Variable friction pendulum system for seismic isolation of liquid storage tanks

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Abstract

Earthquake response of liquid storage steel tanks isolated with variable friction pendulum system (VFPS) is investigated under normal component of six recorded near-fault ground motions. The continuous liquid mass of the tank is modeled as lumped masses known as sloshing mass, impulsive mass and rigid mass. The corresponding stiffness constants associated with these lumped masses are worked out depending upon the properties of the tank wall and liquid mass. The governing equations of motion of the tanks isolated with variable friction pendulum system are derived and solved by Newmark’s step-by-step method assuming linear variation of acceleration over small time interval. In order to verify the effectiveness of the VFPS in tanks, the seismic response of tanks isolated with VFPS is compared with that of the same tanks isolated using the conventional friction pendulum system (FPS). Furthermore, a parametric study is also carried out to critically examine the behaviour of tanks isolated with VFPS. The various important parameters considered are the tank aspect ratio, the isolation period and initial time period of the VFPS. In addition, the seismic response of tanks isolated with VFPS under trigonometric cycloidal pulses is also investigated. From these investigations, it is concluded that with the installation of VFPS in tanks, the seismic response of tanks during near-fault ground motions can be controlled within a desirable range. Finally, it is also observed that the response of tanks isolated with VFPS under the near-fault ground motions and trigonometric cycloidal pulses matches well only when the isolation period reaches high values.

1. Introduction

Liquid storage tanks are lifeline structures and strategically very important, since they have vital use in industries and nuclear power plants. Unlike most structures (such as buildings or bridges), the weight of storage tanks varies in time because of variable liquid storage level, and they may contain low-temperature (e.g., LNG) or corrosive substances. Recent years have seen a number of occurrences of catastrophic failures of liquid storage tanks due to severe, impulsive, seismic events such as the 1994 Northridge earthquake in California, the 1995 Kobe earthquake in Japan and 1999 Chi-Chi earthquake in Taiwan. Such failures have been due to the number of causes with the most common being buckling of tank wall due to excessive development of compressive stresses in the wall, failure of piping system and uplift of the anchorage system. Failures of storage tanks not only instantly disrupts essential infrastructure but can also cause fires or environmental contamination when flammable materials or hazardous chemicals leak. Consequently, protection of liquid storage tanks against severe seismic events has become crucial. For over three decades, seismic isolation technology has been recognized as one of the promising alternatives for protecting liquid storage tanks against severe earthquakes. The main concept in isolation is to increase the fundamental period of structural vibration beyond the energy containing period of earthquake ground motions. The other purpose of an isolation system is to provide an additional means of energy dissipation, thereby, reducing the transmitted acceleration into the superstructure. The innovative design approach aims mainly at the isolation of a structure from the supporting ground, generally in the horizontal direction, in order to reduce the transmission of the earthquake motion to the structure.

A number of authors have discussed the effectiveness of base isolation for aseismic design of liquid storage tanks. Malhotra (1997) investigated the seismic response of base-isolated tanks and found that isolation was effective in reducing the response of the tanks over traditional fixed base tank without any
significant change in sloshing displacement. Shenton III and Hampton (1999) investigated the seismic response of isolated elevated tanks and found that seismic isolation is effective in reducing the tower drift, base shear, overturning moment, and tank wall pressure for the full range of tank capacities. Wang et al. (2001) investigated the response of liquid storage tanks isolated by friction pendulum system (FPS) and observed that the isolation was effective in reducing the response of the tanks. Shrimali and Jangid (2002) investigated the seismic response of liquid storage tanks isolated by lead–rubber bearings under bi-directional earthquake excitation and observed that the seismic response of isolated tanks is insensitive to interaction effect of the bearing forces. Shrimali and Jangid (2004) presented the earthquake analysis of base-isolated liquid storage tanks using linear theory of base isolation. Jadhav and Jangid (2006) investigated the seismic response of liquid storage tanks isolated by elastomeric bearings and sliding systems under near-fault ground motions and observed that both elastomeric and sliding systems were effective in reducing the earthquake forces of the liquid storage tanks. In spite of the above studies, there have not been many attempts to investigate the dynamic behaviour of liquid storage tanks under near-fault ground motions. Consequently, the effects of these motions on liquid storage tanks are not yet understood fully.

