Dynamic Responses of Sliding Isolation Concrete Liquid Storage Tank under Far-Field Long-Period Earthquake

W. Jing1,2† and X. Cheng1,2

1 Key Laboratory of Disaster Prevention and Mitigation in Civil Engineering of Gansu Province, Lanzhou University of Technology, Lanzhou, 730050, PR China
2 Western Engineering Research Center of Disaster Mitigation in Civil Engineering of Ministry of Education, Lanzhou University of Technology, Lanzhou, 730050, PR China

†Corresponding Author Email: jingwei3276@163.com

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ABSTRACT

Under far-field long-period earthquake, liquid storage tanks are easy to be failure because of large amplitude liquid sloshing. In this paper, nonlinear contact is used to simulate behavior of sliding isolation bearing, nonlinear dynamic equation is used to solve fluid-structure interaction, bilinear material model is used to simulate limiting-device, and 3-D calculation model of sliding isolation concrete rectangular liquid storage tank (CRLST) with limiting-devices is established. Firstly, artificial far-field long-period earthquake waves are synthesized based on the existing seismic records. Secondly, dynamic responses of sliding isolation CRLST under the action of short-period and far-field long-period earthquakes are studied. Thirdly, effects of bidirectional earthquake and structure size on dynamic responses are investigated. Lastly, displacement control measures are discussed. Results show that far-field long-period earthquakes mainly affect horizontal displacement of structure and liquid sloshing wave height, and sliding isolation has obvious control effect on liquid sloshing wave height. Besides, horizontal displacement of structure and liquid sloshing wave height are increased with increase of seismic dimension and structure size. The reasonable designs of sliding isolation bearing and limiting-device can solve the problem that the maximum horizontal displacement of sliding isolation CRLST may exceed the limit under far-field long-period earthquake.

Keywords: Sliding isolation; Concrete rectangular liquid storage tank (CRLST); Far-field long-period ground motion; Fluid-structure interaction; Liquid sloshing.

NOMENCLATURE

\( A(\omega) \) fourier amplitude spectrum  \( F_F \) force caused by volume force
\( a(t) \) acceleration time history  \( (F_F)_S \) force caused by area force
\( \omega_0 \) seismic record acceleration  \( I(\omega) \) imaginary parts of Fourier transform
\( a_s(t) \) non-stationary artificial ground motion  \( K_{FF} \) stiffness matrix of liquid itself
\( c \) attenuation constant  \( K_{FU} \) stiffness matrix of liquid contributed by structure
\( C_{SF} \) damping matrix of liquid itself  \( K_{EU} \) stiffness matrix of structure itself
\( C_{FLU} \) damping matrix of liquid contributed by structure  \( M_{FF} \) liquid mass matrix
\( C_{ELU} \) damping matrix of structure contributed by liquid  \( n \) vector of internal normal direction
\( C_{EU} \) stiffness matrix of structure contributed by liquid  \( p \) probability guarantee coefficient
\( C_{ELU} \) damping matrix of structure itself  \( PGA \) peak ground acceleration
\( f(t) \) non-stationary intensity envelope  \( R(\omega) \) real parts of Fourier transform
\( F_F \) force caused by volume force  \( S \) boundary of liquid domain
\( S(\omega) \) power spectrum function  \( S_d(\omega) \) target response spectrum
1. **INTRODUCTION**

Failure of concrete rectangular liquid storage tanks caused by earthquake will not only influence people’s daily life and normal production of industrial enterprises, also will cause secondary disasters such as liquid leakage (Park et al. 2016; Hashimoto et al. 2017), fire and environmental pollution (Uckan et al. 2015), groundwater contamination issue (Dou et al. 2018a; 2018b), even more will threaten the lives of the people. Rubber isolation can reduce dynamic responses of liquid storage tanks, but which may increase liquid sloshing wave height (Calugatu and Mahin 2009); by comparison, sliding isolation will be better than rubber isolation (Shrimali and Jangid 2011).

There are many instances of destruction of oil storage tanks under long-period earthquakes. For example, in 1983, an earthquake (Ms=7.7) occurred in the central Japan Sea, liquid overflow of 13 liquid storage tanks was caused in Niigata city because of far-field long-period earthquake; meanwhile, the tank tops were also destroyed due to the impact force of liquid sloshing. In 1993, a large number of oil storage tanks located at Niigata Basin produced large amplitude liquid sloshing during Nanseioki earthquake, and the maximum wave height reached 1.7m. During the 2003 Tokachioki earthquake in Japan, 7 oil storage tanks located at Tomakomai were seriously damaged because of liquid sloshing (Zama 2004). In order to solve this problem, some researchers have been conducted. Matsui and Nagaya (2013) studied the nonlinear sloshing problem under long-period ground motion using finite element method. Shekari et al. (2010) investigated dynamic responses of isolated liquid storage tanks under long-period ground motion and found that dynamic responses corresponding to large and small height-diameter ratio were effectively controlled. Vakilazadsarabi (2015) found that destruction of liquid storage tank was related to liquid sloshing and studied the effects of long duration and long period resonant excitation on liquid sloshing response using nonlinear calculation method and experiment. Luo et al. (2015) found that dynamic responses of rubber isolation storage tank were effectively reduced under short-period ground motion, but under long-period ground motion, rubber isolation had no reduction effect on wave height.

