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The sloshing law of liquid surface for ground rested circular RC tank under unidirectional horizontal seismic action

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Abstract

The dynamic characteristics and liquid sloshing of a circular tank are analysed using ADINA software through seismic response analyses. The maximum sloshing wave height for the circular tank under unidirectional horizontal seismic action is developed. The calculation method involves three parameters such as tank radius, seismic coefficient and dynamic coefficient. The dynamic coefficient of liquid sloshing is determined corresponding to the long-period seismic design β spectrum with a 5% damping ratio using basic sloshing period. The established method can guide the seismic design of liquid-containing structures. The established method of calculating sloshing wave height is compared with those in the American code.

Keywords: tank; seismic action; liquid-structure coupling; dynamic response; sloshing law

1 Introduction

Reinforced concrete water tanks which play essential functions in the entire water supply system are typical liquid-containing structures. Cracks are prone to occur when tanks suffer from strong earthquakes and may lead to liquid leakage, making liquid-containing structures losing their strength or even completely lost. The internal liquid in the tank under the seismic actions will slosh, and the distribution of the additional hydrodynamic pressure for the tank body will be directly affected by the amplitude of the liquid sloshing. To reasonably guide the seismic design of the tank in the water supply system, the liquid sloshing of the circular tank under seismic action is the focus of this research and further obtaining the law of liquid sloshing is the purpose of this research.

There are three methods to study sloshing wave height and hydrodynamic pressure, and they are theoretical calculation, numerical simulation and experimental test [1]. The theoretical analysis of the sloshing wave height for the liquid-containing is the earliest. In 1957, professor Housner adopted the approximation method [2]

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to derive the formula of the maximum sloshing wave height $h=0.837R\alpha_1$, assuming that the liquid in ideal fluid structure is rigid, and the liquid surface is moving with small amplitude. The sloshing wave height was proportional to the tank radius and the seismic effect coefficient in the formula proposed by Professor Housner. Professor Shen adopted the potential function theory to derive the sloshing wave height formula considering the liquid viscosity, and the sloshing period was the same as that derived by Housner.

The formula $h=0.343\alpha_1 T^2 \tanh(4.77(H/D)^{0.5})$ is used to calculate the sloshing wave height in the code TID7024 [3] of the American nuclear power plant. The Housner formula is used to calculate the sloshing wave height in the code JIS B 8501 of the Japanese steel tank [4]. Still, the parameter 1 is calculated based on the velocity spectrum, and the sloshing wave height under long-period ground motions is overestimated. The formula for calculating the actual displacement of the liquid surface for the circular tank under the horizontal seismic action is given by professor Epstein [5]. The formula is exactly the same as the Housner formula, and only the coefficient values are slightly different. At present, the Housner formula is still used to calculate the sloshing wave height of the liquid surface.

The calculation formula for the sloshing wave height of the oil tank under seismic action is recommended in the Chinese standard for seismic design of petrochemical steel equipment (GB/T 50761-2018). The sloshing wave height is proportional to the tank type coefficient, the seismic effect coefficient and the oil tank's inner radius. But, the formula for estimating the water tank's sloshing amplitude under seismic action is not given in the Chinese code of seismic design of outdoor water supply, sewerage, gas and heating engineering (GB 50032-2003). The numerical simulation method is also widely used in estimating the height of liquid sloshing waves. A numerical model based on the finite volume method is established by professor Goudarzi [6] to estimate the hydrodynamic damping caused by the vertical bounded baffle. The existence of the baffle reduces the sloshing amplitude of the liquid level through comparative analysis. Professor Wang studied the sloshing wave heights of isolated rectangular concrete tanks under unidirectional and bidirectional long-period seismic actions. [7]. The horizontal displacement and sloshing wave height increased under the bidirectional long-period seismic actions than under the unidirectional seismic actions. When other conditions remain unchanged, the larger the tank's structural size, the larger the horizontal displacement and sloshing wave height.