Near-fault ground motion can introduce more devastating response to isolated structures than an equal or larger (higher peak ground acceleration) far-field ground motion (Loh et al., 2002). Such strong response especially large isolator displacement will lead to very large isolators, costly flexible connections for utilities and an extensive and expensive loss of space for a seismic gap or moat. Moreover, if the seismic gap is inadequate to accommodate such large isolator displacement, then the resulting impact response can be undesirable (Nagarajiah and Sun, 2001). To reduce this displacement, supplementary dampers are often prescribed. However, additional damping may also increase the internal motion of the superstructure as well as increase accelerations, thus defeating many gains for which base isolation is intended. Therefore, control of large isolator displacement has been of special concern in recent research. This concern profoundly influenced seismic isolation design requirements in the 1997 Uniform Building Code (ICBO, 1997). In the earlier code, there were no near-fault effects but in the recent code, near-fault effects viz. source type and distance dependent near-fault factors to the customary design spectrum have been introduced. However, it is believed that these factors are not sufficient to solve the problem consistently, because they pay little attention to the physical characteristics of near-fault ground motions. In view of this, it is necessary to conduct the reliable numerical studies on the behaviour of base-isolated liquid storage tanks under near-fault ground motions in order to control the large isolator displacement as well as to provide assistance to current research and engineering practice.

In this paper, the seismic response of liquid storage slender and broad tanks isolated with variable friction pendulum system (VFPS) is investigated under near-fault ground motions. The specific objectives of the present study may be summarized as: (i) to study the dynamic behaviour of liquid storage tanks isolated with VFPS under near-fault ground motions, (ii) to compare the seismic response of liquid storage tanks isolated with VFPS and FPS in order to measure the effectiveness of VFPS, (iii) to investigate the influence of important parameters on the response of liquid storage tanks isolated with VFPS through a parametric study. The important parameters considered are the tank aspect ratio, the isolation period and initial time period of the VFPS and (iv) to study the seismic response of liquid storage tanks isolated with VFPS under trigonometric cycloidal pulses.

2. Near-fault ground motions

Seismologists have identified the forward directivity and fling-step as the primary characteristics of near-fault ground motions. These characteristics make near-fault earthquakes unique compared to far-field ground motions. The fling-step usually induces only limited inertial demands on structures due to the long-period nature of the static displacement. On the other hand, ground motions that are influenced by forward-directivity effects can be very damaging to structures. Forward-directivity effects are seen when the rupture direction is aligned with the direction of slip, and the rupture front moves towards a given site. These conditions occur readily in strike-slip earthquakes when the rupture propagates horizontally towards a given site. Forward directivity can also occur for dip–slip faulting; although, the conditions required are met less readily than for strike-slip faulting. During the last two decades, an ever increasing database of recorded ground motions have demonstrated that the kinematic characteristics of the ground motion near the faults of major earthquakes contain large displacement pulses, say one or two pulses from 0.5 m to more than 1.5 m with peak velocity of 0.5 m/s or higher. Their period is usually in the range of 1–3 s, but it can be as long as 6 s. Such distinct pulses do not exist in ground motions recorded at locations away from the near-fault region, i.e., El Centro 1940 earthquake ground motion. In some cases, the coherent pulse is distinguishable not only in the displacement and velocity histories, but also in the acceleration history. In other cases, acceleration histories recorded near the source contain high-frequency spikes and resemble the traditional random-like signal; however, their velocity and displacement histories uncover a coherent long-period pulse with some overriding high-frequency fluctuations.

Six near-fault ground motions are selected for the present study. The details of these recorded near-fault ground motions are shown in Table 1. The acceleration and displacement spectra of the six ground motions for 5% damping are shown in Fig. 1. The spectra of these ground motions indicate that the ground motions are recorded at a firm soil or rock site.

3. Modeling and idealization

The model considered for the base-isolated cylindrical liquid storage tanks is shown in Fig. 2 in which the VFPS is installed between base and foundation of the tank. The contained liquid is considered as incompressible, inviscid and has irrotational flow. During the base excitation, the entire tank liquid mass vibrates in three distinct patterns such as sloshing or convective mass (i.e.,
Table 1
Details of near-fault ground motions selected for the study