In order to study dynamic responses of liquid storage tank, the corresponding simulation and model works is particularly important. Based on FSI, Shahverdiani et al. (2008) used finite element method to study dynamic responses of concrete liquid storage tank. Ozdemir et al. (2010) pointed out that numerical method was an indispensable and effective tool for evaluating the aseismic capability of liquid storage tank. Richter (2013) proposed a full Euler method for the FSI problem. Nicolici and Bilegan (2013) simulated the interaction between liquid and wall based on complete unidirectional coupling. Lay (2014) used finite element and boundary element methods to simulate structure and fluid domains, respectively, and then solved the coupling equation. Considering free surface liquid sloshing, Jing et al. (2018) and Cheng et al. (2017; 2018) studied the dynamic responses of CRLST by numerical simulation based on potential flow theory. Generally speaking, because numerical simulation method uses special element to simulate the liquid and FSI interface is treated more precisely, which can accurately reflect some particularities of liquid storage tank.

Many earthquake damage cases and research results shows that liquid sloshing is sensitive to far-field long-period ground motion, and it is necessary to study effect of long-period ground motion on design of liquid storage tank (Men et al. 2008; Zhou et al. 2012). At present, there is a lack of research on sliding isolation concrete liquid storage tanks under long-period ground motion. In this paper, the characteristics of far-field long-period ground motion are summarized firstly, and then the corresponding synthetic procedure is given. The

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_a(T)$</td>
<td>spectral acceleration</td>
</tr>
<tr>
<td>$S_{aw}(\omega)$</td>
<td>maximum response spectrum</td>
</tr>
<tr>
<td>$T_0$</td>
<td>predominant period</td>
</tr>
<tr>
<td>$T_d$</td>
<td>duration of artificial seismic wave</td>
</tr>
<tr>
<td>$T_s$</td>
<td>seismic record duration</td>
</tr>
<tr>
<td>$T_r$</td>
<td>dispersion period</td>
</tr>
<tr>
<td>$TOL$</td>
<td>tolerance</td>
</tr>
<tr>
<td>$\Delta u$</td>
<td>unknown increment of displacement vector</td>
</tr>
<tr>
<td>$V$</td>
<td>liquid domain</td>
</tr>
<tr>
<td>$\xi$</td>
<td>damping ratio</td>
</tr>
<tr>
<td>$\phi$</td>
<td>velocity potential</td>
</tr>
<tr>
<td>$\Delta \phi$</td>
<td>increment of velocity potential</td>
</tr>
<tr>
<td>$\beta$</td>
<td>weighted average</td>
</tr>
<tr>
<td>$\Delta \omega$</td>
<td>frequency interval</td>
</tr>
<tr>
<td>$\phi(\omega)$</td>
<td>phase spectrum</td>
</tr>
<tr>
<td>$\phi_0$</td>
<td>initial phase spectrum</td>
</tr>
</tbody>
</table>
mechanical behavior of sliding isolation is simulated by setting contact, and 3-D calculation model of sliding isolation concrete rectangular liquid storage tank (CRLST) with 8 limiting-devices is established considering nonlinear fluid-structure interaction (FSI). Dynamic responses of concrete rectangular liquid storage tank (CRLST) are studied comparatively under the action of short-period and far-field long-period ground motions, influences of far-field long-period ground motions on dynamic responses are evaluated, and effect of seismic response reduction of sliding isolation on CRLST is investigated under far-field long-period ground motion. Besides, in order to control structure displacement under far-field long-period ground motion, three control measures are proposed and their effectiveness is investigated. Lastly, some advices for the design and disaster prevention of sliding isolation concrete rectangular liquid storage tank (CRLST) under far-field long-period earthquake are provided.

2. FAR-FIELD LONG-PERIOD GROUND MOTION

2.1 Basic Concepts

Based on the analysis of San Fernando seismic records, Hanks (1975) first proposed the concept of long-period ground motion. After certain research and attention, starting from the Michoacan earthquake in 1985 and the Landers earthquake in 1992, the adverse effects of far-field long-period ground motion on long-period structure were gotten attention (Koketsu and Miyake 2008).

Some research results show that the characteristics of long-period ground motions are as follows: a) the larger the magnitude, the richer the longer period component; b) long-period component slowly decay with increase of epicenter distance; c) duration of long-period ground motions is long; d) thick cover layer has obvious amplification effect on the long-period component. So the main factors that affect the periodic characteristics of ground motions are site, epicentral distance, magnitude and source characteristics (Hu, 2006). With the deepening of the corresponding research, there are many clear definitions for the long-period ground motion, which are good to quantitatively describe the long-period ground motion. The details are as follows:

1) Rathje et al. (1998) proposed the concept of mean period \( T_r \) and predominant period \( T_p \) of the response spectrum based on the study of the spectral parameters of ground motion, and long-period ground motion is generally referred to as its predominant period \( T_p \) is from several seconds to tens of seconds.

\[
T_r = \frac{\sum T_i \left( \frac{S_a(T_i)}{PGA} \right)^2}{\sum T_i}, \quad (0.02 \leq T_i \leq T) \quad (1)
\]

\[
T_0 = \frac{\sum T_i \ln \left( \frac{S_a(T_i)}{PGA} \right)}{\sum \ln \left( \frac{S_a(T_i)}{PGA} \right)} \quad (2)
\]

where \( T_i \) is dispersion period with equal distance of acceleration response spectrum corresponding to 5% damping ratio; \( S_a(T_i) \) is spectral acceleration corresponding to \( T_i \); PGA is peak ground acceleration.