The shaking table test method is usually used in conjunction with the numerical simulation method. The shaking table test's research results are used to guide the model establishment or verify the numerical model's validity. The time history of liquid sloshing wave height is measured by using the shaking table test of the 1:20 scale model for a large steel storage tank [1]. The maximum value of the sloshing wave height is calculated by numerical simulation is close to the value that obtained from the shaking table test. Still, the shapes of the time history curve for the two both are quite different. Although the size of the oil tank is scaled down during the shaking table test, the material properties of the steel tank and internal liquid water could not be scaled down, and the test results are still quite different from the actual situation. The liquid-containing density has a significant influence on the sloshing wave height of the liquid surface, which is analysed and confirmed by Yazdanian et al. The lower the liquid density, the larger the sloshing wave height [8]. The dynamic characteristics of the rectangular tank system are sensitive to the frequency content of ground motions considering the fluid-solid coupling and soil interaction, which has been confirmed by Safaa et al. [9]. The shaking table tests of three open rectangular tanks with a scale ratio of 1:10 are completed by Jure et al. [10]. The analysis results show that when the period of input ground motion is close to the first-order period of the liquid sloshing, the sloshing amplitude of the liquid surface is huge. The wave height and distribution characteristics of liquid sloshing are directly affected by the stiffness of the tank wall, the amount of liquid, and the types of input dynamic excitation, including period, amplitude, or duration time. The oil tank models with various liquid levels and fixed roof are not tested by Bae et al. through shaking table tests [11]. The results show that the acceleration of the tank along the height direction is increased when the amount of liquid in the tank is large. That is, the sloshing effect of the liquid is significantly different when the amount of liquid in the tank is different. The dynamic behaviour characteristics, including beam-type and oval-type vibration of a cylindrical liquid-containing tank under horizontal earthquake excitation, are investigated by shaking table tests [12]. The dynamic characteristics

and sloshing wave height of the vertical storage tank are analysed by using ADINA finite element software. It is found that the radius of the storage tank and the height of the storage liquid has a more significant influence on the sloshing of the liquid surface [13]. The dynamic characteristics of liquid in sloped bottom tanks are investigated by Amiya by classifying frequency contents of six different ground motions [14].

Based on the above analyses, the ground circular tank's dynamic characteristics in water supply systems with different capacities are analysed by using theoretical analysis and numerical simulation methods. Based on the dynamic characteristics analysis, the relationship between the amplitude of liquid sloshing and ground motion characteristics, liquid-containing sloshing frequency, tank radius, liquid-containing height, and other factors are analysed. Based on the original theoretical formula, the calculation formula of the sloshing wave height for the water tank is fitted.

2 Tank model

The three circular tanks are named as tanks A, B, and C with 500 m³ capacity, 200 m³ capacity, and 2000 m³ capacity. The three tanks have the following structural characteristics: a bottom thickness of 0.3 m, a wall thickness of 0.25 m, a total height of 3.8 m, a maximum water storage height of 3.5 m and a reinforcement diameter of 10 mm. The inner radius of tanks A, B, and C is 6.75 m, 4.3 m and 13.5 m, respectively. For each tank, the height of the water is taken as 0%, 10%, 20%, 30%, 40%, 50%, 60%, and 70% of its maximum water storage height, respectively. The corresponding height is 0 (the state of the empty tank), 0.35 m, 0.70 m, 1.05 m, 1.40 m, 1.75 m, 2.10 m and 2.45 m. This means that there are eight different storage conditions for each tank. Since the water storage height of the tank during normal operation is about 70% of the total height, the 2.45 m height is set to the maximum storage height of the tank. In order to facilitate the analysis of the subsequent results, the 'A-50%' is used to indicate the condition of 500 m³ storage capacity and 1.75 m storage height, and other conditions naming are analogous.

In the process of finite element analyses for ADINA software, the tank body model is simulated as a 3D-Solid element, and the structure material is simulated by using concrete material. The reinforcement is simulated by using the truss unit. The stress-strain curves of the concrete and reinforcement are shown in Figure 1. The liquid model is simulated as a 3D-Fluid element and the element is set as the linear potential fluid element for static and modal analyses, and the subsonic potential fluid element for dynamic analysis. The water properties include a density of 1000 kg/m³, a bulk modulus of 2.3×10^9 Pa and a damping ratio of 0.16%.