<table>
<thead>
<tr>
<th>Near-fault earthquake motions (normal component)</th>
<th>Recording station</th>
<th>Magnitude ($M_w$)</th>
<th>PGA (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 15, 1979 Imperial Valley, California</td>
<td>El Centro Array #5</td>
<td>6.4</td>
<td>0.36</td>
</tr>
<tr>
<td>October 15, 1979 Imperial Valley, California</td>
<td>El Centro Array #7</td>
<td>6.4</td>
<td>0.45</td>
</tr>
<tr>
<td>January 17, 1994 Northridge, California</td>
<td>Rinaldi</td>
<td>6.7</td>
<td>0.87</td>
</tr>
<tr>
<td>June 28, 1992 Landers, California</td>
<td>Lucerne Valley</td>
<td>7.3</td>
<td>0.71</td>
</tr>
<tr>
<td>January 17, 1994 Northridge, California</td>
<td>Newhall</td>
<td>6.7</td>
<td>0.70</td>
</tr>
<tr>
<td>January 17, 1994 Northridge, California</td>
<td>Sylmar</td>
<td>6.7</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Note: PGA, peak ground acceleration.

top liquid mass controlling the free liquid surface), impulsive mass (i.e., intermediate liquid mass vibrating along with tank wall) and rigid mass (i.e., the lower liquid mass which rigidly moves with the tank wall). There are various modes in which sloshing and impulsive masses vibrate but the response can be predicted by considering first sloshing mode and first impulsive mode as observed experimentally by Kim and Lee (1995) and numerically by Malhotra (1997). Therefore, the continuous liquid is modeled by lumped masses as suggested by Haroun (1983) with flexible tank. These lumped masses are referred as sloshing mass, $m_c$, impulsive mass, $m_i$ and rigid mass, $m_r$. Thus, the base-isolated tank system has three degrees of freedom under uni-directional earthquake excitation. These degrees of freedom are denoted by $u_c$, $u_i$ and $u_b$, which denote the absolute displacement of sloshing, impulsive and rigid masses, respectively.

The various assumptions made for the system under consideration are as follows:

1. The sloshing and impulsive masses are connected to the tank wall by corresponding equivalent spring having stiffness $k_c$ and $k_i$, respectively, and are worked out depending upon the properties of the tank wall and liquid mass.
2. The self-weight of the tank is neglected since it is very small (less than 5% of the effective weight of the tank).
3. The damping constant associated with the movement of sloshing and impulsive masses is expressed by the assumed damping ratio.
4. The friction coefficient of the VFPS is assumed to be independent of the relative velocity at the sliding interface. This is based on the findings that such effects do not have noticeable effects on the peak response of the isolated structural system (Fan et al., 1990).
5. The restoring force provided by the VFPS is considered as linear (i.e., proportional to the relative displacement).
6. The system is excited by normal component of near-fault ground motion only and the contribution of parallel component is ignored. This is based on the findings that the resultant maximum isolator displacement is mainly due to the normal motion.
component of the near-fault ground motions (Jangid and Kelly, 2001; Rao and Jangid, 2001; Jadhav and Jangid, 2006).

The sloshing, impulsive and rigid masses in terms of liquid mass, \( m \) are expressed as

\[
m_c = Y_c m \tag{1a}
\]

\[
m_1 = Y_1 m \tag{1b}
\]

\[
m_t = Y_t m \tag{1c}
\]

\[
m = \pi R^2 H \rho_w \tag{1d}
\]

where \( \rho_w \) is the mass density of the tank liquid; \( Y_c, Y_1 \) and \( Y_t \) are the mass ratios which are function of average thickness of tank wall, \( t_h \) and aspect ratio of the tank, \( S = H/R; H \) is liquid height; and \( R \) is radius of the tank.

For \( t_h/R=0.004 \), the various mass ratios are expressed (Haroun, 1983) as

\[
Y_c = 1.01327 - 0.87578S + 0.35708S^2 - 0.06692S^3 + 0.00439S^4 \tag{2a}
\]

\[
Y_1 = -0.15467 + 1.21716S - 0.62839S^2 + 0.14434S^3 - 0.0125S^4 \tag{2b}
\]

\[
Y_t = -0.01599 + 0.86356S - 0.30941S^2 + 0.04083S^3 \tag{2c}
\]

The fundamental frequency of impulsive mass, \( \omega_i \) and of sloshing mass, \( \omega_c \) are given by the following expressions as

\[
\omega_i = \frac{P}{H} \sqrt{\frac{E}{\rho_w}} \tag{3a}
\]

\[
\omega_c = \sqrt{1.84 \left( \frac{g}{R} \right) \tanh(1.84S)} \tag{3b}
\]

where \( E \) and \( \rho_w \) are the modulus of elasticity and density of tank wall, respectively; \( g \) is the acceleration due to gravity; and \( P \) is a dimensionless parameter expressed as

\[
P = 0.037085 + 0.084302S - 0.05088S^2 + 0.012523S^3 - 0.0012S^4 \tag{3c}
\]

The Eqs. (2)–(4) for modeling of liquid storage tank are taken from Shrimali and Jangid (2004) derived by curve fitting of from the charts given by Haroun (1983) for \( t_h/R=0.004 \). The similar equations can also be worked out for other \( t_h/R \) ratios.