2) In order to provide quantitative indicators for the selection of long-period ground motion, Li et al. (2014) defined weighted average \( \beta \) based on dynamic amplification factor spectrum curve, the curve from period 2s to 10s was selected. Based on the analysis of the existing seismic records, it was found that \( \beta \) of short-period ground motion was small, and \( \beta \) of far-field long-period ground motion was large. When \( \beta > 0.4 \), the records were belong to the far-field long-period ground motions.

\[
\beta_i = \frac{\sum T_i^2 \left( \frac{S_a(T_i)}{PGA} \right)}{\sum T_i^2} \quad (3)
\]

where \( T_i \) is equal distance dispersion period of acceleration response spectrum with 5% damping ratio, its range of values is 2-10s; \( S_a(T_i) \) is spectral acceleration corresponding to \( T_i \); PGA is peak ground acceleration.

3) If low frequency components of the seismic records are rich, namely, spectral components are mainly concentrated in 0.1-2Hz, then these records can be divided into long-period ground motions.

2.2 Artificial Synthesis of Far-Field Long-Period Ground Motion

The method of trigonometric series can be used to synthesize artificial seismic wave, the basic process is as follows:

1) Obtaining the target response spectrum \( S_a(\omega) \) by processing the existing far-field long-period seismic record.

2) Converting the target response spectrum \( S_a(\omega) \) to the power spectrum function \( S(\omega) \):
\[ S(\omega) = \frac{\xi^2}{\pi \omega^2} \frac{\pi}{\omega_d^2} \ln \left( \frac{\pi}{\omega_d^2} \ln p \right) \]  

where \( \xi \) is damping ratio; \( \omega \) is circular frequency; \( T_d \) is duration of artificial seismic wave; \( p \) is probability guarantee coefficient (≥0.85).

(3) Converting the power spectrum function \( S(\omega) \) to the Fourier amplitude spectrum \( A(\omega) \):

\[ A(\omega) = \sqrt[4]{4S(\omega) \Delta \omega} \]  

where \( \Delta \omega \) is frequency interval, \( \Delta \omega = 2 \pi \) sampling frequency / FFT length.

(4) Converting the natural seismic wave from time domain to frequency domain by Fourier transform, the phase spectrum \( \phi(\omega) \) used for synthetic seismic wave can be obtained (Liao et al. 1992):

\[
\begin{align*}
R(\omega) &= \frac{1}{2\pi} \int_0^t a(t) e^{-j\omega t} dt \\
I(\omega) &= \int_0^t a(t) e^{-j\omega t} dt \\
\phi(\omega) &= \arctan \left( \frac{I(\omega)}{R(\omega)} \right)
\end{align*}
\]

where \( R(\omega) \) and \( I(\omega) \) are the real and imaginary parts of Fourier transform of the existing record; \( T_d \) is duration of existing long-period seismic record; \( \omega \) is acceleration of existing long-period seismic record.

(5) Converting Fourier amplitude spectrum \( A(\omega) \) and phase spectrum \( \phi(\omega) \) to the real and imaginary parts of Fourier transform, and the approximate acceleration time history \( a(t) \) of artificial ground motion can be obtained by inverse Fourier transform:

\[ a(t) = \text{FFT}^{-1}\left[ A(\omega) e^{j\phi(\omega)} \right] \]  

where \( \phi \) is the initial phase spectrum.

(6) \( a(t) \) is multiplied by non-stationary intensity envelope \( f(t) \), then the acceleration time history \( a_g(t) \) of non-stationary artificial ground motion can be obtained:

\[
 f(t) = \begin{cases} 
 (t/T_1)^2 & 0 < t \leq T_1 \\
 1 & T_1 < t \leq T_2 \\
 \exp[-c(t-T_2)] & T_2 < t \leq T_d
\end{cases} \]  

\[ a_g(t) = a(t)f(t) \]  

where \( c \) is attenuation constant, it is 0.1−1.0; the value of \( T_1 \) and \( T_2 \) can be decided according to the actual situation.

(7) Conducting Fourier transform for the acceleration time history \( a_g(t) \) of non-stationary artificial ground motion. The maximum response spectrum \( S_{al}(\omega) \) corresponding to \( a_g(t) \) at each frequency point can be obtained by convolution operation.

(8) Adjusting the Fourier amplitude spectrum \( A(\omega) \) by the ratio of the target acceleration response spectrum \( S_{al}(\omega) \) and the calculated response spectrum \( S_{al}(\omega) \):

\[ A_{k+1}(\omega) = A_k(\omega) \frac{S_{al}(\omega)}{S_{al}(\omega)} \]  

(9) Repeating steps (2)-(8), when \( k = n \), if the ratio of target acceleration response spectrum \( S_{al}(\omega) \) to calculated response spectrum \( S_{al}(\omega) \) is close to 1.0, then loop end can be achieved.

\[ TOL = \left| \frac{S_{al}(\omega) - S_{al}(\omega)}{S_{al}(\omega)} \right| \]  

Chi-Chi-CHY044 wave and TOM wave are used as the existing far-field long-period ground motions, and artificial wave 1 and artificial wave 2 are synthesized, respectively. Curves of acceleration response spectrum are shown in Figs. 1-2.

