominant by the first mode, the period of which is almost unassociated to nonlinearity. The nonlinearity of the large surface wave amplitude has little effect on the pressure distribution.

Based on potential flow theory, Firouz-Abadi *et al.* (2009) obtained the natural frequencies and vibration mode types of liquid sloshing of tanks with arbitrary geometry through eigen-analysis. The dimensionless elevation of free surface with different active modes was presented out that the reduced order model is useful for sloshing analysis with only a few modes and less computational costs.

The model considering the liquid-structure interaction and a simplified model with the liquid expressed by additional masses were proposed by Nicolici and Bilegan (2013) respectively to investigate the influence of the coupling upon sloshing properties and reaction forces. The results demonstrated that the hydrodynamic pressure acting on tank walls is mainly caused by impulsive pressure and the flexibility of structure has little effect on the liquid sloshing height and convective mode.

With equations expressed in term of physical variables, a simplified sloshing model similar to mass-spring system was presented by Ruiz *et al.* (2015) to research on the sloshing frequencies of tanks and the seismic response of a linear structure with tuned liquid damper. The sloshing period of rectangular tanks with different aspect ratios was illustrated that it's independent of the water depth when the water height to tank length ratio reaches to a certain value.

Based on the principle of virtual displacements, Bochkarev *et al.* (2016) investigated the dynamic performance of thin-walled liquid storage tank considering the hydroelastic interaction and sloshing. The modal analysis was completed for circular and elliptical tanks and the influence of liquid sloshing on the amplitude-frequency curves under harmonic excitation was discussed. It showed that sloshing effects result in reduction of the eigenfrequencies of the system and slightly change the displacements of the structure under non-stationary load, which also affect the hydrodynamic pressure distribution.

Assuming that the liquid was incompressible and inviscid, the coupled boundary element-finite element method was utilized by Saghi and Ketabdari (2012) and Saghi (2016) to solve the Laplace equation with dynamic boundary conditions. The liquid sloshing phenomenon was studied in terms of variable aspect ratio, excitation amplitude and frequency with the pressure distribution and forces exerted on the tank obtained. As a consequence, the maximum pressure and its location changes with different aspect ratios and the hydrodynamic pressure declines from the free surface to the bottom plate. The vertical force fluctuation on the tank perimeter is decreased at the lower level.

8.2 Baffled tanks

Liquid sloshing phenomenon is a long period motion affected by the tank aspect ratio and fluid depth. The flexibility of tank walls has little effect on the sloshing frequency and the surface elevation. To a certain extent, they can be predicted accurately with rigid tanks assumption. However, the impact pressure induced by the sloshing is large enough to cause the nonlinear behavior of the tank even the damage especially when the fundamental frequency of the earthquake ground motion is close to dominant sloshing frequencies. Baffles are sometimes installed in tanks along with surrounding walls to reduce the sloshing effect because of their energy dissipation scheme with the appearance of the vortex motion.

Assuming the liquid to be Newtonian and viscous, using the moving coordinate to simplify the boundary condition, Celebi and Akyildiz (2002) studied the liquid sloshing of a

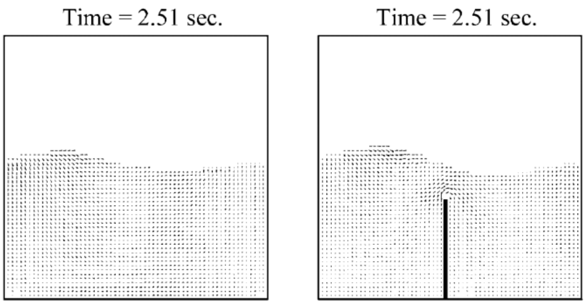

Fig. 9 A snapshot for numerical simulation of the intermediate fill depth sloshing (Celebi and Akyildiz 2002)

rigid tank moving along with a vertical curve and a rolling tank to find peak wave elevations, forces and moments on both walls. Different excitation amplitudes and frequencies were employed. The comparison of the sloshing in baffled and unbaffled tanks was shown in Fig. 9 which can be seen that the baffle decreases the sloshing amplitude with generating additional eddies near the baffle. The vertical baffle is more effective in the shallow tank with the reduction of the overturning moment.

Four types of sloshing waves are formed possibly as the tank vibrates with different liquid depths, tank geometry and oscillation frequencies. Two kinds of pressure were caused including impulsive and non-impulsive pressure. Akyildiz and ünal (2005) designed the experiments of baffled tanks under pitch excitations with different angles and frequency ranges to investigate the sloshing phenomenon which demonstrated that as the pitch amplitude increases, the liquid responds to violent motion with the appearance of turbulence, hydraulic jump and wave breaking. The vertical baffle at the center of the bottom reduces the maximum pressure on side walls.

Another shaking table test of the tank with different types of baffles was presented by Panigrahy *et al.* (2009) to find the effect of baffles on the surface displacement and the pressure variation. The sharp-edged baffles create turbulence of the fluid and the ring baffles perform better for absorbing and dissipating the energy from side walls.

