Scholars Journal of Engineering and Technology (SJET) **ISSN 2321-435X (Online)**
Sch. J. Eng. Tech., 2016; 4(4):175-184 **ISSN 2347-9523 (Print)**
©Scholars Academic and Scientific Publisher
(An International Publisher for Academic and Scientific Resources)
www.saspublisher.com

Research Article

Dynamic Response Research of the Framed Spherical Tank Seismic Subsructure with Liquid Sloshing

Zhou Li-jian, Sun Ming-yang, Wang Xue
College of Civil Engineering, Northeast Petroleum University, Daqing, 163318, China

***Corresponding author**
Zhou Li-jian
Email: 1152948120@qq.com

Abstract: In recent years, the frequency that the earthquakes occur shows a tendency of rising, and the importance of the seismic method is increasing gradually. Towering framed structure as a very important special structure, the application amount is large and the field of usage is wide, and its future will develop for the deriction of large and high. Adopting the finite element analysis software ADINA, this paper established the framed spherical storage tank that height was 52m, modal calculation was proceeded for structures, which structures have different in reservoir volume, respectively 0%, 50% and 85%. Comparing the modal analysis of framed spherical tank in four methods, known that the natural vibration period was most chose to the reality in method two. Determined the structure of the Rayleigh damping factor. Because under earthquake, the liquid sloshing had influence on structure, did time history analysis. It proved that the liquid sloshing had the shock absorption effect on the dynamic response of the structure, it cannot be ignored.
Keywords: framed spherical tank, liquid sloshing, time history analysis, modal analysis, damp.

INTRODUCTION

Frame structure is a kind of the special structure, It uses a lot, it will improve to be larger and higher in the future. Spherical tank has many superior performances; it has a large number of applications in the field of petroleum chemical industry and environmental protection. Liquid sloshing is a typical nonlinear problem. Coupled with the viscous effect, the liquid sloshing problem is more complex, over the years; many scholars have conducted a lot of research on this question [1-10].

This paper established the finite element model by using software ADINA [11]. By the natural vibration periods that calculated in method 1, correction method 1, method 2 and equivalent quality standard, we concluded that liquid sloshing effect on structure should not be neglected, and got the most appropriate structure simplified model through the comparison and analysis. Analyzed and discussed the different structural damping with kinds of reservoir column, determined the structure of the Rayleigh damping factor. Under 8 degree frequency earthquake, calculated the dynamic response of structures. The time history analysis proved that the liquid sloshing had the obvious shock absorption effect on the dynamic response of the structure, it cannot be ignored.

Basic parameters of model

Framed spherical tank support structure and shell used the steel of Q235 - grade B degree, the liquid in tank was water, and other material parameters were shown in table 1. The bottom of the pillar of framed spherical tank and foundation contact as rigid connection, regardless of the relationship between pillar and foundation. Adopting all constraint in 6 freedom degrees, liquid surface set as free surface. The data in the model in this paper mainly adopted the reference [11], considering coupling of tank wall and liquid. Put the gravity load -g of z direction on the framed storage tank.

Table 1: Storage tank material parameters

material	Parameter	Value of number
Steel of Q235-B level	density（kg/m3）	7850
	elasticity modulus（N/m2）	2.06×1011
	Poisson's ratio	0.3
water	density（kg/m3）	1000
	elasticity modulus（N/m2）	2.18×109

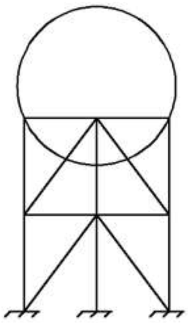
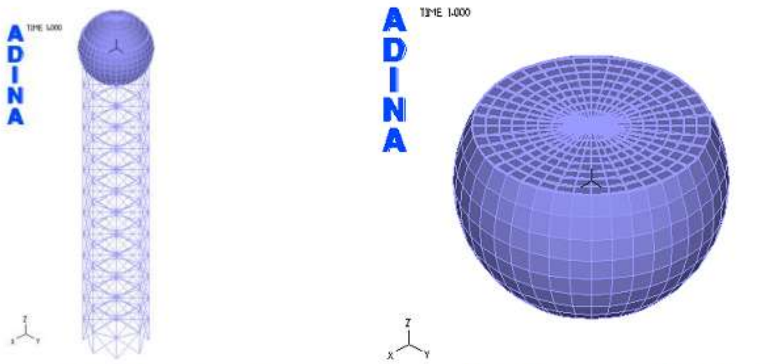


Fig-1: Structure diagram



(a) Spherical tank model (b) liquid model in tank (85%)

Fig-2: spherical tank finite element model

Liquid sloshing

1. The mathematical model of liquid sloshing

The liquid sloshing with free liquid surface in liquid storage tank was solved by adopting turbulence model in ADINA. The Navier - Stokes equations in the no inertial system of coordinate, using VOF (Volume of Fluid) method to track the free surface of the liquid.

