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Study on the Influence of Earthquakes with Different Frequency Content on the Peak Liquid Sloshing Wave Height of Liquid Storage Tank

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Abstract. Liquid storage tank is an irreplaceable and extremely important vessel structure used to store liquid medium. In earthquake disaster, the liquid storage tank will not only be seriously damaged directly, but also cause serious secondary disasters, such as fire, explosion, poisoning, nuclear radiation, etc. The peak liquid sloshing wave height is an important reference index to judge whether the seismic design of the liquid storage tank is reasonable or not. The ratio of peak ground acceleration to peak ground velocity of the earthquake records (shown by A/V ratio) can well represent the characteristics of frequency content of earthquake records. In this paper, the finite element numerical simulation method is used to analyze the seismic response of six rectangular concrete tanks with different liquid heights, and their respective peak liquid sloshing wave heights are calculated. Nine seismic records with different A/V ratios are used, which are low frequency category, medium frequency category and high frequency category and there are three records in each category. At the same time, the equation in Eurocode 8 is used to calculate the peak liquid sloshing wave height of each tank for comparative study. The study results show that the peak liquid sloshing wave height calculated by the Eurocode 8 is greater than that calculated by the finite element method under low frequency and medium frequency earthquake records, indicating that Eurocode 8 is conducive to the preliminary design of the seismic performance of the liquid storage tank. However, in the case of high frequency earthquake records, the calculation result of the finite element method is larger than that of the equation in Eurocode 8. The peak liquid sloshing wave height of the liquid storage tank is more sensitive to the earthquakes with high frequency content, and the Eurocode 8 underestimates the impact of high frequency seismic response on the liquid storage tank.
Keywords: Seismic frequency; Liquid storage tanks; Finite element numerical simulation; Seismic performance.

1. Introduction

Liquid storage tank is an irreplaceable and extremely important vessel structure used to store liquid medium, which is widely used in petrochemical industry, military construction, nuclear energy, civil water, urban water and other related fields. At the same time, it is also one of the indispensable components of various lifeline projects in today's industrial society [1]. In severe destructive earthquake disasters, liquid storage tanks will not only cause severe direct damage, but also will be highly likely to induce more serious secondary disasters. For example, a large number of oil storage tanks were damaged and caused explosions and fires in the 1994 Niigata earthquake in Japan, a large number of water storage tanks were damaged in the 1976 Tangshan earthquake in China, causing drinking difficulties for residents, and the leakage of nuclear material storage tanks at the Fukushima nuclear power plant in the 2011 earthquake in Japan has now threatened the global ecological environment, etc [2-4]. The liquid medium in the storage tank will generate hydrodynamic pressure under the action of seismic force, compared with other solid structures, the damage mechanism of liquid storage tank under seismic force is relatively more complex. Therefore, the study on seismic response characteristics of liquid storage tanks is also one of the hot topics in the field of seismic engineering today.

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2. Review of the literature

Simplified mechanical model of liquid storage tank is an intuitive means to understand its corresponding characteristics under earthquake action. Westergaard [5] calculated the hydrodynamic pressure of the rectangular liquid storage tank for the first time and provided a mathematical and physical basis for them. Graham and Rodriguez [6] divided the hydrodynamic pressure of the liquid storage tank into impulsive pressure and convective pressure. Housner [7] putted forward a simplified mechanical model of liquid storage tank based on the two-particle theory of rigid tank wall and tank bottom based on the previous research results. After fully considering the theory of flexible tank wall and liquid-structure coupling interaction, Haroun and Housner [8] divided the liquid in the tank into convective component, flexible impulsive component and rigid impulsive component, and proposed a three-particle simplified mechanical model for liquid storage tank. Based on the development and perfection of simplified mechanical models for different types of liquid storage tanks, various countries have successively formulated seismic design codes for them to improve the seismic performance. The widely used seismic design codes worldwide include Eurocode 8 in Europe, GB50341 in China, API650 in America and JIS-B8501 in Japan , etc [9-10].