**Fig. 1. Artificial wave 1.**

**Fig. 2. Artificial wave 2.**

### 3. THEORY OF FLUID-STRUCTURE INTERACTION

#### 3.1 Motion Equation of Liquid Domain

Assuming that the unknown increment of velocity potential \( \phi \) is \( \Delta \phi \), the unknown increment of
displacement vector $\mathbf{u}$ is $\Delta \mathbf{u}$, then the equation of motion in liquid domain can be expressed as:

$$
\begin{bmatrix}
0 & 0 \\
0 & -M_{FF}
\end{bmatrix}
\delta \mathbf{u} + \begin{bmatrix}
C_{UU} & C_{UF} \\
C_{FU} & -(C_{FF} + C_{uu})
\end{bmatrix}
\delta \mathbf{u} = \begin{bmatrix}
F_F \\
F_U
\end{bmatrix}
\tag{12}
$$

where $F_F$, $F_U$ and $(F_F)_S$ are the force acting on structural boundary caused by liquid pressure, volume force and area force corresponding to liquid continuity equation; $M_{FF}$ is liquid mass matrix; $C_{UU}$, $C_{FU}$, $C_{UF}$ and $C_{uu}$ are damping matrix of structure itself, damping matrix of liquid contributed by structure, damping matrix of structure contributed by liquid and damping matrix of liquid itself; $K_{UU}$, $K_{FU}$, $K_{UF}$ and $K_{FF}$ are stiffness matrix of structure itself, stiffness matrix of liquid contributed by structure, stiffness matrix of structure contributed by liquid and stiffness matrix of liquid itself.

$$
F_F = \int_V \left( \frac{\partial p}{\partial t} \mathbf{n} \delta \phi - \rho \mathbf{n} \dot{\mathbf{v}} \delta \phi \right) dV
\tag{13}
$$

$$
(F_F)_S = \int_S -p_n \mathbf{n} \delta \mathbf{u} dS
\tag{14}
$$

where $V$ is liquid domain; $S$ is boundary of liquid domain; $\mathbf{n}$ is vector of internal normal direction of $S$; $\mathbf{u}$ is movement velocity of $S$.

A part of the liquid boundary surface $S$ is assumed to be adjacent to the structure (Fig. 3), the boundary surface adjacent to the structure is represented as $S_1$, the force acting on structural boundary caused by liquid pressure $F_U$ can be obtained by Eq. (15).

Fig. 3. Interaction of liquid and structure.

$$
-\delta F_U = - \int_{S_1} p_n \cdot \delta \mathbf{u} dS_1
$$

$$
P = P(h) = P \left[ \frac{\Omega(x + \mathbf{u}) - \mathbf{v} - \mathbf{v} \cdot \mathbf{v}_t}{2} \right]
\tag{15}
$$

where $\mathbf{v}_t$ is liquid movement velocity perpendicular to the boundary, $\mathbf{v}$ is tangential velocity, $P$ is liquid pressure.

$$
\mathbf{v}_n = (\mathbf{u} \cdot \mathbf{n}) \mathbf{n}
\tag{16}
$$

3.1 FSI Equation

Because the system is non-linear, each exact solution needs multiple equilibrium iterations. Adding structure term into liquid motion Eq. (12), then the nonlinear FSI equation based on potential flow theory can be expressed as:

$$
\begin{bmatrix}
M_{SS} & 0 \\
0 & M_{FF}
\end{bmatrix}
\delta \mathbf{u} + \begin{bmatrix}
C_{UU} + C_{SS} & C_{UF} \\
C_{FU} & -(C_{FF} + C_{uu})
\end{bmatrix}
\delta \mathbf{u} = \begin{bmatrix}
F_F \\
F_U
\end{bmatrix}
\tag{17}
$$

where $M_{SS}$, $C_{SS}$ and $K_{SS}$ are mass, damping and stiffness matrix of structure; $F_S$ is load vector acting on structure.

4. NUMERICAL EXAMPLE

4.1 Calculation Model

The length, width and height of concrete rectangular liquid storage tank (CRLST) is 6m×6m×4.8m (Cheng et al. 2017; 2018) or 12m×6m×8.4m, the wall thickness is 0.3m. Assuming the concrete material is elastic, its density is 2500kg/m$^3$, its elastic modulus is 3×10$^9$Pa, and its Poisson’s ratio is 0.2. Liquid level height is 3.6m, liquid density is 1000kg/m$^3$, and the bulk modulus is 2.3×10$^9$Pa. 8 limiting-devices are arranged at the bottom of the rectangular liquid-storage structure, bilinear material model and Beam element are used for these limiting-devices, material parameters of limiting-device are shown in Table 1 (Cheng et al. 2017). 3-D Solid element is used to simulate structure and 3-D Fluid element is used to simulate liquid.

Nonlinear contact surface is set to simulate the behavior the sliding isolation layer. Schematic diagram of connection of limiting-device is shown in Fig. 4, and the corresponding calculation models established by ADINA 9.0 are shown in Fig. 5.
Table 1 Material parameters of limiting-device

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus $E$/Pa</td>
<td>$2 \times 10^{11}$</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu$</td>
<td>0.3</td>
</tr>
<tr>
<td>Yield strength $\sigma$/MPa</td>
<td>235</td>
</tr>
<tr>
<td>Density $\rho$/kg/m$^3$</td>
<td>7800</td>
</tr>
<tr>
<td>Strain hardening modulus $E$/Pa</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>Yield strain $\varepsilon$</td>
<td>0.001</td>
</tr>
<tr>
<td>Maximum plastic strain $\varepsilon_u$</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 2 Earthquake information

<table>
<thead>
<tr>
<th>Ground motion</th>
<th>Station</th>
<th>Date</th>
<th>Ground motion</th>
<th>Station</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>El-Centro</td>
<td>USGS 5115</td>
<td>1979/10/15</td>
<td>ChiChi-TCU052</td>
<td>TCU115</td>
<td>1999/9/20</td>
</tr>
<tr>
<td>Friuli</td>
<td>USGS 5128</td>
<td>1961/4/9</td>
<td>Synthetic wave 1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Northridge</td>
<td>090 CDMG 24278</td>
<td>1994/1/17</td>
<td>Synthetic wave 2</td>
<td>--</td>
<td>--</td>
</tr>
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</table>