Assumed that under the action of earthquake, storage tank only had horizontal movement. If the coordinate system on the framed spherical tank, under the noninertial system of coordinate, the domestic demand equation and momentum equation of the liquid in storage tank they were as follows:

$$\nabla \cdot U = 0 \tag{1}$$

$$\rho \frac{DU}{Dt} = -\nabla P + \rho\left(f - \ddot{x}^t\right) + \nabla \cdot 2\mu\left[\dot{\varepsilon}_{ij}\right] + \nabla\left(\lambda \nabla \cdot U\right) \tag{2}$$

Which, f -mass force, $f_x = 0$, $f_y = 0$, $f_z = -g$, g -acceleration of gravity, $\ddot{x}^t$ -the total acceleration of storage tank horizontal movement, the meaning of the other physical quantities query literature check the reference[12].

VOF method based on the volume ratio function to construct and to track the free surface. If $F = 1$, indicate that the unit dominated by making phase fluid. If $F = 0$,This unit was no specified phase fluid unit. If $0 < F < 1$, the unit was called interface unit.

Transmission equation of VOF method in conservation form was expressed as follows:

$$\frac{\partial F}{\partial t}+\nabla\cdot(FU)=0 \tag{3}$$

2. The swinging force of liquid

When liquid in the tank was shaking, the resultant force that liquid made pressure on tank wall is not 0,the resultant force was swinging force. Liquid swinging force can be obtained by integral of the storage tank wall pressure in different times.

$$F_w=\iint_s pd_s \tag{4}$$

3. The calculation of natural vibration period

3.1 revised specification

Compared this paper with reference [13], we found that the sizes of two models were closed, so we can conclude that the natural vibration periods were closed too. We know, it cannot be ignored that diagonal brace and horizontal support in the structure have a great influence on the whole structural support. Modified the standard by adopting framed spherical tank horizontal displacement simplified calculation method in reference [14].

In fig. 4, EI_{ci} -equivalent bending stiffness of i layer, I_{ci} -algebraic sum that moment of inertia which single column section rounds itself axis produced projected to support section calculation axis. Pillar calculation based on different position, found that because pillar adopted circular cross section, moment of inertia of each column were same. The equivalent moment of inertia for pillars between the layers was shown as follows.

$$I_C=2I_1+4I_2+2I_3=8I$$

Reference[14],a layer of ring beam's contributions to the displacement calculation is:

$$\Delta\delta''=\sum\int\frac{M_y^2}{EI_b}\mathrm{d}s \tag{5}$$

Considering both of them were equal, as $\Delta\delta'=\Delta\delta''$, known about η. According to the three dimensional finite element analysis results, solved that $\eta=1200$ by the above principles.

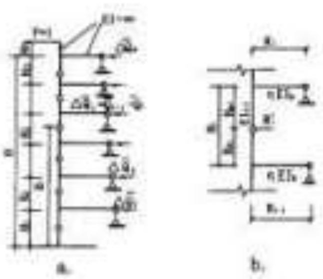


Fig-3: simplified analysis model

According to the simplified model, under top horizontal unit force, its horizontal displacement is

$$\delta = \sum_{i=1}^{n} \frac{Q_i}{3EI_{ci}} \left(H_{di}^3 + H_{ui}^3 \right) + \sum_{i=1}^{n=1} \frac{R_i}{8\eta EI_b} \bullet \left(Q_{i+1} H_{di+1} + Q_i H_{ui} \right) \quad (6)$$

3.2 Method two

According to the calculation method of the seismic response analysis and examples, solved the model the natural vibration period in this paper. In this method, simplified framed spherical storage tank for the two mass points, divided the framed spherical storage tank structure into two parts, the free water and fixed water, the influence ratio of fixed water and free water obtained according to the next formula:

$$W_D = \left(\frac{T_F^2}{T_{F_0}^2} - 1 \right) W_0 \quad (7)$$

Which, W_0—the weight of frame (including the tower), T_{f0}—inherent period of framework when framed spherical tank without water, T_f—inherent period of framework when framed spherical tank fulls of water, W_D—weight of fixed water.

