SEISMIC TEST OF A VERTICAL ISOLATION SYSTEM WITH PROPERTY OF HIGH-STATIC AND LOW-DYNAMIC STIFFNESS

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ABSTRACT

To achieve desired isolation efficiency, a seismic isolation system usually has to be a long-period system. For vertical isolation, this can cause conflict with regard to the demand for isolation stiffness, since a vertical isolation system must have sufficient vertical rigidity to sustain the weight of the isolated object, while it must also have sufficient flexibility in order to elongate the vibration period under seismic excitation. In order to overcome this difficulty, a novel system called an inertial-type vertical isolation system (IVIS) that possesses the property of high-static and low-dynamic stiffness is proposed in this study. The primary difference between the IVIS and a traditional vertical isolation system is that the former has an additional leverage mechanism with a counterweight. The counterweight will provide a static uplifting force and an extra dynamic inertia force, such that the effective vertical stiffness of the IVIS becomes higher in its static state and lower in the dynamic one. In this paper, the theory underlying the IVIS is introduced and verified experimentally by a seismic simulation test. The results show that the IVIS leads to a less static settlement and at the same time a lower effective isolation frequency. The test results also demonstrate that the isolator displacement demand of the IVIS is only about 30-40% that of the traditional in the four earthquakes tested. For mitigating equipment acceleration, the IVIS is particularly effective for near-fault earthquakes, but is less effective for far-field earthquakes with more high-frequency contents, as compared with the traditional system.

Keywords: vertical isolation; inertia type; equipment seismic isolation; anti-resonance isolation; shaking table test.

1. INTRODUCTION

To prevent seismic damage of interior nonstructural components, such as precision equipment or art works, a conventional approach is to use retrofitting technique by anchoring the equipment on the ground or structural floor. However, equipment anchorage may be useful in moderate earthquakes, but may fail to provide seismic protection for precision equipment under earthquakes with higher intensities [Lopez and Soong 2003]. Alternatively, a more effective means for the seismic protection of equipment in buildings is to adopt a seismic isolation technique. Nevertheless, most of existing seismic isolation applications are for isolation of horizontal ground motions only, and isolation systems that are capable of mitigating vertical seismic excitations are few [Araki et al. 2011, Tsuji et al. 2014]. This is due to a number of technical difficulties, as explained below. It is a well-known rule that a seismic isolation system should be flexible enough in the direction where the vibration response is to be mitigated; meanwhile, to ensure the system stability, the isolation system has be stiff enough to sustain the weight of the isolated subject. The above requirements cannot be easily satisfied for vertical isolation in which the directions of isolation and the gravity load are in parallel, and thus the requirements are difficult to satisfy due to conflicts with the demand for stiffness.

Seismic excitations usually have much lower frequency contents (sometimes lower than 1 Hz) and higher

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magnitudes than those of mechanical excitations; therefore, the isolation techniques for mechanical systems may not be applicable for vertical seismic isolation. To achieve desired isolation efficiency, a vertical seismic isolation system (VSIS) must have an isolation frequency much lower than that of seismic excitation. The demand on the lower vertical isolation frequency of a VSIS, which implies a lower vertical stiffness, will lead to several drawbacks, such as the large initial settlement and dynamic stroke, and these will together lead to an excessive demand on the isolation displacement and the size of isolation gap. These issues have hindered the development of vertical seismic isolation systems.

In addition to the aforementioned difficulties, the near-fault ground motions that usually accompany a strong long-period pulse waveform pose another challenging problem when developing a VSIS. Recent studies have revealed that when subjected to a near-fault earthquake with a long-period pulse, a horizontal isolation system may encounter a resonance-like response that leads to an excessive isolator displacement [He and Agrawal 2008, Lu et al. 2013]. A vertical isolation system will encounter a similar problem, since near-fault vertical earthquakes usually have the same characteristics [Ambraseys and Gourglas 2003]. Most existing vertical isolation systems do not address this resonance-like response problem [Kitamura et al. 2005, Shimada et al. 2004, Tsuji et al. 2014, Fujita 1996]. Focused on seismic protection of equipment, the objective of this study is to propose a novel vertical isolation system called an inertia-type vertical isolation system (IVIS), which has sufficient static vertical rigidity to prevent large initial settlement due to the self-weight of the isolated object, while having enough dynamic flexibility to provide isolation efficiency. Additionally, the IVIS will also have anti-resonant ability when a near-fault earthquake is encountered. The results of both theoretical and experimental studies on the proposed IVIS will be elaborated in this paper.