The equivalent stiffness and damping of the sloshing and impulsive masses are expressed as

\[
k_c = m_c \omega_i^2 \tag{5a}
\]

\[
k_i = m_i \omega_i^2 \tag{5b}
\]

\[
c_c = 2 \xi_c m_c \omega_c \tag{5c}
\]

\[
c_i = 2 \xi_i m_i \omega_i \tag{5d}
\]

where \( \xi_c \) and \( \xi_i \) are damping ratio of sloshing and impulsive masses, respectively.

4. Variable friction pendulum system

The VFPS is very similar to FPS in regards of details as shown in Fig. 3(a). The difference between FPS and VFPS is that the friction coefficient of FPS is considered to be constant whereas the friction coefficient of VFPS is varied in form of curve as shown in Fig. 3(b). The equation to define the curve for friction coefficient of VFPS is shown as follows:

\[
\mu = (\mu_0 + a_1 |x_b|) e^{-a_2 |x_b|} \tag{6}
\]

where \( \mu_0 \) is the initial value of friction coefficient; \( a_1 \) and \( a_2 \) are the parameters that describe the variation of friction coefficient along the sliding surface of VFPS; and \( x_b \) is the isolator displacement.

Referring Fig. 1(b), the initial stiffness, \( k_i \) of the VFPS can be written as

\[
k_i = \frac{\mu_{\text{max}} W}{x_{b,\text{max}}} \tag{7}
\]

where \( \mu_{\text{max}} \) is the peak friction coefficient of the VFPS; \( x_{b,\text{max}} \) is the isolator displacement corresponding to peak friction coefficient of VFPS; \( W = Mg \) is the effective weight of the tank; and \( M = m_c + m_i + m_t \) is the total effective mass of the isolated liquid storage tank.

Accordingly, the initial time period, \( T_i \) of the VFPS is given by

\[
T_i = 2\pi \sqrt{\frac{M}{k_i}} \tag{8}
\]

The value of \( x_{b,\text{max}} \) is found out by maximizing the friction coefficient of VFPS and it is given by

\[
x_{b,\text{max}} = \frac{a_1 - \mu_0 a_2}{a_1 a_2} \tag{9}
\]
Knowing initial value of friction coefficient (that is assumed as 0.025) and selecting initial time period and peak friction coefficient, the parameters \(a_1\) and \(a_2\) can be evaluated by using Eqs. (6)–(9).

The restoring force of the VFPS is expressed by

\[
F_b = k_b u_b + F_x
\]

(10)

where \(F_x\) is the frictional force in the VFPS; and \(k_b\) is the stiffness of the VFPS.

The limiting value of the frictional force, \(Q\), to which the VFPS can be subjected (before sliding) is expressed as

\[
Q = \mu W
\]

(11)

where \(\mu\) is the friction coefficient of the VFPS.

The stiffness, \(k_b\), of the VFPS is designed so as to provide the specific value of the isolation period, \(T_b\), expressed as

\[
T_b = 2\pi \sqrt{\frac{M}{k_b}}
\]

(12)

Thus, the modeling of VFPS (refer Fig. 3(c)) requires the specification of two parameters, namely the isolation period, \(T_b\) and the friction coefficient, \(\mu\). The latter parameter can be defined by two parameters, viz. initial time period, \(T_i\) and peak friction coefficient, \(\mu_{\text{max}}\).

