Study on dynamic characteristics of cylindrical-supporting Silos Structures

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Abstract

In order to study the dynamic characteristics of silo storage foundation system under seismic loading, the dynamic response characteristics of silo storage foundation system under different loading conditions were studied by shaking table test, and the response rule of acceleration, displacement and earth pressure of composite structure under seismic loading was studied. The seismic design of the existing silo - storage - foundation system is carried out, and the effectiveness of the aseismic device is verified by numerical calculation. Results show that: (1) silo top acceleration with storage material was first increased and then decreased trend; the peak displacement decreases with the decrease of the quantity of stored material, the upper and lower difference, has obvious amplification effect; (2) under the action of seismic waves, soil pressure fluctuate, but overall showed a gradual upward trend, until stable at a certain value; (3) the displacement peak value of the upper part of the isolation silo decreases greatly compared with that before the isolation. It is only 1/3 before the isolation. Under the action of seismic load, the horizontal deformation of the upper structure of the simple warehouse is changed from the amplification shaking mode of the traditional aseismic storage tank to the whole translational type of the isolation bin. The research results have a certain reference value for the design, operation and maintenance of the silo structure in China.

Keywords

Silo-stock-foundation system; seismic load; dynamic characteristics; seismic design; shaking table test.

1. Introduction

With the advantage of simple operation, environmental protection, land saving, less loss and the like, Silo structure has become a universal structure widely used in industry, enterprises and transportation departments (Xuecheng et al 1993., Zongda et al 1998., Wójcik, M. et al 2017). At present, domestic and foreign scholars have done a lot of theoretical and experimental research on static characteristics of silo structure (Ayuga, F. et al 2008., Livaoglu et al 2016., Palermo, M. et al 2017., Yu et al 2017). Pieraccini et al. (2015) studied the buckling of a silo with different structure types caused by the impact load during the storage loading and unloading process, and several different models were used to carry out experimental research and numerical simulation analysis. K Knebel et al. (1995) studied the bending buckling problem of full bunker. The results show that the compressive stress of bulk can greatly increase the buckling critical load of thin shell wall. Butenweg C et al. (2017) compared two methods of silo force analysis under static and dynamic equivalent load. The interaction between silos and storage materials had been considered in the analysis. Through geometric nonlinear analysis, Ji (2005) researched systematically on the influence of cylindrical support steel silo's geometric parameters such as diameter and thickness of columns, steel stall, column height, radius and ratio of pillar to width on structural stability and strength. On the basis of the interaction of silos and bulk materials, the dynamic behavior of the silo system under the earthquake action is evaluated by Durmuş, A. et al. (2015), and a simplified method for the approximation of the finite element model is proposed for the analysis. The results show that the method has high accuracy. However, most of these studies only relate to the engineering mechanical properties of a single silo structure (Wang et al 2013., Kanyilmaz et al 2017), lack of the research on silo storage foundation interaction system under dynamic load. and the related mechanism is not clear, but seismic action is one of the main factors that cause instability and failure of silo structure (Livaoglu et al 2016., Toma et al 2017., Tu et al 2017., Kermiche et al 2017). Therefore, it is of great practical significance to study the dynamic characteristics of silo storage foundation interaction system under earthquake load.

In this paper, the silo-storage-foundation system is taken as the research object. Through the shaking table, the dynamic characteristics of the silo-storage-foundation system under different storage conditions are tested, The seismic design of the existing silo - storage - foundation system is carried out, and the effectiveness of the aseismic device is verified by numerical calculation.The research results can provide some theoretical basis and reference value for the design of safe operation of silo structures under special conditions.

2. Basic Equations of Dynamic Model

Silo storage foundation interaction system can be regarded as a composite thin-walled cylindrical shell with one end fixed and another end free. In the role of external periodic load changes, the cylindrical shell diagram and its stratification shown in Figure 1. Cylindrical shell in the movement process will have a displacement of each point in the cylindrical coordinate system with u, v, w and the three displacement components are simultaneously a function of the spatial coordinates x , θ, r and time t.