2. THEORY OF INERTIAL-TYPE VERTICAL ISOLATION SYSTEM (IVIS)

2.1 Mathematic model and dynamic equation of IVIS

Figures 1 and 2 show the schematic diagrams of a traditional VSIS and the IVIS, respectively. As shown, a traditional VSIS typically consists of an isolation spring and a supplementary damping device. The spring is to provide a soft layer so that the vertical seismic motion of the isolated equipment can be mitigated, the supplementary damping device is to reduce the peak isolation displacement and prevent the occurrence of large isolator stroke, the friction element is to simulate all kinds of inherent mechanical friction effects, including the friction of the guide rails. As shown in Figure 2, different from the traditional system, the IVIS is composed of a counterweight and a leverage mechanism, in addition to the isolation spring, supplementary damping and friction elements. There are two purposes for adding the counterweight and leverage mechanism. One is to prevent a large initial deformation of the spring due to the self-weight of the equipment. The other is to provide the isolated equipment with a dynamic reactive force generated by the inertia effect of the counterweight when the IVIS is vibrating, in order to prevent excessive displacement.

Before the dynamic equation of the IVIS is given, let us first define some key system parameters. As shown in Figure 2, \( M \) and \( m \) denote the mass of the isolated equipment and the counterweight, respectively. The symbols \( y_M \) and \( y_m \) represent the relative-to-ground vertical displacements of the equipment and counterweight, respectively, while \( \ddot{y}_g \) denotes the vertical ground acceleration. The variables \( f_M \) and \( f_m \) represent the reactive forces applied on the equipment and counterweight through the lever arm. The symbols \( L_M \) and \( L_m \) represent the moment arms on the equipment and counterweight sides, respectively. The parameters \( k \) and \( c \) represent the stiffness of the isolation spring and the viscous coefficient of the supplemental damping, while \( u_f \) denotes the overall friction force of the system. With the system parameters defined above, the governing equation of motion for the IVIS may be expressed as

\[
[(1 + R R_L) M] \ddot{y}_M (t) + (R^2 c) \dddot{y}_M (t) + k y_M (t) = -(1 - R) M (\ddot{y}_g (t) + g) - u_f (t)
\]

where
\[ R = \frac{mL_m}{ML_M}, \quad R_L = \frac{L_m}{L_M} \quad (2) \]

In Equation 2, \( R_L \) is moment-arm ratio. The parameter \( R \) is equivalent to the ratio of static moments applied on the two sides of the lever-arm, when the IVIS is at rest, it is called the ratio of moment. Notably, in the derivation of Equation 1, the force in each element or link is assumed positive for tension, while the displacement is assumed positive upward. Equation 1 represents the independent dynamic equation for the equipment isolated by the IVIS. In the equation, the variable \( y_M(t) \) is the only degree of freedom. Notably, Equation 1 will reduce to the dynamic equation of the traditional system shown in Figure 1, if we let \( R = 0 \) (the counterweight is removed) and \( R_L = 1 \) (no leverage effect). As compared with the equation of the traditional system, which is a simple single-DOF system, the first and second terms on the left-hand side of Equation 1 indicate that the equivalent mass and damping coefficient of the IVIS are increased by a factor of \((1 + RR_L)\) and \( R_L^2 \), respectively, due to the existence of the leverage mechanism and the inertia effect of the counterweight.