Akyildiz (2012) solved the Navier-stokes equation by the finite difference method and studied the nonlinear liquid sloshing phenomenon of the rigid tank under rolling motion by the VOF scheme. The sloshing wave elevation and the hydrodynamic pressure distribution are influenced by the baffle height to initial liquid level ratio. It was found out that the strength of the liquid flow vortex, the free surface displacement and the maximum pressure decrease by larger ratio.

Using the rigid tank with the bottom-mounted vertical baffle, the surface-piercing wall-mounted vertical baffle and the bottom-mounted submerged block, the liquid sloshing phenomenon was investigated by Nayak and Biswal (2015) with shaking table experiments under harmonic excitation. The sloshing frequency was obtained by different liquid depths and vertical baffle heights, and the damping effect of baffles on the first sloshing mode was evaluated by the logarithmic decay method of the free vibrating liquid wave amplitude. It illustrated that the fundamental sloshing frequency decreases with the internal block and the damping ratio increases obviously with the top of the baffle approaching to the liquid surface.

Based on a viscous fluid numerical model, Lu *et al.* (2015) studied the behavior of baffled tanks in time domain and frequency domain by the three-step high-order upwind finite element method with the emphasis on the influence of the baffle location and width. The excitation amplitude on resonant response, the vortical flow and the dissipation effect, were discussed. The baffle increases the physical dissipation, the width and the position of which influence the resonant frequency and the amplitude of liquid.

Using a numerical analysis model of the liquid storage tank of different aspect ratios installed with baffles, Goudarzi and Danesh (2016) studied the damping effect on the liquid sloshing under real earthquake based on the finite volume method. The free surface displacement matched well with the result of the experiment by Chalhoub and Kelly (1990) who concluded that the water wave elevation increases slightly due to lower frequency of characteristic isolated tanks. Then a simplified evaluation procedure for the reduction in the maximum sloshing wave height was proposed out with the presence of vertical baffles. It concluded that the damping ratio increases as the baffle is placed closer to the tank center. Baffles with larger size decrease the sloshing amplitude more and elongate the oscillation period more.

Sanapala *et al.* (2016) analyzed the liquid sloshing problem of two dimensional tanks with a computational fluid dynamic program under harmonic excitation. The surface wave height and the pressure distribution were presented in both resonant and non-resonant states with focus on the configuration of a ring baffle and a vertical baffle. The vertical baffle with the height of 0.14m reduces the earthquake response of tanks most. It provides an optimal design method for tanks with vertical baffle.

Liquid sloshing phenomenon is considered by linear theory, then by nonlinear theory because of the wave with large amplitude. And taking liquid viscosity into account leads to more accurate results. In order to impede the strong sloshing, baffles with different configuration and type are always used and confirmed effective. The calculation of liquid sloshing is usually based on FEM or boundary element method and valuable experiments are preferred more in research. Instead of the grid-based method, the meshfree approach tends to be an advance with better surface tracking algorithm.

9. The engineering practice and research progress in China

The construction of large liquid storage tanks began in mid-1990s including two 80000 m^3 cryogenic LPG storage tanks of Guangdong and one 10000 m^3 low-temperature ethylene storage tank of Yangzi Petrochemical. The first 20000 m^3 LNG storage tank was built in Shanghai in the late 1990s and a 160000 m^3 full containment of LNG was completed in Shenzhen in 2006. The large-scale fabrication of the liquid storage tank has become a trend in China because of its potential development prospect. In order for this, some Chinese scholars have studied the structural

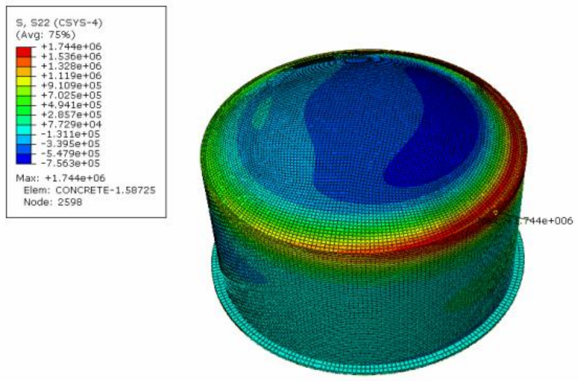

Fig. 10 Maximum loop tensile stress position of concrete tank (Li *et al.* 2015)

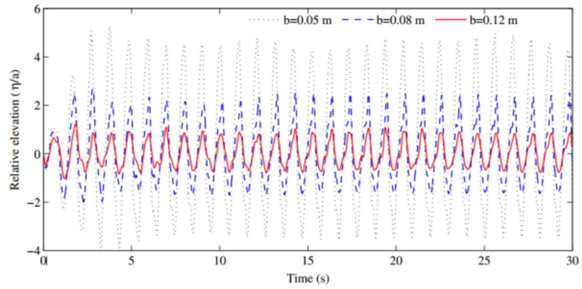

Fig. 11 Time histories of free surface elevation for different ring baffle widths (Xue and Lin 2011)

response of tanks in recent years.