5. Governing equations of motion

The governing equations of motion of isolated liquid storage tank subjected to uni-directional near-fault ground motion are expressed in the matrix form as

\[
[M]\ddot{x} + [C]\dot{x} + [K]x + \{F\} = -[M]\{r\} \ddot{u}_g
\]

(13)

where \(\{x\} = \{x_c, x_r, x_b\}\) and \(\{F\} = \{0, 0, F_i\}\) are the relative displacement and frictional force vectors, respectively; \(x_c = u_c - u_0\) is the displacement of the sloshing mass relative to bearing displacement; \(x_r = u_r - u_0\) is the displacement of the impulsive mass relative to bearing displacement; \(x_b = u_b - u_0\) is the displacement of the bearing relative to ground; \([M]\), \([C]\), and \([K]\) are the mass, damping and stiffness matrix of the system, respectively; \(\{r\} = \{0, 0, 1\}\) is the influence coefficient vector; \(\ddot{u}_g\) is the earthquake ground acceleration; \(T\) denotes the transpose; and over-dots indicate derivative with respect to time.

The matrices \([M]\), \([C]\) and \([K]\) are expressed as

\[
[M] = \begin{bmatrix} m_c & 0 & m_c \\ 0 & m_i & m_i \\ m_c & m_i & M \end{bmatrix}; \quad [C] = \begin{bmatrix} c_c & 0 & 0 \\ 0 & c_i & 0 \\ 0 & 0 & 0 \end{bmatrix}; \quad \text{and} \quad [K] = \begin{bmatrix} k_c & 0 & 0 \\ 0 & k_i & 0 \\ 0 & 0 & k_b \end{bmatrix}
\]

(14)

The coupled governing equations of motion of the base-isolated liquid storage tanks cannot be solved using the classical modal superposition technique due to non-linear force-deformation behaviour of the VFPS. As a result, the governing equations of motion are solved in the incremental form using Newmark’s step-by-step method assuming linear variation of acceleration over small time interval, \(\Delta t\). Due to the highly non-linear behaviour of the system, a very small time steps of the order of 0.001 s such that it is at least one-hundred of the impulsive period of the liquid storage tank. To stop the Newmark iterations in each time step, the following convergence criteria is selected

\[
\text{Relative error} = \frac{|(\Delta x)^{j+1} - (\Delta x)^j|}{|(\Delta x)^j|} \leq \varepsilon
\]

(15)

where \(\Delta x\) is the incremental relative displacement; \(j\) is the iteration number; and \(\varepsilon\) is a small threshold parameter. The convergence parameter \(\varepsilon\) is taken as \(10^{-5}\) in each time step.

6. Numerical study

The seismic response of liquid storage tanks isolated with VFPS under normal component of six near-fault ground motions is investigated. For comparative and detailed parametric study, two different types of tanks, namely, the broad and slender tanks are considered. The tank parameters such as damping ratio of convective mass, \(\xi_c\) and the impulsive mass, \(\xi_i\) are taken as 0.5% and 2%, respectively. The tank wall considered is made of steel with a modulus of elasticity of \(E = 200\ \text{GPa}\) and mass density, \(\rho_s = 7900\ \text{kg/m}^3\). The properties of the broad and slender tanks taken from Shrimali and Jangid (2002) are: (i) aspect ratio, \(S\) for broad and broad tanks is 1.85 and 0.6, respectively; (ii) the height, \(H\), of water filled in the slender and broad tanks is 11.3 and 14.6 m, respectively; (iii) the natural frequencies of convective mass, \(\omega_c\) and impulsive mass, \(\omega_i\) for the broad and slender tank are 0.123, 3.944 Hz and 0.273, 5.963 Hz, respectively; and (iv) the ratio of tank wall thickness to its radius, \(t_\|/R\) is taken as 0.004 for both the tanks. Note that the same value of \(t_\|/R = 0.004\) is used in deriving Eqs. (2a)–(2c) and (4).

The response quantities of interest of liquid storage tank are base shear, \(F_b\) and relative displacements of sloshing mass, \(x_c\), impulsive mass, \(x_i\), and isolation system, \(x_b\). The base shear is directly proportional to hydrodynamic forces generated in the liquid storage tank. The impulsive component controls the hydrodynamic pressures, thus, the base shears and overturning moments, while the convective component controls the vertical displacements of the free-surface, hence the freeboard requirement. On the other hand, the relative isolator displacement is crucial from the design point of view of the isolator.