![Figure 1. Mathematical model of a traditional vertical isolation system.](image1)

![Figure 2. Mathematical model for the IVIS](image2)

### 2.2 Static property of IVIS

Since a seismic isolation system is at rest for most of its lifetime, investigating its static property is important. To this end, let \( \ddot{y}_M = \dot{y}_M = \dot{y}_g = 0 \) and \( u_f = 0 \) (friction neglected temporarily) in Equation 1, and we...
have
\[ y_M = y_{M,0} = -\frac{Mg}{k_s}, \text{ where } k_s = k/(1-R) \] (3)
or
\[ y_M = y_{M,0} = (1-R)y_0, \text{ where } y_0 = -Mg/k \] (4)

In Equations 3, and 4, \( k_s \) denotes the equivalent static stiffness of the IVIS, and \( y_{M,0} \) and \( y_0 \) represent the static initial settlements of the IVIS and its counterpart traditional system in which the leverage mechanism is removed. Notably, Equations 3, and 4 indicate that \( k_s \) and \( y_{M,0} \) are adjusted by the factor \( R \) (the moment ratio), exclusively. Furthermore, from Equation 4, we have

\[ k_s > k \text{ and } |y_{M,0}| < |y_0| \] (if \( 0 \leq R \leq 1 \)) (5)

Equation 5 states that, as compared with the traditional system, the IVIS has a higher static stiffness \( k_s \) that results in a less static deformation \( y_{M,0} \), provided that the parameter \( R \) is properly selected in the range of \( 0 \leq R \leq 1 \). The lower initial deformation has the advantage of less demand on the total elongation of the isolation spring.

### 2.3 Dynamic property of IVIS

In order to investigate the dynamic property of the IVIS, first let \( \tilde{y}_M(t) = y_M(t) - y_{M,0} \) represent the dynamic response of the IVIS that excludes the static deformation \( y_{M,0} \), then one may rewrite Equation 1 as the following non-dimensional equation

\[ \ddot{\tilde{y}}_M(t) + 2\zeta \omega \dot{\tilde{y}}_M(t) + \omega^2 \tilde{y}_M(t) = -\alpha \tilde{y}_s(t) - \frac{1}{(1+RR_L)M}u_f(t) \] (6)

In Equation 6, the non-dimensional coefficients are defined as

\[ \tilde{\omega} = \left( \frac{1}{\sqrt{1+RR_L}} \right) \omega, \quad \tilde{\zeta} = \left( \frac{R^2}{\sqrt{1+RR_L}} \right) \zeta, \quad \alpha = \frac{1-R}{1+RR_L}, \quad \omega = \sqrt{\frac{k}{M}}, \quad \zeta = \frac{c}{2\sqrt{kM}} \] (7)

where \( \tilde{\omega} \) and \( \tilde{\zeta} \) represent the equivalent isolation frequency and damping ratio of the IVIS respectively; \( \alpha \) can be treated as an influence factor of the ground excitation; \( \omega \) and \( \zeta \) represent the original isolation frequency and damping ratio without considering the leverage effect. For a special case where \( R = 0 \) (the counterweight is removed) and \( R_L = 1 \) (no leverage effect), we have \( \alpha = 1 \). In this case, Equation 1 reduces to the single-DOF dynamic equation of the tradition system (see Figure 1), with \( \omega \) and \( \zeta \) being its original isolation frequency and damping ratio, respectively. Most importantly, Equations 6, and 7 together state that the dynamic property and behavior of the IVIS can be adjusted through properly choosing the factors \( R \) and \( R_L \). Since both factors must be positive, i.e., \( R \geq 0 \) and \( R_L \geq 0 \), we have

\[ \tilde{\omega} \leq \omega, \quad \alpha \leq 1 \] (if \( 0 \leq R \leq 1 \)) (8)

Equations 7, and 8 indicate that the equivalent isolation frequency \( \tilde{\omega} \) of the IVIS is reduced by a factor of \( \sqrt{1+RR_L} \) due to the inertia effect of the counterweight, as compared with that of the traditional isolation system. The reduction in the isolation frequency implies that the IVIS is a softer system dynamically, and it generally also implies better isolation efficiency. On the other hand, Equations 6, and 8 together state that the influence of the seismic excitation \( \tilde{y}_s \) on the IVIS can be reduced by multiplying a factor of \( \alpha \leq 1 \), if \( 0 \leq R \leq 1 \).
3. FREQUENCY RESPONSE PROPERTY OF IVIS

The dynamic behavior of a system subjected to different excitation frequencies can generally be observed by its frequency response functions (FRFs). In this section, the FRFs of the IVIS will be investigated; meanwhile, in order to obtain the closed form solutions of the FRFs, the friction force of the IVIS is neglected for the time being.