Fig. 1 The stress-strain curve of the materials in the numerical simulation. (a) The concrete and (b) The reinforcement.

3 Dynamic characteristic

The dynamic characteristics of liquid-solid coupling system with different water storage heights are analysed to obtain the mode period and mode shape. The partial mode periods obtained by numerical calculations are shown in Table 1. The calculation results in Table 1 show that when the tank radius is the same, the higher the water storage height, the shorter the liquid sloshing period, the longer the structural vibration period, and the more significant the liquid-solid coupling effect. When the water storage height is the same, the larger the tank radius, the longer the liquid sloshing period and the structural vibration period, and the less significant the liquid-solid coupling effect. The same order modal shape of liquid sloshing is almost the same. Most of the shapes of structural vibration modes appear in pairs due to the rotational symmetry of the circular tank structure.

Table 1 Modal periods of part conditions (s).

Condition	Sloshing mode			Structural vibration mode		
	First-order	Second-order	Third-order	First-order	Second-order	Third-order
A-0%	/	/	/	0.026	0.026	0.023
A-10%	12.195 (12.500)	4.255	2.695	0.026	0.026	0.023
A-30%	7.143 (7.299)	2.688	1.873	0.027	0.026	0.023
A-50%	5.650 (5.770)	2.364	1.770	0.028	0.027	0.024
A-70%	4.926 (5.025)	2.268	1.754	0.030	0.029	0.027
B-70%	3.333 (3.472)	1.754	1.370	0.025	0.024	0.020
C-70%	9.091 (9.615)	3.704	2.632	0.040	0.039	0.039

Note: The data in parentheses are the results of the theoretical formula calculation.

Assume that the liquid-containing structure is a rigid body, and the liquid in the tank is non-viscous, non-rotating, incompressible and slightly vibrating. The calculation formula of the fundamental natural frequency $\tilde{\omega}_n$ for liquid-containing is shown in Eq. (1), and the calculation formula of the natural vibration period is given by Eq. (2).

$$\tilde{\omega}_n^2 = \frac{g}{a} \sigma_n \tanh\left(\sigma_n \frac{h}{a}\right) \quad (1)$$

$$T_n = \frac{1}{\tilde{\omega}_n} \quad (2)$$

where g is the acceleration of gravity, and the unit is square second per metre (m/s^2). The parameter a is the inner radius of the tank, and the unit is metre. The parameter h is the water storage height, and the unit is metre. σ_n is the root of the derivative for the first-order Bessel function, which is the root of the $J_1'(\sigma_n) = 0$ equation. The first six root values are 1.84, 5.33, 8.53, 11.71, 14.86 and 18.00 in turn.

The theoretical formula is used to calculate the first-order period of liquid-containing sloshing under various working conditions. The values are shown in the brackets of the second column in Table 1. The numerical calculation results are similar to the theoretical calculation results. It shows that the established tank model is reliable. They are the basis for the correct analyses of the seismic time-history response of liquid sloshing for water tanks.

4 Seismic motion input

The dynamic characteristics of the liquid-containing structure differ from that of a general building structure. The impacts of the epicentre distance and the site type on the liquid-structure coupled system must be considered in the seismic response analysis. As such, seven natural seismic motions with amplitudes of about 100 gal during the Wenchuan earthquake's mainshock are selected for structural analysis. A gal is a unit of acceleration (cm/s^2). These seven natural seismic motions are labelled according to their collection locations and directions, as follows: HSDB-EW, JZGYF-NS, PJW-NS, BJ-EW, CC-NS, YL-NS and HX-NS. The time intervals of all seismic motions are 0.005 s, and the time lengths of all natural seismic ground motions are taken as 30 s. The predominant periods of seismic ground motions are obtained by Fourier transformation. Table 2 lists details of the seismic ground motions, and Figure 2 shows the time-history curves of the HSDB-EW and HX-NS seismic ground motions which are selected as examples.

Table 2 Basic information of the selected seismic ground motions.