Table 3 Predominant period of ground motion

<table>
<thead>
<tr>
<th>Ground motion</th>
<th>Predominant period $T$/s</th>
<th>Ground motion</th>
<th>Predominant period $T$/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>El-Centro</td>
<td>0.56</td>
<td>ChiChi-CHY044</td>
<td>1.28</td>
</tr>
<tr>
<td>Friuli</td>
<td>0.26</td>
<td>HWA013</td>
<td>1.44</td>
</tr>
<tr>
<td>Imperial</td>
<td>0.14</td>
<td>ChiChi-TCU052</td>
<td>1.08</td>
</tr>
<tr>
<td>Loma</td>
<td>0.22</td>
<td>ChiChi-TCU115</td>
<td>2.22</td>
</tr>
<tr>
<td>Trinidad</td>
<td>0.28</td>
<td>TOM</td>
<td>1.14</td>
</tr>
<tr>
<td>Hollister</td>
<td>0.38</td>
<td>Artificial wave 1</td>
<td>1.14</td>
</tr>
<tr>
<td>Northridge</td>
<td>0.26</td>
<td>Artificial wave 2</td>
<td>1.30</td>
</tr>
</tbody>
</table>

In order to study the effect of far-field long-period ground motions on dynamic responses of sliding isolation concrete rectangular liquid storage tanks (CRLSTs), 6 short-period ground motions and 6 far-field long-period ground motions (4 natural ground motions and 2 synthetic waves) are selected, and the details are shown in Table 2. Acceleration, acceleration response spectra, Fourier spectra and power spectra of far-field long-period ground motion (TOM) and short-period ground motion (El-Centro) are shown in Fig. 6. Predominant periods of the selected waves are shown in Table 3.

4.2 Ground Motion Selection

In order to study the effect of far-field long-period ground motion on dynamic responses of sliding isolation concrete rectangular liquid storage tank (CRLST), 6 short-period ground motions and 6 far-field long-period ground motions (4 natural ground motions and 2 synthetic waves) are selected, and the details are shown in Table 2. Acceleration, acceleration response spectra, Fourier spectra and power spectra of far-field long-period ground motion (TOM) and short-period ground motion (El-Centro) are shown in Fig. 6. Predominant periods of the selected waves are shown in Table 3.
The predominant period compared with the ground motion is longer, and the acceleration decays slowly with period. As shown in Table 3, the predominant period of far-field long-period ground motion is obviously larger than that of short-period ground motion. Besides, the predominant period of artificial wave is also longer, so the feasibility that long-period artificial wave can be synthesized with the help of existing far-field long-period wave can be proved. In summary, duration, acceleration response spectrum, Fourier spectrum, Power spectrum and predominant period can be comprehensively used to judge whether one record is belong to far-field long-period ground motion.

### 4.3 Effect of Far-Field Long-Period Earthquake on Dynamic Responses

Because the amplitude of far-field long-period ground motion is generally small, the PGAs of the selected ground motions are adjusted to 0.22g. For concrete rectangular liquid storage tank (CRLST), the most important two types of failure modes are liquid overflow and wall cracking. After the sliding isolation measures being taken, the pipeline destruction due to excessive horizontal...
displacement will also be a failure mode. Besides, liquid pressure is also an important problem in the study of liquid storage tank. Therefore, the effect of far-field long-period earthquakes on the maximum horizontal displacement, the maximum wave height, the maximum wall tension stress and the maximum liquid pressure should be focused on research, and the specific calculation results are shown in Table 4, Table 5, Table 6, and Table 7.

As shown in Table 4, Table 5, Table 6 and Table 7, although the amplitude of PGA of far-field long-period ground motion is relatively small, the horizontal displacement and the wave height caused by this kind of ground motion is much greater than that of the short-period ground motion. On the contrary, the wall tension stress caused by far-field long-period ground motion is smaller than that of short-period ground motion, and the wall tension stress corresponding to the far-field long-period ground motion is far less than the tensile strength of concrete, so the occurrence probability of wall cracking under far-field long-period earthquake is small after sliding isolation being taken. Besides, the liquid pressure caused by far-field long-period ground motion is obviously smaller than that of short-period ground motion. It can be seen that far-field long-period ground motion mainly affects the displacement responses (horizontal displacement and wave height) of sliding isolation concrete rectangular liquid storage tank (CRLST), so the main failure modes of sliding isolation concrete rectangular liquid storage tank (CRLST) under the action of far-field long-period earthquake may be excessive horizontal displacement and liquid overflow.

### 4.4 Analysis of Seismic Isolation Effect

From the analysis of Section 4.3, wall tensile stress is small under far-field long-period ground motion, but wave height is large, which is easy to cause the occurrence of liquid overflow. Under the action of far-field long-period ground motion, it is necessary to investigate the control effect of sliding isolation on wave height. The maximum wave heights corresponding to no-isolation and isolation liquid storage tank are shown in Table 8.

As shown in Table 8, sliding isolation has certain control effect on wave height; on the contrary, the existing research results have shown that the commonly used rubber isolation had amplification effect on wave height under the action of far-field long-period ground motion (Luo et al. 2015). Because the amplitude of far-field long-period ground motion is small, the dynamic responses of structure are generally small, and sliding isolation effect on liquid storage tank can be reflected by the reduction of wave height. Compared with rubber isolation, sliding isolation has more important meaning for disaster control of concrete rectangular liquid storage tank (CRLST) under the action of far-field long-period ground motion. The control mechanism of sliding isolation for wave height needs to be further studied in the future under the action of far-field long-period ground motion.