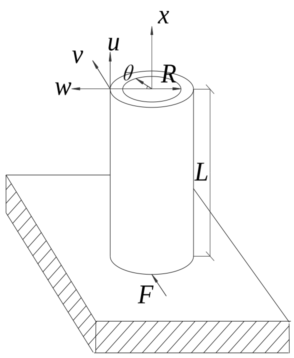


Figure 1. Model of a circular cylindrical shell

2.1 Geometric Equation

The strain component at any point of a thin-walled cylindrical shell has the following relationship with the mid-plane strain, mid-plane bending deflection, and mid-plane distortion:

$$\varepsilon_x = \varepsilon_x^0 + z\chi_x \tag{1}$$

$$\varepsilon_\theta = \varepsilon_\theta^0 + z\chi_\theta \tag{2}$$

$$\varepsilon_{x\theta} = \varepsilon_{x\theta}^0 + z\chi_{x\theta} \tag{3}$$

In the formula: ε_x^0, ε_θ^0, $\varepsilon_{x\theta}^0$ is the film strain component of the middle curve, χ_x , χ_θ is the mid-plane bending deflection, $\chi_{x\theta}$ is the mid-plane twist, and z is the distance from any point on the shell to the middle.

According to the Donnell shell theory, the first-order derivative nonlinearity of the normal deflection is taken into account in the relationship between the mid-surface strain and the mid-surface displacement.

$$\varepsilon_x^0 = \frac{\partial u}{\partial x} + \underline{\frac{1}{2}(\frac{\partial w}{\partial x})^2} \tag{4}$$

$$\varepsilon_\theta^0 = \frac{1}{R}(\frac{\partial v}{\partial \theta} + w) + \underline{\frac{1}{2}(\frac{\partial w}{R\partial \theta})^2} \tag{5}$$

$$\varepsilon_{x\theta}^0 = \frac{\partial v}{\partial x} + \frac{1}{R}\frac{\partial u}{\partial \theta} + \underline{\frac{\partial w}{\partial x}\frac{1}{R}\frac{\partial w}{\partial \theta}} \tag{6}$$

Of these: Underlined items represent non-linear terms.

In the Donnell nonlinear shell theory, the mid-plane bending strain component remains linear:

$$\chi_x = -\frac{\partial^2 w}{\partial x^2} \tag{7}$$

$$\chi_\theta = -\frac{1}{R^2}\frac{\partial^2 w}{\partial \theta^2} \tag{8}$$

$$\chi_{x\theta} = -\frac{2}{R}\frac{\partial^2 w}{\partial x \partial \theta} \tag{9}$$

2.2 Physical Equations

Taking into account the elastic modulus of the composite material with the vibration frequency changes, the two have the following relationship:

$$E_1(\omega) = E_2(\omega) = E_3(\omega) = 2.5751\times 10^9 + \frac{2\times 3.2283\times 10^{12}}{\pi}\times\left[\frac{238.62}{4\times(\omega/2\pi - 0.46787)^2 + 238.62^2}\right] \tag{10}$$

$$E_4(\omega) = 5.04289\times 10^8 + 9.2387\times 10^9 \times e^{-0.0064\omega/2\pi} \tag{11}$$

Physical equation of layer K of isotropic laminated shell:

$$\begin{bmatrix}\sigma_x\\ \sigma_\theta\\ \tau_{x\theta}\end{bmatrix}_k = \begin{bmatrix}Q_{11} & Q_{12} & 0\\ Q_{21} & Q_{22} & 0\\ 0 & 0 & Q_{66}\end{bmatrix}_k \begin{bmatrix}\varepsilon_x\\ \varepsilon_\theta\\ \varepsilon_{x\theta}\end{bmatrix}_k \tag{12}$$

Among them: Q_i^j is reduced stiffness matrix, the element expression is:

$$(Q_{11})_k = (Q_{22})_k = E_k(\omega)/(1-\mu_k^2) \tag{13}$$

$$(Q_{12})_k = (Q_{21})_k = E_k(\omega)\cdot\mu_k/(1-\mu_k^2) \tag{14}$$

$$(Q_{66})_k = E_k(\omega)/2(1+\mu_k) \tag{15}$$

Among them: $E_k(\omega)$ is k-th elastic modulus, μ_k is k-th layer of Poisson's ratio.