Firstly, let us assume that the IVIS is subjected to a sinusoidal ground motion, i.e., $\ddot{y}_g(t) = a_g e^{i\bar{\omega}t}$, where $a_g$ and $\bar{\omega}$ being the amplitude and frequency of the excitation. As a result, the steady-state response of the IVIS can be expressed as $\ddot{y}_M(t) = y_0 e^{i\omega t}$, where $y_0$ is the vibration amplitude that can be solved by using Equation 6 and has the following form

$$y_0 = y_0(\omega) = \frac{-\left(\alpha/\bar{\omega}\right)^2}{1 - (\bar{\omega}/\omega)^2 + 2\bar{\zeta} (\bar{\omega}/\omega)i} a_g$$

(9)

The above equation is also called the displacement FRF of the IVIS. Notably, in Equation 9 $y_0$ is a complex function of $\omega$, which contains not only the information of the amplitude but also the phase angle information. Additionally, Equation 9 also defines the relationship between the amplitude $y_0$ and the parameters $\alpha$, $\bar{\omega}$ and $\bar{\zeta}$, which in turn are all functions of the factors $R$ and $R_\alpha$ (see Equation 7). On the other hand, the FRF for the absolute acceleration of the equipment isolated by the IVIS can be written as

$$a_0 = a_0(\omega) = \left\{ \frac{\alpha (\bar{\omega}/\omega)^2}{1 - (\bar{\omega}/\omega)^2 + 2\bar{\zeta} (\bar{\omega}/\omega)i} + 1 \right\} a_g$$

(10)

where $a_0$ represents the amplitude of the equipment absolute acceleration, which is equal to the sum of the relative acceleration $\ddot{y}_M$ and ground acceleration $\ddot{y}_g$. Equation 10 indicates that $\alpha$ is an important factor in determining the level of the IVIS equipment acceleration, which is a measure of isolation efficiency.

Using Equations 9, and 10, Figures 3(a), and 3(b) depict the frequency responses of the isolator displacement and equipment absolute acceleration of the IVIS, respectively, for various values of $\alpha$ and the fixed value $R_\alpha = 1$. In the figures, the system parameters and ground motion amplitude are taken to be: $\omega = 0.74$ Hz, $\bar{\zeta} = 0.15$ and $a_g = 1.0$ g. Notably, for $\alpha = 1$ where $R = 0$ (i.e., the counterweight is removed), the IVIS is reduced to a traditional isolation system. It is observed from the figures that for both displacement and acceleration responses the traditional system exerts obvious resonant behavior when the excitation frequency is close to its natural frequency, $\omega = 0.74$ Hz, whereas the resonant response is very effectively mitigated in the IVIS with a lower value of $\alpha$. However, in the range of higher excitation frequency, the acceleration
response is increased when a smaller $\alpha$ is adopted. Furthermore, from Equation 10, it is observed that the acceleration response $a_0 \approx (1-\alpha)a_g$ when the excitation frequency $\Omega$ increases, i.e., $\Omega \to \infty$. Therefore, it is not recommended to adopt an extremely small $\alpha$, even though a smaller $\alpha$ is advantageous for anti-resonance. Notably, in Figures 3(a), and 3(b), $\alpha = 0$ represents the case where the moment ratio is equal to one ($R = 1$). In this case, the moments on the two side of the lever arm are balanced statically, so the ground motion cannot exert any relative motion on the IVIS. Consequently, the absolute acceleration of the IVIS is equal to the ground acceleration, $a_0 = a_g = 1g$, regardless of the excitation frequency.