Assuming that the liquid was incompressible, a finite element model was built by Cheng *et al.* (2015) for rectangular reinforced-concrete storage tank with rubber isolation. The liquid sloshing wave height, the displacement of tank walls and the equivalent stress were analyzed to study the seismic performance of tanks. The concrete constitutive model and elastic constants were determined while the mesh density and the element selection were considered. It concluded that the wallboard displacement and the equivalent stress ascend with increasing values of the seismic intensity especially for the tank with lower liquid fill height.

Li *et al.* (2015) presented a finite element model by ABAQUS to simulate a large concrete cylindrical storage tank with the consideration of the rebar's effect in order to examine the dynamic response and failure parameters of the structure. The modal analysis was conducted first to study the empty storage tank and then the seismic analysis to give an insight into the cracking process of concrete during earthquake. The maximum von-Mises stress of the rebar and the hoop tensile stress of concrete were observed, as shown in Fig. 10. It turned out that the cracking of concrete starts at the connection of outermost tank wall and the dome and then spreads along the circumference until the failure of entire tank roof.

Zhou and Liu (2007) separated the velocity potential of liquid into three variables and then combined them to consider the flexible effect of side walls with a series of admissible functions. The eigenfrequencies of symmetric and asymmetric rectangular liquid storage tanks were obtained by Rayleigh-Ritz and Galerkin's method with the parameter study of the liquid depth, rigidity matters and the liquid-tank mass ratio. It showed that the sloshing eigenfrequencies decrease for flexible tanks and the bulging eigenfrequencies increase accounting for the surface waves. Lin *et al.* (2015) studied the liquid sloshing problems of tanks with arbitrary cross section and axisymmetric tanks by the scaled boundary finite element method. The two-dimensional eigen equation was established with the boundary of liquid domain discretized in one dimensional space. Sloshing frequencies and mode shapes were carried out that more periodical sinusoidal wave along the periphery occurs with increasing number of mode.

Xue and Lin (2011) studied the effect of ring baffles with different heights and widths in liquid storage tanks under surge motion and pitch excitation by virtual boundary force method. The dominant response frequencies of the system were identified by a fast Fourier transformation technique. The ring baffle is more effective on reducing the violent liquid sloshing when it's placed near the free surface with larger width, as shown in Fig. 11.

The geometry, elastic modulus, density of baffles with three kinds of boundary conditions and the liquid density on the vibration of the liquid-structure system were carried out by Jing *et al.* (2016). The liquid domain was divided into two subdomains with the expression of different velocity potential functions and the gravity of the surface wave was neglected. It showed that the basic frequency of the coupling vibration is significantly affected by the baffle geometry with correlation to the baffle boundary conditions and liquid densities.

Fang *et al.* (2013) studied the dynamic response of liquid storage tanks under horizontal and vertical earthquake excitation by shaking table experiment with the emphasis on the effect of liquid height, earthquake amplitude, excitation frequency as for absolute displacement and the uplift behavior of the structure. It was observed that when the excitation frequency is close to the natural frequency of the tank, the absolute displacement is very large with small uplift value. The uplift response is larger under horizontal excitation than under vertical load.

The construction of liquid storage tanks starts late in China and it's always based on foreign techniques. Although the design code for earthquake is almost consummate, the one for tanks is insufficient with simplified algorithm used, which doesn't consider the liquid-structure interaction well either. For the achievement of establishing the complete system in China, further studies still need to be promoted.

10. Conclusions

A review of several aspects of researches on liquid storage tanks including the seismic response, the soil-structure interaction, the base isolation, the liquid-structure interaction, the liquid sloshing phenomenon and the uplifting effect is presented out in order to provide an available reference to the practical design of tanks under earthquake motions. However, the mentioned work on the subject is still inadequate which requires a further study in future to understand their dynamic performances better and assist in the improvement of current design codes for the seismic safety of liquid storage tanks. These are as follows.

• High stress is always generated in members of the structure under seismic motions especially when uplifting of tanks occurs. And due to special properties of substances, the structure suffers an additional thermal stress likewise. The optimal design of members and connections is important for reliability of the structure.

• The traditional seismic resistance is usually based on isolation systems. They always suffer large plastic deformation resulting in failure of the structure. In order to improve the potential ability of the structure for rapid recovery and reuse, the replaceable system provides a bright future for a new isolation system.

• The dynamic records used in research papers are determinate in general. However, the earthquake motion is a random process with uncertainty. To take the indeterminacy of structural responses by dynamic loads into account, the stochastic earthquake and the probability analysis may be used in the seismic study of tanks.

• The liquid sloshing phenomenon is a strong nonlinear behavior which has a significant effect on dynamic characteristics of liquid storage tanks. It needs to be carefully considered in engineering. And a simplified model of liquid with high efficiency is required for the seismic design of tanks.

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