Calculating natural vibration period starting from the basic formula of forced vibration, the movement equations (8) and (9) was set up.

$$\mathrm{m}_1 \ddot{y}_1 + C_1 \dot{y}_1 + k_1 y + k_2 (y_1 - y_2) = -m_1 \ddot{y}_0 \quad (8)$$

$$\mathrm{m}_2 \ddot{y}_2 + k_2 (y_2 - y_1) = -m_2 \ddot{y}_0 \quad (9)$$

Based on modal analysis method, ignored damping and forced term, and considered the free vibration.Take a fixed value of the matrix $M^{-\frac{1}{2}} K M^{-\frac{1}{2}}$ is λ.and the inherent period was next formula.

$$T = 2\pi \lambda^{-\frac{1}{2}} \quad (10)$$

3.3 Equivalent quality standard

In general references, all see the liquid as the form of equivalent mass and attach it to the spherical shell wall, this method that ignores liquid sloshing caused great errors on the result. This article, first of all, used equivalent mass method to establish the finite element model, and calculated the natural vibration frequencies of spherical tanks which one had 50% water and other had 85% water, as shown in table 2.

Table 2: Equivalent quality standard under different reservoir model first ten order natural frequency

number of frequency		1	2	3	4	5	6	7	8	9	10
50% water	frequency（Hz）	0.5288	0.5288	1.6165	5.004	5.004	5.3462	9.0318	9.0318	11.851	15.224
	period（s）	1.891	1.891	0.619	0.200	0.200	0.187	0.111	0.111	0.084	0.066
85% water	frequency（Hz）	0.4303	0.4303	1.3143	4.3412	4.3711	4.3711	8.3712	8.3712	11.77	15.115
	period（s）	2.324	2.324	0.761	0.231	0.229	0.229	0.119	0.119	0.085	0.066

3.4 The analysis of natural vibration period

The first order period of the finite element mode is the basic natural vibration period the structure. With the above several methods, comparing the results as shown in table 3.

Table 3: All kinds of method to calculate tall the natural vibration period of framed storage tank

	Model of this paper	Equivalent quality method		Method 1		revised method1		Method 2	
Amount of liquid storage	period(s)	period (s)	error(%)	period (s)	error(%)	period (s)	error(%)	period (s)	error(%)
0%	0.983	0.983	0	1.082	10.07	1.088	10.68	1.437	54.68
50%	2.706	1.891	30.12	2.233	17.48	2.245	17.04	2.864	5.84
85%	3.474	2.324	33.10	2.767	20.35	2.782	19.92	3.525	1.47

Based on the above several methods, compared and got the following conclusions:

(1) Method 2 focuses on full tank status to calculate, so when tank is full of water, data error is very small, and when tank without water, it exists a relatively large error. The rules that can get from other data are that with the increase of liquid, the period becomes larger. Compared with model, when liquid has in tank, method 2 is closest to the model data and errors are very small and revised method 1 behind method 2. When under empty cans, the equivalent quality method is closest to the model data, when calculating the empty cans, method 1 can be selected for calculation.

(2) The error of equivalent quality method is more than 30%, and when tank has water, the errors of method 1 (specification) and revised method 1 are about 20%. It illustrates that after considering the liquid sloshing, the natural vibration period of spherical tank has increased, although the structure is very high, the influence of liquid sloshing on the period can’t be ignored.

(3) Method 2 according to the formula (1) divided the liquid into two parts that are the free water and fixed water and divided the equivalent mass, fully considered the liquid sloshing factors, and analyze the influence which the different heights of water affect on the natural vibration period. Compared with method 1, method 2 is more accurate, the calculation results of tank with water are more closed. Finite element model compared with the specifications and the reference, and analyzed the results, fully verified the reliability of the finite element model in this paper.