2.3 Dynamic Balance Equation

According to the principle of D'Alembert, the dynamic equilibrium equation of a laminated composite cylindrical shell can be established:

$$\frac{\partial N_x}{\partial x}+\frac{1}{R}\frac{\partial N_{x\theta}}{\partial \theta}-\sum_{k=1}^{4}\rho_k(z_k-z_{k-1})\frac{\partial^2 u}{\partial t^2}=0 \tag{16}$$

$$\frac{1}{R}\frac{\partial N_\theta}{\partial \theta}+\frac{\partial N_{x\theta}}{\partial x}+\frac{Q_\theta}{R}-\sum_{k=1}^{4}\rho_k(z_k-z_{k-1})\frac{\partial^2 v}{\partial t^2}=0 \tag{17}$$

$$\begin{aligned}&\frac{\partial Q_x}{\partial x}+\frac{1}{R}\frac{\partial Q_\theta}{\partial \theta}-\frac{1}{R}N_\theta+N_x\frac{\partial^2 w}{\partial x^2}+\frac{N_\theta}{R^2}\frac{\partial^2 w}{\partial \theta^2}+\\&\frac{2N_{x\theta}}{R}\frac{\partial^2 w}{\partial x\partial \theta}-\sum_{k=1}^{4}\rho_k(z_k-z_{k-1})\frac{\partial^2 w}{\partial t^2}-c\frac{\partial w}{\partial t}-q_r=0\end{aligned} \tag{18}$$

Among them:

$$Q_x=\frac{1}{R}\frac{\partial M_{x\theta}}{\partial \theta}+\frac{\partial M_x}{\partial x} \tag{19}$$

$$Q_\theta=\frac{\partial M_{x\theta}}{\partial x}+\frac{1}{R}\frac{\partial M_\theta}{\partial \theta} \tag{20}$$

3. Model Test of Silo-Storage-Foundation Dynamic Interaction System

In order to reveal the mutual response mechanism of silo-stocking-foundation system under the action of power, the shaking table, data acquisition system, strain gauge, earth pressure sensor and accelerometer were used to design the test of small shaking table silos to analyze the deformation of silo wall , The acceleration inside the silo, the earth pressure on the foundation and the deformation of the foundation, the dynamic characteristics of the silo-stocking-foundation dynamic interaction system are studied.

3.1 Test Materials

In this experiment, an acrylic cylinder with a diameter of 220mm and a wall thickness of 4mm was used as the silo body. The bulk density of the acrylic material was 12N/cm3 and the elastic modulus was 4GPa. The inner and outer walls of the cylinder were respectively fixed with acceleration sensors and strain gauges shown in Figure 2, experimental storage of selected short coal storage coal.

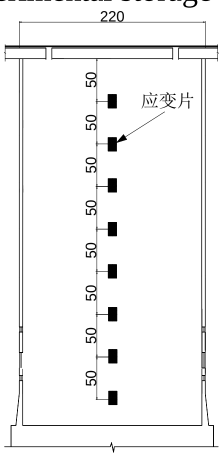


Figure 2. Distribution diagram of strain gauge

3.2 Test Equipment

Test selected Shanghai YiHua Custom shaker, data acquisition system used DongHua 3817k data acquisition system. Experimental model of the overall effect shown in Figure 3.

Figure 3. The whole diagram of the model

3.3 Test Program

This experiment designs a total of five conditions (1 #, 2 #, 3 #, 4 #, 5 #), corresponding to silo storage status for full positions, 3/4 positions, 1/2 positions, 1/4 positions and Short positions. Considering that in the seismic response analysis, the horizontal direction wave plays a major role in the seismic engineering. The Lanzhou wave is selected as the input seismic wave and the peak acceleration is 196.2 cm/s2. Select 20s of which time, the Lanzhou wave duration curve and spectral curve is shown in Figure 4.