Name	Site condition	Collecting stations	Epicentral distance (km)	Peak acceleration (gal)	The moment of peak acceleration (s)	Predominant period (s)
HSDB-EW	II class	Sichuan Province	125.9	-102.643	6.160	0.095
JZGYF-NS	II class		263.3	100.224	18.425	0.168
PJW-NS	II class		81.0	101.149	10.105	0.297
BJ-EW	III class	Shanxi Province	513.1	120.292	15.720	0.611
CC-NS	III class		528.6	107.719	14.980	1.138
YL-NS	III class		569.9	-94.005	16.730	1.862
HX-NS	III class		599.0	92.090	13.835	4.096

Fig. 2 Time-history curves of the seismic ground motions. (a) HSDB-EW seismic ground motion and (b) HX-NS seismic ground motion.

5 Sloshing wave height of the liquid surface

5.1 Theoretical calculation

Calculation formulas for the sloshing wave heights of liquid surfaces have been provided by Professor Housner [2] and they are provided in the Japanese welded steel tank standard JIS B 8501 [4] and the U.S. Atomic Energy Commission TID7024 standard [3]. Because Professor Housner's calculation formula is practical and continues to be widely used, this formula is used in this paper to perform the theoretical calculations of the sloshing wave height. This calculation formula is shown in Eq. (3):

$$h = 0.837R\beta_1 k \quad (3)$$

where R is the inner radius of the tank (m). β_1 is the dynamic coefficient corresponding to the basic sloshing period T_1 , the value of which is determined according to the β spectrum with a 0.16% damping ratio for each seismic motion, which is listed in the β_1 row of Table 3. The letter k represents the horizontal seismic coefficient corresponding to the fortification intensity, for which 0.1 is taken at 7° , 0.2 is taken at 8° and 0.4 is taken at 9° [15].

Table 3 The result of β_1 , h_T , and h_A under seismic actions with 100 gal peak acceleration.

Condition	Parameter	Seismic motion input						
		HSDB-EW	JZGYF-NS	PJW-NS	BJ-EW	CC-NS	YL-NS	HX-NS
A-10%	β_1	0.043	0.092	0.056	0.057	0.054	0.165	0.164
	h_T	0.024	0.052	0.032	0.032	0.030	0.093	0.093
	h_A	0.074	0.112	0.162	0.154	0.249	0.345	0.339
A-30%	β_1	0.055	0.137	0.143	0.088	0.268	0.977	0.394
	h_T	0.031	0.077	0.081	0.049	0.151	0.552	0.223
	h_A	0.101	0.163	0.233	0.201	0.466	1.504	0.586
A-50%	β_1	0.064	0.154	0.370	0.261	0.441	0.559	0.807
	h_T	0.036	0.087	0.209	0.148	0.249	0.316	0.456
	h_A	0.109	0.203	0.487	0.348	0.589	0.736	0.946
A-70%	β_1	0.082	0.148	0.377	0.344	0.609	1.020	0.721
	h_T	0.046	0.083	0.213	0.194	0.344	0.576	0.407
	h_A	0.115	0.151	0.461	0.393	0.860	1.259	0.910
B-70%	β_1	0.149	0.142	0.497	0.307	0.335	0.944	1.233
	h_T	0.054	0.051	0.179	0.111	0.121	0.340	0.444
	h_A	0.113	0.114	0.398	0.220	0.484	0.943	1.075
C-70%	β_1	0.062	0.111	0.074	0.061	0.104	0.377	0.261
	h_T	0.070	0.125	0.084	0.068	0.118	0.426	0.295
	h_A	0.158	0.259	0.267	0.223	0.275	0.958	0.717

According to the calculated dynamic coefficient β_1 , the theoretical maximum sloshing wave heights of each working condition under seismic ground motions with 100 gal peak acceleration is calculated by using Eq. (3), and the results are listed in the h_T row of Table 3.

5.2 Numerical simulation calculation

The unidirectional horizontal seismic actions in the liquid-structure coupled tanks are analysed under X-direction input with modulated peak amplitudes of 100 gal, 200 gal and 400 gal. The distribution of the sloshing wave height is analysed by collating the calculation results. The sloshing wave height indicates the liquid surface's sloshing degree, which affects the hydrodynamic pressure distribution directly.