Determination of the framed spherical tank damping

In structural dynamics equation of dynamic analysis, the damping as part of the indispensable important moment exists. Based on structural dynamics equation, we got the first j mode shape eigenvalue and modal vector were ωj and Φj. Proceed modal orthogonality for equation, both sides divided the modal mass at the same time, the power that system according to the first j order modal vibration shakes one week lost is ΔWr, the displacement vector of system is xj and the biggest deformation energy of the j vibration mode is Ur, damping ratio can be expressed by energy,

$$\xi_j = \frac{\Delta W_r}{4\pi U_r} \tag{11}$$

Damping model is established through the damping ratio, the damping coefficient in structural dynamic analysis can't be analyzed. We need to build a structural damping model combined with dynamics; it can be the very good application in structural analysis. It can be seen from the structural dynamic equation, the simplest way that establishes the equivalent viscous damping matrix is to use simple Rayleigh damping to express:

$$[c] = a_0[m] + a_1[k]$$

Introducing the modal damping ratio($C_n = 2\omega_n M_n \xi_n$) , n order vibration mode for equivalent damping ratio of n order vibration mode can express,

$$\xi = \frac{a_0}{2\omega_n} + \frac{a_1\omega_n}{2}$$

Assumed that damping ratio of every order is same, as $\xi_i = \xi_j = \xi$,we can get the undetermined coefficients,

$$\begin{bmatrix} a_0 \\ a_1 \end{bmatrix} = \frac{2\xi}{\omega_i + \omega_j} \begin{bmatrix} \omega_i\omega_j \\ 1 \end{bmatrix}$$

a_0, a_1-the quality damping and stiffness damping of structure, When the viscosity damping as a major factor,a_0 has a specified value. Framed spherical tank model in this paper only considers stiffness damping a_1.It represents the intrinsic characteristics of most materials, regulate for each material (as DAMP material properties), or as a single value.a_1 can be calculated by a known damping ratio ζ and the main first order natural vibration frequency ω.

$$\beta = {}^{2\zeta}\!/_{\omega} \tag{12}$$

Because tank and reservoir fluid solid have coupling effect, the first order natural vibration period is more close to a l rigid structure. The values of a_1 in equivalent quality method and the liquid sloshing model of this paper, so that when the earthquake response analysis, it is convenient for liquid sloshing model analysis under earthquake excitation. By looking at the standard for seismic design of buildings, the steel structure in calculation under frequency earthquake, which height is between 50 to 200 m, damping ratio is 0.03.Under rare earthquake, the damping ratio is 0.05.

Table 4: Damping of framed spherical tank

Amount of liquid storage	the first order frequency ω	The finite element mode lβ		Equivalent quality model β	
		frequency	rare	frequency	rare
0%	1.0173	0.0094	0.0156	0.0094	0.0156
50%	0.3695	0.0259	0.0431	0.0187	0.0312
85%	0.2879	0.0332	0.0553	0.0231	0.0385

5 Time history analysis of the framed spherical tank considering sloshing

In order to study the dynamic response of spherical tank under seismic excitation, and different ground motion, different height and different quantity of liquid storage effects on structural dynamic response. This article selects four kinds of seismic analysis of structure, respectively is: El-centro wave, Taft wave, Tianjin Ninghe wave and Qianan wave.

According to the fortification intensity of 8 considerations, when we importing four types of seismic waves. design basic earthquake acceleration is 0.20g, multiple, severe earthquake peak acceleration of 0.7 m/s^2.

5.1 Time history analysis of the displacement

Table 5: Maximum vertex horizontal displacement considering the liquid sloshing under different amount of liquid storage

amount of liquid storage		El-centro wave		Taft wave		Tianjin Ninghe wave		Qianan wave	
		Non sloshing	sloshing	Non sloshing	sloshing	Non sloshing	sloshing	Non sloshing	sloshing
50%	Displacement(mm)	36.80	15.10	32.23	23.21	69.11	63.02	7.83	3.58
	time(s)	15.54	16.06	14.22	19.56	18.16	18.00	15.36	13.00
85%	displacement(mm)	46.20	22.29	26.72	23.22	66.29	68.73	8.53	5.79
	time(s)	15.66	17.24	14.32	14.22	18.24	18.16	18.38	23.28

Without considering the model of the liquid sloshing, vertex displacement vibration range is widely larger than liquid sloshing model. When considering the liquid sloshing, under the effect of four kinds of seismic waves, the vertex displacement of the framed spherical tank increases with the reservoir. After considering the liquid, vertex displacement of all the models decline .Different seismic wave excitation leads to the different scaffolding dynamic response of spherical storage tank. Under the action of Tianjin wave, vertex displacement peak is the largest; qianan wave's minimum vertex displacement is minimum. And under the same action of seismic wave, different liquid storage quantity result in changes of quality and level, and also affects the vibration characteristics of structure.