4. SHAKING TABLE TEST OF A PROTOTYPE IVIS

4.1 The prototype IVIS and instrumentation

In order to verify experimentally the isolation theory of the IVIS explained in Sections 2 and 3, a prototype IVIS was fabricated and its seismic performance was tested by using a shaking table capable of reproducing vertical seismic ground motions. The test was conducted in the seismic simulation laboratory of the National Center for Research on Earthquake Engineering (NCREE, Taipei). Figure 4 illustrates the configuration of the prototype IVIS used in the test. Moreover, the instrumentation of the test is also shown in Figure 4. An accelerometer was placed on the equipment and the shaking table to measure the acceleration of the isolated equipment and ground acceleration. Displacement sensors were placed on both the equipment and the counterweight to measure their relative-to-the-ground displacements.

Table 1 lists all the parametric values of the prototype system. These parameters show that the IVIS possesses an equivalent vibration frequency $\bar{\omega} = 0.68$ Hz that is lower than its original frequency $\omega = 0.78$Hz. This implies that the equivalent dynamic stiffness of the IVIS is softer than the original stiffness $k$. On the other hand, Table 1 also shows that the static settlement (initial displacement) of the IVIS, caused by the equipment weight, is reduced from 0.40m to 0.26m. This indicates that the IVIS has an equivalent static stiffness $k_s$ that is 50% stiffer than its original stiffness $k$. Moreover, since no viscous damping was added in the prototype IVIS, Table 1 shows $c = 0$. The primary source of damping in the system comes from the friction effect contributed by the linear bearings embedded in the joints or guide rods of the IVIS.

Figure 4. Configuration of the prototype IVIS and instrumentations for the shaking table test
Table 1. System parameters of the prototype IVIS and traditional vertical seismic isolation system used in the test.

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
<th>IVIS</th>
<th>Traditional系统</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component property</td>
<td>Mass of equipment, $M$</td>
<td>15.38 kg</td>
<td>15.38 kg</td>
</tr>
<tr>
<td></td>
<td>Counterweight, $m$</td>
<td>5.25 kg</td>
<td>5.25 kg</td>
</tr>
<tr>
<td></td>
<td>Isolation stiffness, $k$</td>
<td>372 N/m</td>
<td>372 N/m</td>
</tr>
<tr>
<td></td>
<td>Friction force, $u_{f,\max}/Mg$</td>
<td>0.031</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td>Supplemental damping coeff., $c$</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Design factor</td>
<td>Ratio of Moment, $R$</td>
<td>0.34</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Ratio of moment arm, $R_L$</td>
<td>1.00</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Reduction factor, $\alpha$</td>
<td>0.50</td>
<td>--</td>
</tr>
<tr>
<td>System frequency</td>
<td>Original frequency, $\omega = \sqrt{k/M}$</td>
<td>0.78 Hz</td>
<td>0.78 Hz</td>
</tr>
<tr>
<td></td>
<td>Effective frequency, $\bar{\omega} = \omega/\sqrt{1 + RR_L}$</td>
<td>0.68 Hz</td>
<td>--</td>
</tr>
<tr>
<td>Static settlement</td>
<td>Original settlement, $y_0 = -Mg/k$</td>
<td>-0.40 m</td>
<td>-0.40 m</td>
</tr>
<tr>
<td></td>
<td>IVIS settlement, $y_{IVIS,0} = (1 - R)y_0$</td>
<td>-0.26 m</td>
<td>--</td>
</tr>
</tbody>
</table>

4.2 Selection of ground motions

In the experiment, the vertical acceleration components of four ground motions recorded in historic earthquakes were used as the input excitations. The names and occurrence dates of these four earthquakes are as follows: (i) El Centro earthquake, 18 May 1940; (ii) Kobe (JMA) earthquake, 17 January 1995; (iii) Chi-Chi (TCU075) earthquake, 21 September 1999; and (iv) Chi-Chi (TCU102) earthquake, 21 September 1999. These four ground motions were carefully chosen, as they represent earthquakes with different characteristics. Figures 5(a) and 5(b) compares the normalized acceleration and displacement response spectra (5%-damped) of these four earthquakes, respectively. It is shown in Figure 5 that due to the characteristics of long-period pulse-like waveforms in the Kobe(JMA), Chi-Chi (TCU075) and Chi-Chi (TCU102) and earthquakes, these three earthquakes induce larger spectral values for long-period structures, whose natural period is larger than 1s, when compared to that of the El Centro earthquake. Therefore, these three earthquakes are classified as near-fault earthquakes in this study, while the El Centro earthquake is classified as a far-field earthquake.