---

**Table 6 Maximum wall tension stress/MPa**

<table>
<thead>
<tr>
<th>Short-period earthquakes</th>
<th>El-Centro</th>
<th>Imperial-Valley</th>
<th>Loma-Prieta</th>
<th>Trinidad</th>
<th>Hollister</th>
<th>Northridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far-field long-period earthquakes</td>
<td>1.445</td>
<td>1.500</td>
<td>1.446</td>
<td>1.306</td>
<td>1.390</td>
<td>1.389</td>
</tr>
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</table>

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<thead>
<tr>
<th>Far-field long-period earthquakes</th>
<th>CHY044</th>
<th>TCU052</th>
<th>TCU115</th>
<th>TOM</th>
<th>Artificial wave 1</th>
<th>Artificial wave 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid pressure/kPa</td>
<td>0.975</td>
<td>0.958</td>
<td>0.970</td>
<td>0.988</td>
<td>0.984</td>
<td>0.956</td>
</tr>
</tbody>
</table>

**Table 7 Maximum liquid pressure/kPa**

<table>
<thead>
<tr>
<th>Short-period earthquakes</th>
<th>El-Centro</th>
<th>Imperial-Valley</th>
<th>Loma-Prieta</th>
<th>Trinidad</th>
<th>Hollister</th>
<th>Northridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far-field long-period earthquakes</td>
<td>63.253</td>
<td>60.722</td>
<td>68.681</td>
<td>66.381</td>
<td>69.479</td>
<td>66.314</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Far-field long-period earthquakes</th>
<th>CHY044</th>
<th>TCU052</th>
<th>TCU115</th>
<th>TOM</th>
<th>Artificial wave 1</th>
<th>Artificial wave 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid pressure/kPa</td>
<td>46.204</td>
<td>45.345</td>
<td>41.955</td>
<td>41.827</td>
<td>43.584</td>
<td>43.090</td>
</tr>
</tbody>
</table>

**Table 8 Isolation effect on wave height/m**

<table>
<thead>
<tr>
<th>Far-field long-period earthquakes</th>
<th>CHY044</th>
<th>TCU052</th>
<th>TCU115</th>
<th>TOM</th>
<th>Artificial wave 1</th>
<th>Artificial wave 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-isolation liquid storage tank</td>
<td>0.665</td>
<td>0.810</td>
<td>0.878</td>
<td>0.754</td>
<td>0.524</td>
<td>0.682</td>
</tr>
<tr>
<td>Isolation liquid storage tank</td>
<td>0.398</td>
<td>0.511</td>
<td>0.588</td>
<td>0.420</td>
<td>0.314</td>
<td>0.391</td>
</tr>
<tr>
<td>Damping coefficient</td>
<td>0.401</td>
<td>0.369</td>
<td>0.330</td>
<td>0.443</td>
<td>0.401</td>
<td>0.427</td>
</tr>
</tbody>
</table>
Table 9 Effect of bi-directional earthquake on horizontal displacement/mm

<table>
<thead>
<tr>
<th>Far-field long-period earthquakes</th>
<th>CHY044</th>
<th>TCU052</th>
<th>TCU115</th>
<th>TOM</th>
<th>Artificial wave 1</th>
<th>Artificial wave 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional</td>
<td>60.988</td>
<td>60.226</td>
<td>100.949</td>
<td>53.483</td>
<td>79.484</td>
<td>84.900</td>
</tr>
<tr>
<td>Bi-directional</td>
<td>70.051</td>
<td>77.014</td>
<td>141.983</td>
<td>55.187</td>
<td>95.429</td>
<td>124.249</td>
</tr>
</tbody>
</table>

Table 10 Effect of bi-directional far-field long-period earthquake on wave height/m

<table>
<thead>
<tr>
<th>Far-field long-period earthquakes</th>
<th>CHY044</th>
<th>TCU052</th>
<th>TCU115</th>
<th>TOM</th>
<th>Artificial wave 1</th>
<th>Artificial wave 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional</td>
<td>0.398</td>
<td>0.511</td>
<td>0.588</td>
<td>0.420</td>
<td>0.314</td>
<td>0.391</td>
</tr>
<tr>
<td>Bi-directional</td>
<td>0.795</td>
<td>0.952</td>
<td>1.120</td>
<td>0.749</td>
<td>0.622</td>
<td>0.744</td>
</tr>
</tbody>
</table>

Table 11 Effect of structural size on horizontal displacement/mm

<table>
<thead>
<tr>
<th>Far-field long-period earthquakes</th>
<th>CHY044</th>
<th>TCU052</th>
<th>TCU115</th>
<th>TOM</th>
<th>Artificial wave 1</th>
<th>Artificial wave 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>6m×6m×4.8m</td>
<td>60.988</td>
<td>60.226</td>
<td>100.949</td>
<td>53.483</td>
<td>79.484</td>
<td>84.900</td>
</tr>
<tr>
<td>12m×6m×4.8m</td>
<td>96.856</td>
<td>351.792</td>
<td>281.161</td>
<td>524.317</td>
<td>124.737</td>
<td>408.847</td>
</tr>
</tbody>
</table>