The time variation of base shear, sloshing displacement, impulsive displacement and isolator displacement of slender tank under Imperial Valley, 1979 earthquake ground motion (recorded at El Centro Array #5 station) is shown in Fig. 4. Two types of friction base isolators i.e., FPS (\(T_b = 2.5\ s\) and \(\mu = 0.05\)) and VFPS (\(T_b = 2.5\ s, T_i = 1.5\ s\) and \(\mu_{\text{max}} = 0.15\)) are considered for comparison of the seismic response. Figure indicates that there is significant reduction in the base shear, sloshing displacement and isolator displacement of the slender tank isolated with VFPS as compared to slender tank isolated with FPS. The peak values of the base shear, sloshing displacement and isolator displacement for FPS and VFPS are 0.25 and 0.22 W,
2004.09 and 1584.88 mm, and 310.22 and 158.73 mm, respectively. The impulsive displacement is more or less same in both isolators. The peak values of the impulsive displacement for FPS and VFPS are 2.3 and 2.5 mm, respectively. This implies that with the installation of VFPS in liquid storage tanks, the base shear, sloshing displacement and isolator displacement during the near-fault ground motions can be controlled without much alteration in the impulsive displacement. Similar differences in the response of slender tank isolated with FPS and VFPS are also depicted in Fig. 5 for Northridge, 1994 earthquake ground motion (recorded at Sylmar station). The response of the corresponding non-isolated slender tank is also shown in Figs. 4 and 5 in order to show the effectiveness of isolators. It is demonstrated from figures that isolation is quite effective in reducing the base shear and impulsive displacement without any significant change in sloshing displacement, implying that the isolation is quite effective for the aseismic design of liquid storage tanks.

Fig. 6 exhibits isolator displacement variation of base shear of liquid storage tanks isolated with FPS ($T_b = 2.5$ s and $\mu = 0.05$) and VFPS ($T_b = 2.5$ s, $T_i = 1.5$ s and $\mu_{\text{max}} = 0.15$) under Northridge, 1994 earthquake ground motion (recorded at Sylmar station). This figure shows same trends to those observed in Figs. 4 and 5. Also, it indicates that the relatively better performance of VFPS as compared to the FPS appears to be not due to energy dissipation through friction as there is not many force reversal cycles.

The effects of aspect ratio of the tank, $S$ on the peak seismic response of slender tank isolated with VFPS ($T_b = 2.5$ s, $T_i = 1.5$ s and $\mu_{\text{max}} = 0.15$) under different near-fault ground motions is shown in Fig. 7. The response of slender tank is obtained for different tank aspect ratios (i.e., 0.5–4). The figure shows that the base shear and isolator displacement initially increase as the aspect ratio increases up to 1.5 and beyond that there is no significant change in the base shear and isolator displacement. This implies that in slender tank the base shear and isolator displacement is more in comparison to that of the broad tank. The increase in sloshing displacement of isolated tank is relatively less but gets amplified with an increase of the aspect ratio. On the other hand, the impulsive displacement decreases significantly with an increase in aspect ratio. This implies that in slender tank the sloshing displacement is more than broad tank whereas the impulsive displacement is much lower than that of the broad tank.

In Fig. 8, variation of peak response of slender tank isolated with VFPS is plotted against the period of isolation under different near-fault ground motions. It is observed from Fig. 8
that the base shear of liquid storage tank isolated with VFPS under near-fault ground motions decrease with an increase of flexibility of the VFPS. This is due to the fact that with an increase of isolation period the system becomes more flexible and, as a result, transmits less earthquake acceleration into the tanks leading to a reduction in the base shear. Also, the sloshing displacement decreases with an increase in the isolation period. On the other hand, isolator displacement increases with an increase of its flexibility whereas the impulsive displacement is not much influenced due to variation of isolation period.

The variation of peak base shear, sloshing displacement, impulsive displacement and isolator displacement of slender tank against the initial time period of VFPS is shown in Fig. 9 for the six selected near-fault ground motions. It is observed from the figure that the base shear, sloshing displacement and isolator displacement first decrease, attain the minimum value, and then increase with an increase of the initial time period. On the other hand, impulsive displacement is not much influenced due to variation of initial time period. This implies that there exists a particular value of the initial time period (i.e., optimum initial time period) for which the base shear, sloshing
Fig. 8. Variation of peak base shear, sloshing displacement, impulsive displacement and isolator displacement of slender tank isolated with VFPS against isolation period under different near-fault ground motions.

Fig. 9. Variation of peak base shear, sloshing displacement, impulsive displacement and isolator displacement of slender tank isolated with VFPS against initial time period under different near-fault ground motions.
displacement and isolator displacement attain the minimum value under near-fault ground motions. The optimum initial time period of VFPS is found in the vicinity of 1.5 s.