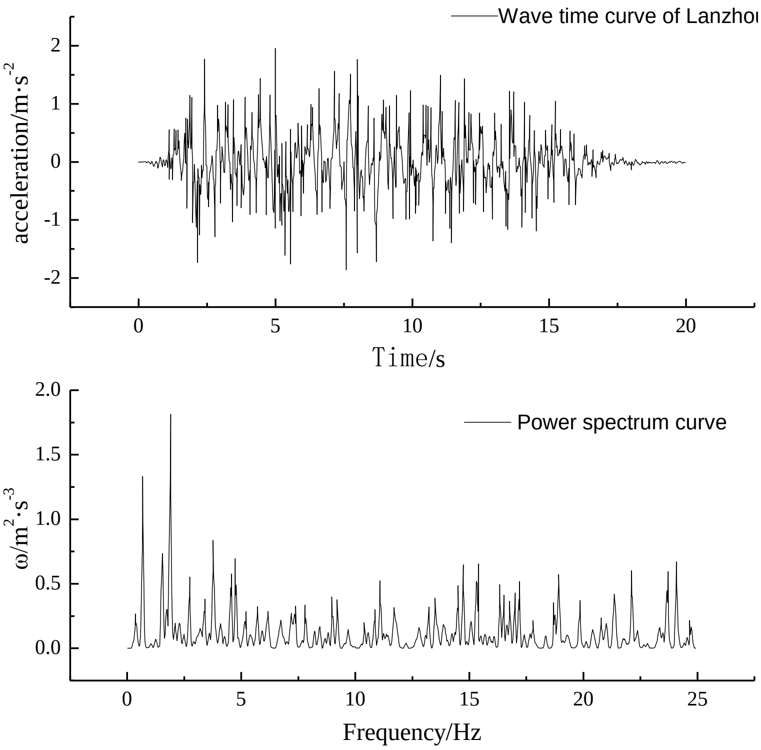


Figure 4. The time history curve and spectrum curve of Lanzhou wave

3.4 Test Results Analysis

3.4.1 Acceleration and Displacement Time History Analysis

Different storage conditions, the top of the silo monitoring point of acceleration and displacement time curve shown in Figure 5. As can be seen from the figure, the peak acceleration of the short positions, 1/4 positions, 1/2 positions and 3/4 positions and full positions are 4.35m / s-2,4.86m / s-2,5.78m / s-2, 2.85m / s-2, 3.92m / s-2, the acceleration peak increases first and then decreases with the increase of storage. This is due to the fact that the period of natural vibration of a small amount of storage material is similar to that of a silo, thus aggravating the vibration tendency of the silo system and increasing the peak acceleration of the roof. However, with the increase of storage volume, the difference of the natural period of the two vibrations becomes larger, and the vibration of the two vibrations does not synchronize with the trend of silo vibration, so the acceleration peak decreases.

It can also be seen from the figure that the displacement peak of silo top with different storage of empty positions, 1/4 positions, 1/2 positions and 3/4 positions, and the positions of full positions are 5.88mm, 7.22mm, 7.81mm, 8.32mm and 9.29mm respectively.The peak displacement of the top of the silo gradually increases with the increase of the storage amount. Comparing the displacement curves at the top of silos in different working conditions, it can be seen that the displacements on the same bus bar in the same working condition are the same, the displacement peak decreases with the decrease of storage volume, and the difference between upper and lower sides is larger.Therefore, it is necessary to take vibration isolation measures to reduce the magnifying effect on the silo.