The maximum and minimum values of the vertical displacement for the liquid surface are equal at each moment of the unidirectional horizontal seismic actions with different peak accelerations. When only the peak acceleration of the seismic ground motion is changed while the other conditions remain unchanged, the liquid surface's sloshing wave height increases with increasing peak acceleration in multiples. The growth multiple is

the seismic coefficient k , and the moment at which the maximum sloshing wave height appears is precisely the same, as shown in Figure 3. Based on the above characteristics of liquid sloshing and considering the limitations in this thesis's scope, only the maximum sloshing wave heights of the liquid surface is analysed under the HSDB-EW and HX-NS seismic ground motions with a peak acceleration of 100 gal.

Fig. 3 The maximum and minimum sloshing wave heights for the A-70% condition.

Figure 4 shows the time histories of the maximum sloshing wave height for a liquid surface under long- and short-period seismic ground motions. For the same seismic ground motion and different water storage heights, the liquid surface's maximum sloshing wave height has no apparent change in law. The sloshing responses at different storage heights differ due to the other seismic motion inputs. Figures 4a and 4b show that the liquid in the tank sloshes more violently under long-period seismic ground motion than under short-period seismic ground motion. The maximum sloshing wave heights of different working conditions under the seismic actions with 100 gal peak acceleration are calculated using ADINA and are listed in the h_A row of Table 3.

Fig. 4 Time-history curves of the maximum sloshing wave heights for tank A. (a) HSDB-EW seismic ground motion and (b) HX-NS seismic ground motion.

5.3 Results comparison

From the analysis results of the sloshing wave height, it can be observed that the plane positions of the maximum and minimum sloshing wave heights under different seismic ground motions are near the centre or the circumferential radius, and their spatial positions indicate the direction of the ground motion input. The first three-order modal shape of liquid sloshing under different conditions are similar. When the tank radius is

the same, and the water storage heights are different, the sloshing shapes of the liquid surface in the maximum wave height moment are basically the same. When the water storage height is the same and the tank radii are different, the sloshing shapes of the liquid surface in the maximum wave height moment are also basically the same under long-period seismic ground motions. In addition, the position of the maximum wave height is usually at the circumferential radius, and the sloshing amplitude of the liquid surface is larger than that under short-period seismic ground motions. Figure 5 shows plots of the theoretical and ADINA calculation results for the maximum sloshing wave height of the liquid surface in each condition.

Fig. 5 Theoretical and ADINA calculation results of the maximum sloshing wave height. (a) A-10% condition, (b) A-30% condition, (c) A-50% condition, (d) A-70% condition, (e) B-70% condition and (f) C-70% condition.

It can be seen from Figure 5 that the maximum wave height calculation results obtained using ADINA numerical simulation are larger than the theoretical calculation results regardless of the water storage height, the tank radius, or the long- and short-period seismic ground motions, but the changing trends are basically the same.

Under short-period seismic motion actions, the wave heights obtained by the ADINA numerical simulation are not much different from the theoretical results. Due to the large periodic component of seismic ground motion, large-amplitude sloshings of liquid surfaces occur under long-period seismic actions. The numerical simulation results are much larger than the theoretical results, i.e. the maximum ratio between the two approaches eight. The calculation formula for the liquid-surface sloshing wave height derived by Housner assumes that the liquid-containing structure is rigid and the liquid surface exhibits a linear small-amplitude motion. However, the actual liquid sloshing will not be completely linear. For a large-amplitude motion of the liquid surface under long-period seismic actions, the nonlinear effect is enhanced. Therefore, using Eq. (3), the maximum sloshing wave of a free surface is predicted to be unsafe. The sloshing amplitude of the liquid surface under long-period seismic actions is underestimated.