The better performance of VFPS under near-fault ground motions can be attributed to optimum initial time period. This optimum initial time period has shifted an effective period of the isolated bridge further away from the typical pulse periods (i.e., in the range of 1–3 s) of near-fault ground motions.

7. Behaviour of liquid storage tank isolated with VFPS under trigonometric cycloidal pulses

It was shown that the near-fault ground motions come in large variations which make a consistent evaluation of near-fault effects difficult and cumbersome. If simple cycloidal pulses can be found that represent the impulsive characteristics of near-fault ground motions with reasonable accuracy, the process of response evaluation or prediction is significantly facilitated. Furthermore, the study of simple pulses along with real ground motions provides a more transparent picture of near-fault response properties and leads to a better understanding of near-fault phenomena (Alavi and Krawinkler, 2004). Trigonometric pulses are preferred to the square pulses used by Hall et al. (1995) because they do not induce infinite accelerations or jerks and allow for a simple closed-form solution that describes most of the physics of the problem at hand. Physically realizable trigonometric pulses have been introduced, and their resemblance to selected near-source ground motions has been examined in the past studies (Makris, 1997; Makris and Chang, 2000a,b) and also discussed further in Makris and Black (2004). In view of this, it will be interesting to study the behaviour of liquid storage tanks isolated with VFPS under trigonometric cycloidal pulses.

Among six near-fault ground motions, two near-fault ground motions are selected for this part of study viz. Northridge, 1994 earthquake motion (recorded at Rinaldi station) and Northridge, 1994 earthquake motion (recorded at Newhall station). Fig. 10 (left) portrays the fault-normal components of the acceleration, velocity and displacement time histories of the Northridge, 1994 earthquake recorded at the Rinaldi station. This motion resulted in a forward ground displacement that recovered partially. The velocity history has a large positive pulse and a smaller negative pulse that is responsible for the partial recovery of the ground displacement. Had the negative velocity pulse generated the same area as the positive velocity pulse, the ground displacement would have fully recovered. Accordingly, the fault-normal component of the Rinaldi station record is in between a forward and a forward-and-back pulse. Fig. 10 (right) plots the fault-normal components of the acceleration, velocity and displacement time histories of Northridge, 1994 earthquake recorded at the Newhall station. The displacement history of this ground motion exhibits one or more long-duration cycles.

Two types of cycloidal pulse (i.e., type-A and type-C) which had been developed by Makris and Chang (2000a,b) are used herein to approximate the near-fault ground motions. The cycloidal type-A pulse approximates the Northridge, 1994 (Rinaldi) earthquake motion and its mathematical models for ground acceleration, $\ddot{u}_g$, velocity, $\dot{u}_g$, and displacement, $u_g$ are expressed as

$$\ddot{u}_g(t) = \omega_p \frac{v_p}{2} \sin(\omega_p t), \quad 0 \leq t \leq T_p$$

Fig. 10. Acceleration, velocity and displacement time histories of different near-fault ground motions and trigonometric cycloidal pulses.
Fig. 11. Variation of peak base shear of liquid storage tanks isolated with VFPS against isolation period under near-fault ground motions and trigonometric cycloidal pulses.

Fig. 12. Variation of peak base shear, sloshing displacement, impulsive displacement and isolator displacement of slender tank isolated with FPS ($T_b = 2.5 \text{ s} \text{ and } \mu = 0.05$) and VFPS ($T_b = 2.5 \text{ s}, T_b = 1.5 \text{ s} \text{ and } \mu_{\text{max}} = 0.15$) against pulse period, $T_p$, under cycloidal type-A pulse.
\[ \ddot{u}_g(t) = \frac{v_p}{2} - \frac{v_p}{2} \cos(\omega_p t), \quad 0 \leq t \leq T_p \]  
\[ \dot{u}_g(t) = \frac{v_p}{2} t - \frac{v_p}{2\omega_p} \sin(\omega_p t), \quad 0 \leq t \leq T_p \]  

where \( v_p \) is peak ground velocity of near-fault pulse; \( \omega_p = 2\pi/T_p \) is circular frequency of near-fault pulse; \( T_p \) is near-fault pulse period; and \( t \) is time.

In constructing the cycloidal type-A pulse as shown in Fig. 10 (left), the values of \( T_p = 0.8 \) s and \( v_p = 1.75 \) m/s were used. These are approximations of the period and velocity amplitude of the main pulse. The peak velocity of cycloidal type-A pulse was adjusted to occur at the same time as the peak velocity of the earthquake record. Similarly, Northridge, 1994 (Newhall) earthquake motion can be approximated with cycloidal type-C pulse as shown in Fig. 10 (right).