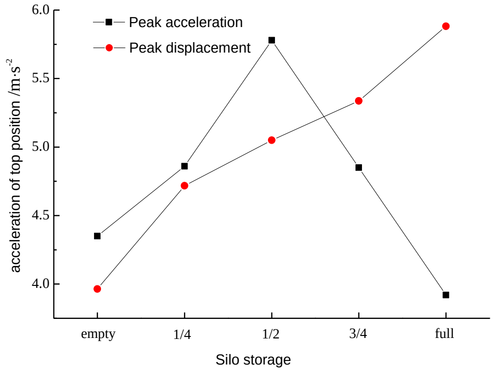
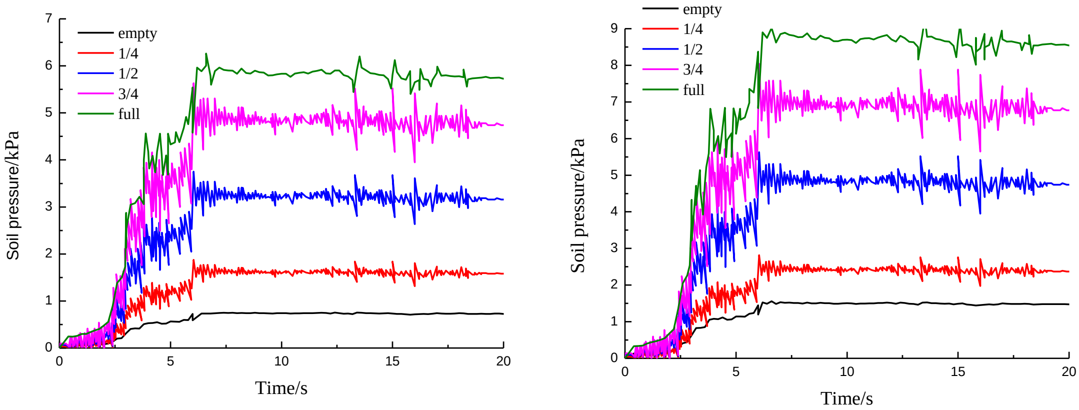


Figure 5. Acceleration and displacement time history curve of the top monitoring point of the model

3.4.2 Earth Pressure Time History Analysis

Under different storage conditions, the soil pressure time history curve of the model monitoring point is shown in Fig.6. It can be seen from the figure that the peak readings of the top earth pressure sensor are 0.8kPa, 1.8kPa, 3.7kPa, 5.1kPa, 6.0kPa for the short positions, 1/4 positions, 1/2 positions 3/4 positions and full positions, respectively. corresponding to the underlying earth pressure sensor peak readings were: 1.6kPa, 2.8kPa, 5.4kPa, 2.7kPa, 7.3kPa, 9.0kPa.



(a) Upper measuring point (b) Lower measuring point

Figure 6. Soil pressure time history curve of model monitoring point

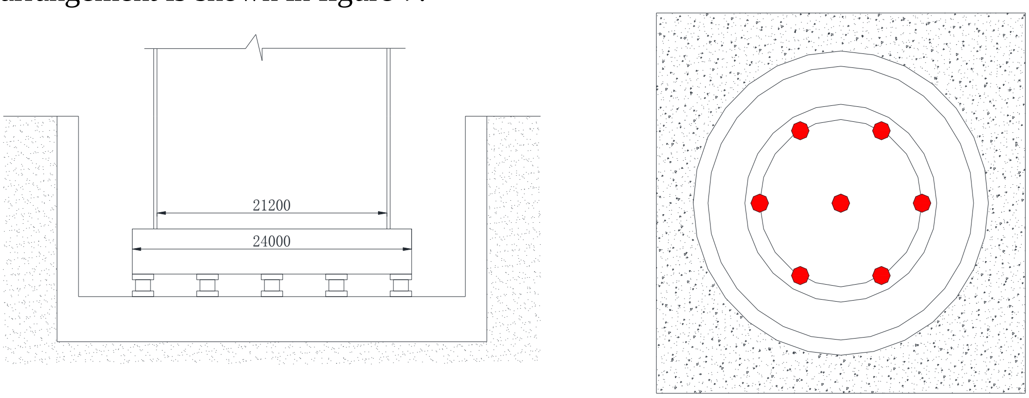
4. Seismic Behavior Analysis of Silo-Storage-Foundation Interaction System

4.1 Project Examples

Shenyang Jinshan Thermal Power "To the small" heating project is located in Sujiatun District, Shenyang City Hunhe South Bank. Its coal handling system needs 5 silos of 10000 tons, with a diameter of 22m and a height of 39.730m. According to the specifications of the proposed silo construction project for the warehouse. Coal is lignite, bulk density by 10kN/m3. Seismic fortification intensity of 7 degrees, the design of the basic seismic acceleration 0.10g, Seismic structural measures at 7 degrees fortification, the first group of seismic sub-group design, seismic grade two; structural safety rating of two; fire rating of two; silo foundation design grade B, design life of 50 years. The base bearing layer is medium sand, and the silo wall is made of reinforced concrete.