6 Calculation formula fitting of sloshing wave height

The maximum sloshing wave height of the liquid surface under seismic ground motions has significant relationships with seismic coefficient, ground motion characteristic, tank radius and liquid sloshing frequency. The calculation formula of the maximum sloshing wave height for the liquid-containing structure is fitted based on the ADINA calculation results and the theoretical calculation formula. The maximum sloshing wave height data under unidirectional seismic actions with 100 gal peak acceleration are used to fit the formula with the above analyses. The $R\beta_1 k$ value of each condition is calculated first. And Figure 6 shows a plot of the two-dimensional distribution of the $R\beta_1 k$ value and the maximum sloshing wave height h .

Fig. 6 Two-dimensional distribution of h and $R\beta_1 k$ values.

It can be seen from Figure 6 that the maximum sloshing height h of the liquid surface in different conditions is approximately positively correlated with $R\beta_1 k$, and that the h and $R\beta_1 k$ in the calculation formula given by Housner have a linear relationship. The relationship between h and $R\beta_1 k$ in Figure 6 is fitted as follows:

$$h = 1.896R\beta_1 k \quad (4)$$

Eq. (4) is the formula for calculating the maximum sloshing wave height of the liquid surface, for which the linear correlation coefficient is 0.956, and the standard deviation is 0.063.

The effect of the damping ratio on liquid sloshing is not negligible. The smaller is the damping ratio, the

larger is the dynamic amplification factor of the sloshing vibration. The damping of the liquid is much smaller than that of the structure. The damping-ratio correction coefficient C of the design response spectrum relative 5% damping ratio is specified in the Japanese equipment seismic standard, as shown in Table 4, and the seismic response increases as the damping ratio decreases.

Table 4 Damping ratio correction coefficient C of the design response spectrum.

Damping ratio ξ	30%	20%	10%	5%	3%	2%	1%	0.5%
Correction coefficient C	0.44	0.56	0.78	1.00	1.18	1.32	1.53	1.79

The dynamic amplification factor corresponding to a 0.5% damping ratio is 1.79 times as shown in Table 4. The sloshing damping ratio of water measured by Tianjin University in China in a simulation test was 0.16%. The response spectra of different damping ratios recorded during several typical earthquakes are compared in the text by compile a group of earthquake engineering. The zero damping response spectrum was found to be about 1.5 to 3 times that of the damping ratio of 5%. To obtain the correction coefficient for a 0.16% damping ratio, data with damping ratios $<5\%$, as shown in Table 4, were fitted, and the following fitting Eq. (5) obtained:

$$C = 1.081 \cdot e^{-53.76\xi} + 0.9393 \quad (5)$$

Eq. (5) calculated that the correction factor for the 0.16% damping ratio is 1.931. The zero damping ratio's correction factor is 2.02, which is consistent with the conclusions reported in the literature.

According to the above analyses, the 5% damping ratio long-period response spectrum shown in Figure 7 can be used to design the sloshing wave height of a water storage tank under unidirectional ground motion. Simultaneously, the response spectrum value can be corrected according to the water sloshing damping ratio. That is, the damping coefficient directly increases 1.931 times based on the 5% response spectrum value. Thus, Eq. (4) becomes Eq. (6).

$$h = 3.662R\beta_1k \quad (6)$$

Fig. 7 Long-period seismic design β spectrum with 5% damping ratio.

When using Eq. (6) to calculate the sloshing wave height of a liquid surface for a liquid-containing structure under unidirectional seismic ground motion action, β_1 is directly obtained based on the long-period response

spectrum in Figure 7 according to the first-order sloshing period T_1 .

7 Sloshing height calculation in the ACI 350.3-01 code

The article R7.1 in the ACI 350.3-01 code [16] gives the calculation formula of sloshing wave height d_{max} of circular tank subjected to seismic action, as shown in Eq. (7).

$$d_{max} = (D/2)(ZSI \times C_c) \quad (7)$$

where D is the inside diameter of the circular tank, the unit is feet or metres.

Z is the seismic zone factor, from Table 5. The distribution of seismic zone is given on the map of the U.S.

S is the site profile coefficient representing the soil characteristics as they pertain to the structure, from Table 6.

I is the importance factor, from Table 7.