Fig. 11 shows the variation of peak base shear of liquid storage tanks isolated with VFPS against isolation period under near-fault ground motions and trigonometric cycloidal pulses. The response of liquid storage tanks is obtained for different isolation periods (i.e., 2–5 s). By comparing the response obtained from near-fault ground motions and trigonometric cycloidal pulses, it can be concluded that the structural response quantities due to near-fault ground motions resemble the structural response quantities due to trigonometric cycloidal pulses only when the isolation period reaches high values. On the other hand, the response of liquid storage tanks with relatively low or moderate isolation periods is affected. This is due to the fact that the trigonometric cycloidal pulses can capture many of the kinematic characteristics of the displacement and velocity histories of recorded near-fault ground motions but the resulting accelerations are poor predictions of the recorded histories. This is because in near-fault ground motions there are high-frequency fluctuations that override the long-duration pulse.

Fig. 12 shows the variation of peak base shear, sloshing displacement, impulsive displacement and isolator displacement of slender tank against pulse period, \( T_p \) under cycloidal type-A pulse. The response is plotted for FPS (\( T_p = 2.5 \) s and \( \mu = 0.05 \)) and VFPS (\( T_p = 2.5 \) s, \( \mu = 1.5 \) s and \( \mu_{\text{max}} = 0.15 \)). It is observed from this figure that the cycloidal type-C pulses results in significant amplification of response when the pulse period is close to 2.5 s. This is due to the fact that the effective natural period for FPS and VFPS is 2.5 s. On the other hand, the value of \( T_P \) increases further, the near-fault effect decreases in general.

Thus, the trigonometric cycloidal pulses are very useful for obtaining the satisfactory response as well as understanding the near-fault phenomena in a better way.

8. Conclusions

The seismic response of liquid storage tanks isolated with variable friction pendulum system is investigated under six recorded near-fault ground motions. The normal component of six near-fault ground motions is utilized as input to study the variation of base shear, sloshing displacement, impulsive displacement and isolator displacement. The comparison of the seismic response of liquid storage tanks isolated with VFPS and FPS is made in order to verify the effectiveness of VFPS. Further, a parametric study has been carried out to critically examine the behaviour of liquid storage tanks isolated with VFPS. The important parameters considered are the tank aspect ratio, the isolation period and initial time period of the VFPS. In addition, the seismic response of liquid storage tanks isolated with VFPS under trigonometric cycloidal pulses is also investigated. From the trends of the results of the present study, the following conclusions may be drawn:

1. With the installation of VFPS in liquid storage tanks, the base shear, sloshing displacement and isolator displacement during near-fault ground motions can be controlled within a desirable range without much alteration to impulsive displacement.

2. The base shear and isolator displacement of liquid storage tanks isolated with VFPS under near-fault ground motions increase as the aspect ratio increases up to 1.5 and beyond that there is no significant change in base shear and isolator displacement. On the other hand, the sloshing displacement gets amplified with an increase in aspect ratio whereas the impulsive displacement decreases significantly with an increase in the aspect ratio.

3. The base shear and sloshing displacement of liquid storage tank isolated with VFPS under near-fault ground motions decrease with an increase of flexibility of isolator implying that effectiveness of VFPS increases with increase of its flexibility. On the other hand, the isolator displacement increases with an increase of its flexibility whereas the impulsive displacement is not much influenced due to variation of isolation period.

4. Under near-fault ground motions, there exists an optimum value of the initial time period of the VFPS for which the base shear, isolator displacement and sloshing displacement in liquid storage tank attain the minimum value. On the other hand, the impulsive displacement is not much influenced due to variation of initial time period.

5. The optimum initial time period of the VFPS for the liquid storage tank is found in the vicinity of 1.5 s.

6. In liquid storage tanks isolated with VFPS, the structural response quantities due to the recorded near-fault ground motions resemble the structural response quantities due to trigonometric cycloidal pulses only when the isolation period reaches high values. On the other hand, the response of liquid storage tanks with relatively low or moderate isolation periods is affected by the high-frequency fluctuations that override the long-duration pulse.

7. The trigonometric cycloidal pulses amplify the seismic response of the base-isolated liquid storage tank when the pulse period is close to the effective period of the VFPS and FPS. The amplification decreases as the pulse period becomes larger than the effective period.

References