4.2 Silo Isolation Device Design

In this paper, a sandwich rubber cushion is used as a seismic isolation layer to design the shock absorption and vibration control of the silo structure.After calculation, the total weight of the silo is about 118,600kN at full position. this paper selects 7 sandwich rubber cushion, each sandwich rubber cushion average required to assume the dead load is 17000kN, select the 7 meet the bearing capacity and other conditions of the mezzanine rubber cushion, they will positively hexagonal arrangement, specific arrangement is shown in figure 7.



(a) Orthographic view (b) Overlook map

Figure 7. Layout of rubber bearing

4.3 Isolation Silos Dynamic Characteristics Of Numerical Calculations

The finite element software ANSYS was used to carry out the modal analysis of the silo dynamic system to compare the natural frequencies of the silo system before and after isolation and the dynamic characteristics of each order of earthquake type. Finite element numerical calculation model shown in Figure 8, divided into a total of 32640 units. Vibration isolator selection * MAT_ MOONEY _RIVLIN_RUBBER material model, used to describe the mechanical properties of rubber materials.

In order to study the effect of isolator, the dynamic response of the isolated silo system under the action of EL centro wave was simulated under the conditions of empty position, 1/4 position, 1/2 position, 3/4 position and full position respectively. Dynamic response of isolated silos for comparative analysis.

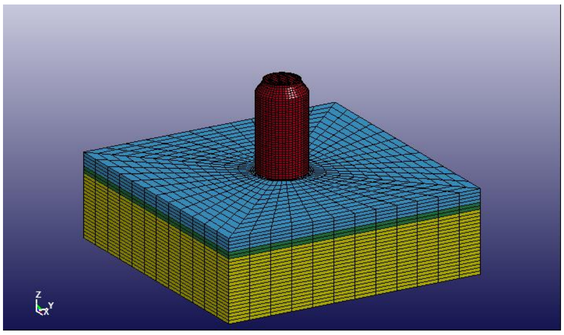


Figure 8. A schematic diagram of a numerical model

4.4 Evaluation of Vibration Isolation Effect of Simple Isolation

Due to the displacement condition of each storage when the variation curves are roughly the same, so here only lists the displacement curve of empty positions, 1/2 position and full position under the condition of vertex, silo foundation and bulk top center node, as shown in figure 9~ 11is shown in figure 14.