Table 12 Effect of structural size on wave height/m

<table>
<thead>
<tr>
<th>Far-field long-period earthquakes</th>
<th>CHY044</th>
<th>TCU052</th>
<th>TCU115</th>
<th>TOM</th>
<th>Artificial wave 1</th>
<th>Artificial wave 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>6m×6m×4.8m</td>
<td>0.398</td>
<td>0.511</td>
<td>0.588</td>
<td>0.420</td>
<td>0.314</td>
<td>0.391</td>
</tr>
<tr>
<td>12m×6m×4.8m</td>
<td>0.575</td>
<td>0.601</td>
<td>0.958</td>
<td>0.779</td>
<td>0.602</td>
<td>0.690</td>
</tr>
</tbody>
</table>

4.5 Effect of Bi-directional Earthquake on Dynamic Responses

The sliding isolation system could behave differently under bi-directional earthquake, so it is necessary to study dynamic responses of sliding isolation concrete rectangular liquid storage tank (CRLST) under bidirectional far-field long-period seismic action. The ratio of PGA in x-axis direction and y-direction is adjusted to 1:0.85. It is obtained that far-field long-period ground motion mainly affects structure displacement responses of the system through the above analysis, so the influences of bi-directional far-field long-period earthquake actions on the structure displacement and liquid sloshing wave height are listed in Tables 9 and 10.

As shown in Tables 9 and 10, the maximum structure displacement and liquid wave height are obviously increased after bi-directional far-field long-period seismic action being considered. For example, under bidirectional ChiChi-TCU115 earthquake action, the structural displacement is increased by 40.65%; while under the 5 far-field long-period earthquake action, liquid sloshing wave height is amplified about 2 times. Thus, in the research and application of sliding isolation concrete rectangular liquid storage tank (CRLST) under far-field long-period earthquake action, in order to get more reasonable results and improve structure safety, effect of horizontally bi-directional far-field long-period earthquake action should be considered.

4.6 Effect of Structure Size on Dynamic Responses

In order to study the influence of structural size on the sliding isolation concrete rectangular liquid storage tank (CRLST), two sizes 6m×6m×4.8m and 12m×6m×4.8m are selected, for the latter, ground motion is input along the long axis direction. The maximum horizontal displacement and the maximum wave height corresponding to the two sizes are listed in Table 11 and Table 12.

As shown in Tables 11 and 12, the maximum horizontal displacement increases with the increase of structural size, and when the designs of friction coefficient and limiting-device are unreasonable, it is easy to produce the problem of excessive horizontal displacement. The maximum wave height also increases with the increase of structural size, when the structural size is 12m×6m×4.8m, the maximum wave height of sliding isolation liquid storage tank reaches 0.958m under the action of ChiChi-TCU115 earthquake, if the reserved no-liquid wall height is not enough, it is easy to cause liquid overflow. It can be seen that the larger the structure is, the effect of far-field long-period ground motion on displacement and wave height will be more significant.
4.7 Control Measures of Horizontal Displacement

Based on the above analysis, maximum horizontal displacement of sliding isolation concrete rectangular liquid storage tank (CRLST) increases with the increase of structure size. When the designs of friction coefficient and the limiting-device are unreasonable, the horizontal displacement is easy to exceed the limit. As shown in Table 8, horizontal displacement of concrete rectangular liquid storage tank with size of 12m×6m×4.8m are the largest, its value is 524.317mm, which has affected the effectiveness of sliding isolation structure. Therefore, the displacement control measure under the action of TOM wave is taken as an example.

4.7.1 Measure I- Adjusting Friction Coefficient

Friction coefficient is an important design parameter, which not only directly affects the effect of shock absorption, but also has a great effect on the horizontal displacement. The variation law of the maximum horizontal displacement when the friction coefficient is 0.02, 0.04, 0.06 and 0.08 is shown in Fig. 7.

As shown in Fig. 7, when the diameter of limiting-device is constantly equal to 7 cm, the maximum horizontal displacement of structure decreases with the increase of friction coefficient, but when the friction coefficient is 0.06, the horizontal displacement is still larger. Although the horizontal displacement can be reduced by further increasing the friction coefficient, the reduction effect of sliding isolation on liquid storage tank will be weakened. Therefore, controlling the horizontal displacement by only changing the friction coefficient is not enough.

4.7.2 Measure II- Adjusting Diameter of Limiting-Device

The diameter of limiting-device can affect the stiffness of isolation layer. In order to discuss the control effect of the limiting-device on the horizontal displacement, it is assumed that the diameters of limiting-device are 7cm, 8cm, 9cm and 10cm, respectively. Effect of measure II on horizontal displacement is shown in Fig. 8.

As shown in Fig. 8, when the coefficient of friction is constantly equal to 0.02, increasing the diameter of limiting-device can effectively control the horizontal displacement of structure. When the diameter of limiting-device is 10cm, the maximum horizontal displacement can be controlled within the scope of the requirements. However, if the diameter of the limiting-device is too large, the stiffness of the isolation layer will be great, as a result, the structure motion under the action of some earthquakes will be greatly restricted, so as to reduce the use range of isolation effect.

4.7.3 Measure III- Adjusting Friction Coefficient and Diameter of Limiting-Device Simultaneously

There are certain defects when only measure I or measure II is taken to achieve the displacement control, so it is necessary to study the control effect on displacement when the measures I and II are taken simultaneously. The friction coefficient is increased from 0.02 to 0.04, 0.06 and 0.08; the diameter of limiting-device is increased from 7cm to 8cm, 9cm and 10 cm. The effect of measure III on the horizontal displacement of structure is shown in Fig. 9.

As shown in Fig. 9, the horizontal displacement can be significantly reduced by increasing the friction coefficient and the diameter of limiting-device at the same time. Smaller friction coefficient can be selected, it is good to give full play to the advantage of sliding isolation for concrete rectangular liquid storage tank (CRLST); besides, the diameter of limiting-device can be designed to be smaller, the structure can still move under the action of some small earthquakes. Therefore, adjusting the friction
coefficient and the diameter of limiting-device at the same time is an effective method to control horizontal displacement of sliding isolation concrete rectangular liquid storage tank (CRLST) under the action of far-field long-period ground motion.