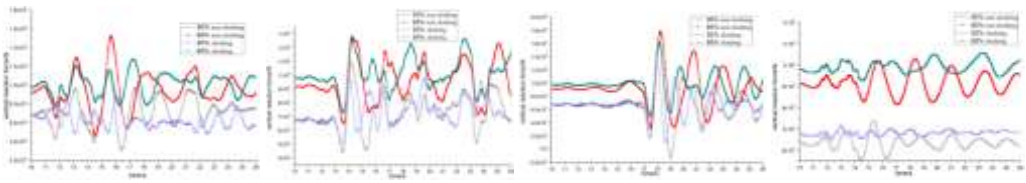
5.2 Time history analysis of the acceleration

Table 6 Maximum peak horizontal acceleration considering the liquid sloshing under different amount of liquid storage

amount of liquid storage		El-centro wave		Taft wave		Tianjin Ninghe wave		Qianan wave	
		Non sloshing	sloshing	Non sloshing	sloshing	Non sloshing	sloshing	Non sloshing	sloshing
50 %	acceleration (m/s^2)	0.856	0.936	0.932	1.008	-1.374	-1.448	0.722	0.752
	time(s)	12.14	12.14	14.2	16.64	18.22	18.6	11.86	11.86
85 %	acceleration (m/s^2)	0.775	0.836	0.864	0.866	-1.308	1.228	0.730	0.746
	time(s)	12.14	12.14	16.64	19.82	17.56	17.56	11.86	11.86

Without considering the liquid sloshing model, the peak acceleration vibration range is widely smaller than liquid sloshing model, but not big. under four farming vibration ,the peak acceleration decrease with the reservoir volume increasing .Applying the maximum value of seismic waves is 0.7 m/s$^{2.}$ from the above table, the vertex maximum acceleration of structure are enlarged and accumulated in different levels, which improves that the acceleration amplification coefficient changes with the seismic response types. Because the hight of the structure, amplification effect is obvious, and the acceleration amplification coefficient of without considering the liquid sloshing model range from 1.07 to 1.64. When considering the liquid sloshing, Peak acceleration change at the same change trend. Increase due to reservoir, the structure of weight increase, the liquid itself under the earthquake response of structure has a certain effect of energy consumption. Although the maximum position may be slightly different, but the trend of vibration and seismic waves conform to the well.

5.3 Time history analysis of the vertical force

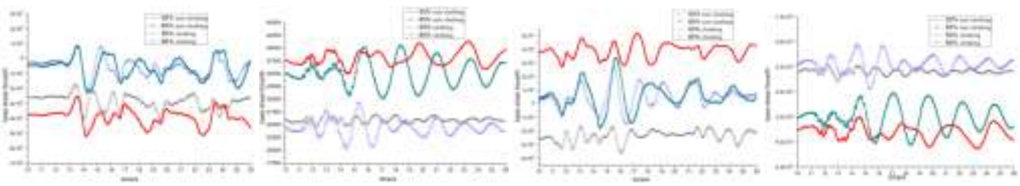


(a) El-centro wave (b) Taft wave (c) Tianjin Ninghe wave (d) Qianan wave

Fig-4: Time history curve of the vertical force

As seen from the figure 3-a under the action of El-centro wave, the column bottom vertical reaction force of 50% reservoir volume is widely larger than the 85% models, the result is larger without considering the liquid sloshing model. With the increasing of the reservoir volume, natural vibration period extends and the change is weakened. Under the action of Tianjin Ninghe wave, the maximum vertical reaction was biggest in 85% reservoir volume model, calculated that the maximum vertical stress reached 99MPa, meet the design requirements. When without liquid sloshing in El-centro wave and Qianan wave, the amount of change of vertical reaction force of 85% reservoir volume is larger than 50%,In Taft wave and Tianjin Ninghe wave action, the the amount of change of vertical reaction force of 85% reservoir volume is smaller than 50%.In the case of liquid sloshing, El-centro wave and Tianjin Ninghe wave under 85% liquid storage quantity change than 50% under the situation. qianan waveunder 85% liquid storage quantity, the liquid sloshing in the vertical reaction force increases, the fluid dynamic magnification coefficient is 1.53.Conclusion: even in more than 50m liquid storage tank, influence of liquid sloshing in a single reaction is still big, and cannot be ignored, but the change in size and liquid storage quantity had no obvious relationship.