C_c is the spectral amplification factor. When the natural period T_c of the first (convective) sloshing mode is >2.4 s, C_c is equal to the ratio of 6.0 to the square of T_c .

Table 5 Seismic zone factor Z .

Seismic map zone	1	2A	2B	3	4
Factor Z	0.075	0.15	0.2	0.3	0.4

Table 6 Soil profile coefficient S .

Type	Soil profile description	Coefficient
A	A soil profile with either: (a) a rock-like material characterised by a shear wave velocity >2500 ft/s (762 m/s), or by other suitable means of classification; or (b) medium-dense to dense or medium-stiff to stiff soil conditions where the soil depth is <200 ft (60,960 mm)	1.0
B	A soil profile with predominantly medium-dense to dense or medium-stiff to stiff soil conditions, where the soil depth exceeds 200 ft (60,960 mm)	1.2
C	A soil profile containing >20 ft (6096 mm) of soft to medium-stiff clay but not >40 ft (12,192 mm) of soft clay	1.5
D	A soil profile containing >40 ft (12,192 mm) of soft clay characterised by a shear wave velocity <500 ft/s (152.4 m/s)	2.0

Table 7 Importance factor I .

Tank use	Factor I
Tanks containing hazardous materials	1.5
Tanks that are intended to remain usable for emergency purposes after an earthquake or tanks that are part of lifeline systems	1.25
All other tanks	1.0

From Eq. (7), it can be seen that the maximum wave height of liquid sloshing in liquid-containing structures calculated by the American code takes into account the structure size of the tank, seismic map zone, site profile,

structural importance and the spectral amplification effect corresponding to the first sloshing period. Eq. (7) covers various types of liquid-containing structures, and Eq. (6) established in this paper is only for reinforced concrete liquid containing tanks in water supply systems. In Eq. (7), the influence of seismic action on liquid sloshing is divided into three aspects of parameters Z , S and C_c . In Eq. (6), the effect of parameter k and Z in Eq. (7) is the same, and parameter β_1 comprehensively characterises the effect of parameter S and C_c . The sloshing wave height is calculated and compared in Table 8, assuming that the soil profile type is A, so soil profile coefficient S is 1.0. The water tanks are parts of lifeline systems, so the importance factor I is 1.25. The ground characteristic period T_g is 0.20 s. When k or Z changes, the parameters h and d_{max} change proportionally, so only when $k=Z=0.075$ is calculated here.

Table 8 Calculation results of h and d_{max} when $k = Z = 0.075$.

Condition	A-10%	A-30%	A-50%	A-70%	B-70%	C-70%
h	0.034	0.088	0.134	0.171	0.211	0.114
d_{max}	0.013	0.037	0.059	0.078	0.109	0.046
h/d_{max}	2.626	2.360	2.252	2.191	1.941	2.476

It can be seen from the calculation results in Table 8 that the maximum sloshing wave height of the liquid surface obtained by both calculation methods has the same order of magnitude, and h is about twice that of d_{max} . The main reason for the above differences is that many parameters cannot be accurately determined due to the limitation of known conditions, and their values are determined by the estimation method. In the seismic design of liquid-containing structures, Chinese codes are relatively more conservative. When all conditions are known, there are still some differences between the calculation results due to the different expressions of various factors on liquid sloshing used in the two methods. The main difference exists in the seismic design concept of liquid-containing structure.

8 Conclusions

The dynamic characteristics and seismic responses of the ground-rested circular reinforced concrete tank are researched. Based on the calculation results of the sloshing responses with different water storage heights and different tank radii, the calculation formula for the maximum sloshing wave height of a liquid surface under unidirectional horizontal seismic actions is fitted, and the obtained formula has a good estimation effect for long- and short-period seismic actions. The maximum sloshing wave height of a liquid surface is proportional to the tank radius, the ground motion amplification factor and the seismic coefficient. Combining the long-period seismic design spectrum and the damping ratio correction coefficient, the calculation method for the maximum sloshing wave height is proposed based on the seismic design response spectrum 5% damping ratio. Because of the current research comparison, the Chinese code is more conservative than the American code in calculating the sloshing wave height of liquid-containing.

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