Earthquake records with different source distances will show different frequency content characteristics. The damage degree of earthquakes with different frequency content to various structures, including liquid storage tanks, is different. In particular, the hydrodynamic pressure of the liquid in the storage tank is also extremely sensitive to the frequency content [11]. The seismic design codes mentioned above specifies the maximum sloshing wave height threshold of contained liquid in various storage tanks, and provides the formula for calculating the maximum value, however, the influence of earthquake frequency content on it is not well considered [12]. Overestimating or underestimating the maximum sloshing wave height of the liquid will misjudge the the risk level of the liquid storage tank in the earthquake disaster, resulting in resource waste and property loss indirectly.

This paper intends to select earthquake records with different frequency contents, carry out finite element numerical simulation analysis for rectangular concrete liquid storage tanks with different liquid heights and internal diameter ratios, get the influence characteristics of earthquake records with different frequency contents on the maximum liquid sloshing wave height, and compare the calculation results with those in seismic design codes, so as to provide theoretical basis and suggestions for seismic design of liquid storage tanks in the future.

3. Establishment of finite element models

The finite element numerical simulation analysis software used in this paper is ANSYS, the version of the software is 18.2. The element used to model the tank wall and tank bottom is PLANE 42, which is mainly used for two dimensional modeling of solid structures. This element can be used either to solve the problems of plane stress and plane strain or to solve the problems of axial symmetry. The shape of the element is quadrilateral, which is defined by four nodes, and each node has two degrees of freedom and can be translated in the x and y directions. The element used to model the liquid in the storage tank is FLUID 79, which is mainly used to simulate the liquid without net flow rate in various vessels and it is particularly suitable for the calculation of hydro-static pressure and liquid-structure coupling interaction. The element is defined by four nodes, each node has two degrees of freedom, which can translate in the x direction and y direction.

In this paper, the finite element models will be established in a 2-dimensional environment. All the elements selected for modeling the storage tank, liquid in the tank are also two-dimensional structures, and their degrees of freedom can only be translated in the X and Y directions. For the constraint of boundary conditions, this paper defined the master degrees of freedom for all nodes on the liquid surface, and set the liquid surface on the plane where the origin is located during the modeling process, that is, the coordinates of the center point of the liquid surface are (0, 0). The

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surface around the liquid in the tank and the surface inside the tank wall are in contact with each other. During the establishment of the finite element numerical simulation analysis model, the nodes on their contact surfaces are also overlapped. Therefore, it is necessary to define the coupled degrees of freedom at the interface. The purpose of this is to ensure that the forces on the liquid in the tank and the tank wall can be transferred to each other, forming liquid-structure coupling interaction. Secondly, it can avoid the mutual penetration of their nodes of the liquid in the tank and the tank wall, which will cause errors in the analysis results. Moreover, this definition can enable the liquid in the tank to slide freely after being stressed, which conforms to the natural stress condition of the liquid. the element sizes of tank wall, tank bottom and liquid are determined to be one meter for this paper. An example of the finite element models involved in this paper is shown in Figure 3.