![Graph showing horizontal displacement over time](image)

**Fig. 9. Effect of measure III on horizontal displacement.**

### 4.8 Effects of Control Measures on Maximum Horizontal Displacement and Wave Height

In order to study the effects of displacement control measures on the system response, and provide reference for engineering application, the maximum horizontal displacement of structure and wave height corresponding to different displacement control measures are listed in Tables 13 and 14.

As shown in Table 13, purely from the point of view of displacement control, the three control measures are all effective, effect of measure III on displacement control is best, measure I is the second, measure II is the third. Comparing Tables 13 and 14, it is found that as the displacement decreases, the wave height of the liquid increases. If the displacement limit 150mm proposed in the literature (Cheng et al., 2017) is used as the control target, when friction coefficient is 0.08 and diameter of limiting-device is 7cm, the maximum displacement of the structure corresponding to measure I is 83.481mm, which meets the requirement, in this case, the maximum liquid wave height is 1.177m; when friction coefficient is 0.02 and diameter of limiting-device is 10cm, the maximum displacement of the structure corresponding to measure II is 105.544mm, which meets the requirement, in this case, the maximum liquid wave height is 1.161m; when friction coefficient is 0.06 and diameter of limiting-device is 9cm, the maximum displacement of the structure corresponding to measure III is 54.154mm, which meets the requirement, in this case, the maximum liquid wave height is 1.173m. On the whole, on the premise that the three types of control measures make the structural displacement meet the requirement, the wave height difference is small, so measures III are relatively best for displacement control of sliding isolation concrete rectangular liquid storage tank (CRLST) under far-field long-period earthquake.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Displacement/mm</th>
<th>Measure</th>
<th>Displacement/mm</th>
<th>Measure</th>
<th>Displacement/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02-7cm</td>
<td>524.317</td>
<td>0.02-7cm</td>
<td>524.317</td>
<td>0.02-7cm</td>
<td>524.317</td>
</tr>
<tr>
<td>0.04-7cm</td>
<td>397.756</td>
<td>0.02-8cm</td>
<td>386.099</td>
<td>0.04-8cm</td>
<td>216.770m</td>
</tr>
<tr>
<td>0.06-7cm</td>
<td>216.407</td>
<td>0.02-9cm</td>
<td>199.709</td>
<td>0.06-9cm</td>
<td>54.154mm</td>
</tr>
<tr>
<td>0.08-7cm</td>
<td><strong>83.481</strong></td>
<td>0.02-10cm</td>
<td><strong>105.544mm</strong></td>
<td>0.08-10cm</td>
<td>19.364mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measure</th>
<th>Wave height/m</th>
<th>Measure</th>
<th>Wave height/m</th>
<th>Measure</th>
<th>Wave height/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02-7cm</td>
<td>0.779m</td>
<td>0.02-7cm</td>
<td>0.779m</td>
<td>0.02-7cm</td>
<td>0.779m</td>
</tr>
<tr>
<td>0.04-7cm</td>
<td>0.995m</td>
<td>0.02-8cm</td>
<td>0.963m</td>
<td>0.04-8cm</td>
<td>1.093m</td>
</tr>
<tr>
<td>0.06-7cm</td>
<td>1.104m</td>
<td>0.02-9cm</td>
<td>1.125m</td>
<td>0.06-9cm</td>
<td><strong>1.173m</strong></td>
</tr>
<tr>
<td>0.08-7cm</td>
<td><strong>1.177m</strong></td>
<td>0.02-10cm</td>
<td><strong>1.161m</strong></td>
<td>0.08-10cm</td>
<td>1.183m</td>
</tr>
</tbody>
</table>

### 5. CONCLUSIONS

1. Artificial far-field long-period ground motion can be synthesized with the help of the existing far-field long period earthquake records, and the artificial wave can reflect the characteristics of far-field long-period ground motion, which can provide convenience for time history analysis of engineering structure.

2. Wave height is sensitive to far-field long-period ground motion, and far-field long-period ground motion will cause large wave height, so the risk of liquid overflow will be increased. Fortunately, the sliding isolation has certain reduction effect on wave height.

3. Large horizontal displacement of concrete rectangular liquid storage tank (CRLST) will be caused under the action of far-field long-period ground motion. Adjusting the friction coefficient and the limiting-device synthetically, the horizontal displacement of
sliding isolation concrete rectangular liquid storage tank (CRLST) could be effectively controlled.

(4) Horizontally bidirectional far-field long-period earthquake actions can further increase the horizontal displacement of structure and liquid wave height; the larger the structural size, horizontal displacement and wave height of concrete rectangular liquid storage tank (CRLST) will be larger.

(5) Far-field long-period earthquake has a great influence on the displacement responses of the system, in order to improve the effectiveness of sliding isolation concrete rectangular liquid storage tank (CRLST) under the action of far-field long-period ground motion, it should be paid attention to the control of horizontal displacement and wave height, then the reasonable design of sliding isolation concrete rectangular liquid storage tank (CRLST) can be achieved.

(6) The FSI method adopted in this paper can not consider the non-linearity of liquid sloshing completely and truly, in order to study the dynamic responses of concrete rectangular liquid storage tank (CRLST) more truly, it is necessary to simulate the sloshing behavior of liquid more reasonably based on discrete element method in future work.

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REFERENCES