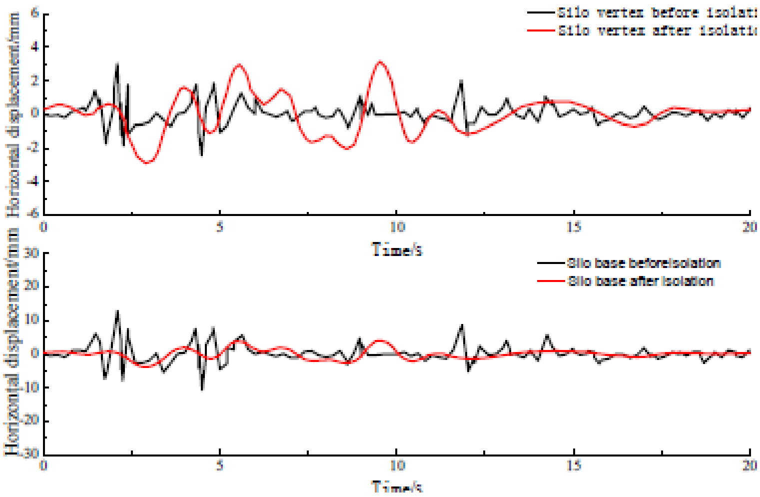


Figure 9. Displacement time history curves under the condition of empty storage

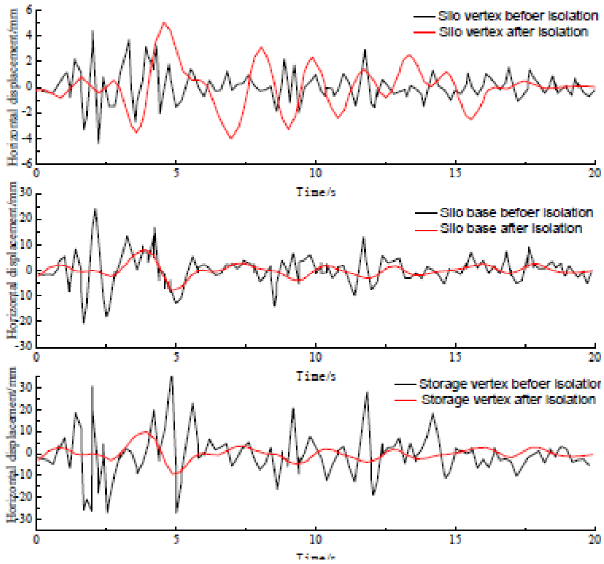


Figure 10. Displacement time history curves under 1/2 storage condition

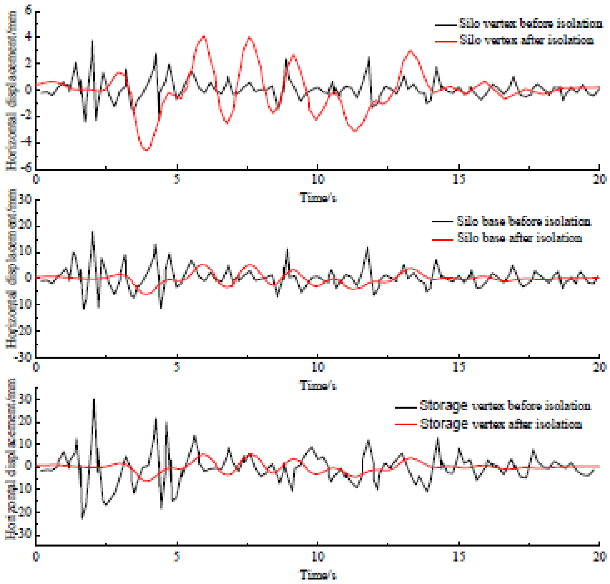


Figure 11. Displacement time history curves under full storage condition

According to the displacement curve of each working condition before and after isolation, the displacements of the roof and the top of bulk silo are greatly reduced due to the existence of vibration isolator. Due to the large deformation of the vibration isolation device at the silo foundation, As a result, the peak displacement of silo foundation increased, but the horizontal deformation of the superstructure in the earthquake changed from the amplifying and swaying type of the traditional anti-seismic structure to the integral translational type of the isolation structure. therefore, the displacement of the superstructure was greatly reduced. The maximum displacement response of the upper part of the isolated silo after isolation is only about one third of the maximum displacement before isolation, so it is feasible and effective to use the rubber isolator to separate the silo.

The analysis shows that under the same seismic wave, the response of the isolated silo is obviously smaller than that of the non-silo silo, which shows that the effect of absorbing the transmitted energy of the seismic wave is obvious by prolonging the basic cycle of silo through the isolation layer. Isolation program is effective.

5. Conclusion

(1)The peak acceleration of silo top firstly increases and then decreases with the increase of storage. When the storage capacity is small, the natural period of a small amount of storage material is similar to that of a silo, which aggravates the vibration of the silo system and increases the peak acceleration of the silo roof. With the increase of storage volume, the difference of the natural period of the two vibrations becomes larger. The unsynchronized vibration makes the silo to suppress the vibration of the silo and reduce the acceleration peak.

(2)The displacement of the same busbar in the same working condition is the same. The displacement peak decreases with the decrease of the storage amount, and the difference between the upper and the lower is large, which has a significant amplification effect. Therefore, it is necessary to take measures to reduce vibration Magnification effect on the silo hazards.

(3) Under the action of seismic waves, the earth pressure fluctuates up and down, but on the whole it shows a gradual upward trend until it stabilizes at a certain value. The foundation should be reinforced to prevent the instability of the vibration.

(4)The peak displacement of the superstructure of isolation silos greatly decreased compared with that before isolation, only about one-third of that before isolation. The horizontal deformation of the superstructure of the silo under the action of the earthquake loads is larger than that of the traditional silo Type into the overall translation of silos, translation design effect is significant.

Acknowledgments

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