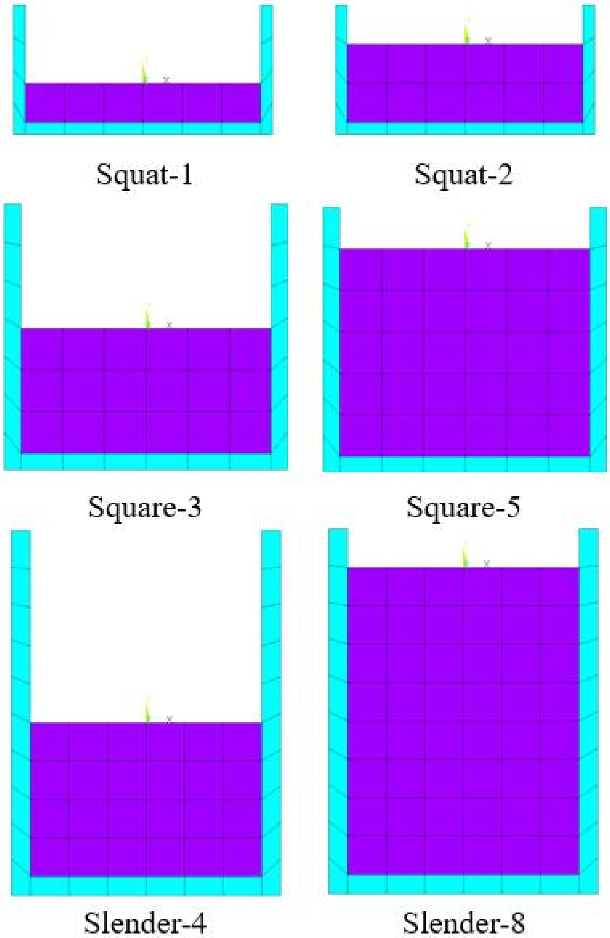

Figure 3. An example of the finite element models

Modal analysis is the most basic and important method to obtain structural dynamic characteristics. A mode shape can reflect the natural vibration characteristics of a structure. Each mode contains the specific natural frequency[19], damping ratio and deformed shape of the structure. In this paper, the free surface of the liquid in the tank is set with the master degrees of freedom, the reduced householder method is required to solve the modal analysis of the liquid in the tank. This method will first select the key nodes that have defined the master degree of freedom from the finite element numerical simulation analysis model of the liquid storage tank, and then define the mass matrix and stiffness matrix of the model according to the master degree of freedom, so as to obtain the natural frequency[20], vibration mode and other results of the model, and then expand the calculation results to the entire model [15-16]. The command to call it in ANSYS (18.2) software is MODOPT, REDUC.

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Transient dynamic analysis, also known as time history analysis, is mainly used to determine the dynamic response of the structure when the load changes with time according to any rule. The transient analysis can determine the displacement, stress and strain of the structure changing with time under any combination of static load, transient load and sinusoidal load. It can feedback the correlation between load and time, as well as mass effect and damping effect. The method used in this study is the Full method in transient analysis. Compared with Mode-superposition method, Full method is easy to use, allowing all types of nonlinear characteristics, and it uses a complete matrix without considering the approximation of the mass matrix. After one calculation, it can obtain all displacements and stresses, and it is allowed to apply all types of loads. However, its disadvantage is that it requires high computing power of the computer, which is time-consuming, and the computing cost is correspondingly large [17-18]. The command to call it in ANSYS (18.2) software is TRNOPT, FULL.

4. Conclusion

In this paper, the seismic response of a rectangular concrete storage tank is analysed based on the finite element method using seismic records with different frequency contents, and the peak height of the liquid shaking wave of the storage tank is mainly calculated. The results show that the peak height of the liquid sloshing wave calculated by the finite element method is smaller under the low frequency content seismic records and the medium frequency content seismic records, and the peak height of the liquid sloshing wave calculated by the finite element method is larger under the medium frequency content seismic records. The peak height of the liquid sloshing wave of the storage tank is more sensitive to the high frequency content seismic record.

5. Discuss

In this paper the first three natural frequencies are calculated using the modal analysis method of the finite element method. The calculated swinging frequencies are in good agreement with the frequencies obtained from the finite element model. The maximum difference between the swishing frequencies is approximately 13.48%. That is, the tank wall is considered to be rigid. Furthermore, the calculations show that the increase in liquid height increases the first three natural frequencies. The elastic response spectrum of the records used was plotted using software with a damping ratio of 5%. Se values for each liquid storage tank were extracted from the elastic response spectrum of each record by referring to the first natural period (the reciprocal of the first natural frequency) [21]. Secondly, the maximum swell height of the liquid storage tank for different seismic records was calculated using the dynamic time history analysis in the finite element numerical simulation analysis method. The results show that the peak height of the liquid shaking wave in the high frequency seismic records will be underestimated. A sketch of the peak sloshing wave heights for different finite element models is shown. Under seismic excitation in the x-direction, the liquid in the storage tank swings from left to right, and the liquid at the edges of the tank moves up and down within the constraints of the tank walls. In general, the displacement of the liquid on each side of the rim is in the opposite direction, i.e. when the height of the liquid sloshing wave on one side of the rim reaches its peak, the other side of the rim reaches its minimum and is below the horizontal.

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