5.4 Time history analysis of the base shear force



(a) El-centro wave (b) Taft wave (c) Tianjin Ninghe wave (d) Qianan wave

Fig-5: Time history curve of the base shear force

With the increasing of the reservoir volume, under the effect of four kinds of seismic waves, the base shear force extends. under the action of El-centro wave, the base shear force is the biggest, is 1.66 times of the smallest one-Qianan wave's, the bottom of the relative shear force is 5.02 times of Qianan wave's. Considered the liquid sloshing model at the bottom of the shear force is the largest, reached 46.3kN, not considering the shear at the bottom of the model of liquid sloshing reached 68.6kN, relative to the bottom of the maximum shear are respectively 20.9kN, 31.0kN.By calculating maximum shear stress is 3.7MPa, whether is far less than the shear strength of 125MPa. Proved that the liquid sloshing increases shear at the bottom of the structures.

CONCLUSIONS

In this paper, using different specification of scaffolding analyzed the simplified model of the framed spherical tank and the finite element model for modal, studied the Rayleigh damping coefficient of the structure, and research time history analysis of the structure under frequent earthquakes, get the main conclusions:

1. with the increase of liquid storage quantity, natural period of vibration period. Compared with model, under the empty cans equivalent quality standard and model data closest to and are very small, method 1 times, while method 2 deviation; Under reservoir condition method 2 model next to the model.

2. Method 2 factors consider the liquid sloshing; the calculation results are more close to. Equivalent quality standard in reservoir condition cycle differ in more than 30%, that of the liquid sloshing increases the natural vibration period of spherical tank, although the towering structure, liquid sloshing is not negligible.

3. Through the study on the performance of the structural damping, liquid sloshing has great effect on damping.

4. Through to the vertex displacement, acceleration, vertical reaction force and shear force at the bottom—the four aspects of time history analysis. Known for framed spherical storage tanks, considering the liquid sloshing can reduce peak displacement and vertical reaction force, but enlarge the peak acceleration and bottom shear force, which will have energy dissipation damping effect to the whole structure. The structure of the dynamic response is associated with liquid sloshing, also related to the seismic wave, and should not be neglected.

REFERENCES

1. Housner GW; Dynamic Pressure on Accelerated Fluid Container. Bull. Seism. Soc. AM., 1957; 47(1): 15-35.
2. Housner GW; The Dynamic Behavior of Water Tanks. Bull. Seism. Soc. AM., 1963; 53(2): 381-387.
3. Froydis S, Oddm F; Combined Numerical and Analytical Solution for Sloshing in Two-Dimensional Tanks of General Shape. Journal of Ship Research, 1997; 41(2): 118-129.
4. Abramson HN; The Dynamic Behavior of Liquid in Moving Containers. Report SP 106 of NASA, 1996.
5. Huang ZJ, Hsiung CC; Nonlinear Shallow-Water Flow on Deck. Journal of Ship Research, 1996; 40(4): 303-315.
6. Jones AF, Hulme A; The Hydrodynamics of Water on Deck. Journal of Ship Research, 1987; 31(2): 125-135.
7. Koh HM, Kim JK, Park JH; Fluid-Structure Interaction Analysis of 3-D Rectangular Tanks by a Varationally Coupled BEM-FEM and Comparison with Test Results. Earthquake Engineer and Structural Dynamcis, 1998; 27: 109-124.
8. Ma QW, Wu GX, Eatock Taylor R; Finite Element Analysis of the Non Linear Transient Waves in Three Dimensional Long TANK//12th International Workshop on Water Waves and Floating Bodies, Carryle-Rouet, France, 1997.
9. Okamoto T, Kawahara M; Two-dimensional Sloshing Analysis by Lagrangian Finite Element Method. International Journal for Numerical Methods in Fluids, 1990; 11: 453-477.
10. Chunyu S; With free surface water body structure seismic response analysis method and its application. Shanghai Jiaotong University, 2008.
11. Bin G; The Seismic Behavior Analysis of Steel Structure Water-tower. Daqing: Northeast Petroleum University, 2014.
12. Davenport AG; Spectrum of Horiolntal Gustiness near the Ground in Strong Winds. Quart. J. R. Mct. Soc., 1961; 87(4): 194-211.

13. Chunyu S, Haijun Z, Jianguo Z; Research on Seismic Response of Ellipsoidal Water Tower Considering Water Sloshing. Steel Construction, 2010; 1(25):15-20
14. Junfa Z, Bo W, Dixiong Y; Horizontal displacement of scaffolding towers practical simplified calculation. Special Structures, 2004; 21(3): 39-41