![Figure 5](image-url)
The PGA levels of the four selected earthquakes that can be reproduced by the shaking table were restrained by the vertical stroke of the table, which has a limitation of ±100 mm. Generally speaking, a ground motion with more long-period contents (such as a near-fault earthquake) usually requires a larger table stroke. For this reason, the PGA level for each of the four ground motions in the test will be different and adjusted to the largest level that can be achieved by the shaking table. Additionally, since the Chi-Chi (TCU075) and Chi-Chi (TCU102) earthquakes have very strong long-period components (see Figure 5(b)), they are expected to have a lower achievable PGA.

5. DISCUSSIONS OF TEST RESULTS

5.1 Comparison of theoretical and experimental results

In this section, the results of the shaking table test will be presented and used to verify the IVIS isolation theory developed earlier. Figures 6(a) and 6(b) compare the experimental and simulated equipment acceleration due to the El Centro and Kobe (JMA) earthquakes, respectively. Notably, in the numerical simulations, the parametric values for the prototype IVIS listed in Table 1 were adopted, and the measured acceleration of the shaking table were taken as the input ground accelerations, so the theoretical system has exactly same excitations as the experimental one. From Figure 6 it is observed that all the simulated responses match very well with the experimental ones, this indicates that generally the dynamic equation described in Equation 1 is able to accurately predict the seismic behavior of an IVIS.

![Comparison of experimental and simulated equipment absolute acceleration of IVIS.](image1)

![Comparison of experimental and simulated hysteresis loop of IVIS.](image2)

Figure 6. Comparison of experimental and simulated equipment absolute acceleration of IVIS.

Figure 7. Comparison of experimental and simulated hysteresis loop of IVIS isolator layer.
To further investigate the isolation hysteretic behavior of the IVIS, Figure 7 compares the experimental and simulated hysteresis loops of the IVIS isolation layer, when subjected to the El Centro and Kobe (JMA) earthquakes. In the figure, because it is difficult to directly measure the total force of the isolation layer, the force in Figure 7 was obtained by using the following force-acceleration relation

\[ F_M(t) = M \ddot{a}_M(t) \]  

(11)

where \( \ddot{a}_M(t) \) is the measured equipment absolute acceleration, \( F_M(t) \) is the total force of IVIS isolation layer. Both the diagrams in Figure 7 demonstrate that the theoretical loops are able to catch the feature of the experimental loops. It is also observed that, unlike a horizontal isolator, which usually has a smooth hysteresis loop, the IVIS has more rugged loops. The irregularity is contributed by the reactive force \( f_M \) (see Figure 2) exerted by the counterweight through the lever arm. It is this force that reshapes the dynamic property of the IVIS, and affects its seismic response.

Table 2. Peak responses and isolation efficiency of the IVIS and traditional system.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>(a) PGA (g)</th>
<th>Peak responses</th>
<th>Isolation efficiency*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Isolator disp. (m)</td>
<td>Equipment acc. (g)</td>
</tr>
<tr>
<td>EL Centro</td>
<td>0.527</td>
<td>0.009</td>
<td>0.023</td>
</tr>
<tr>
<td>Kobe (JMA)</td>
<td>0.364</td>
<td>0.060</td>
<td>0.170</td>
</tr>
<tr>
<td>Chi-Chi (TCU075)</td>
<td>0.219</td>
<td>0.015</td>
<td>0.046</td>
</tr>
<tr>
<td>Chi-Chi (TCU102)</td>
<td>0.183</td>
<td>0.023</td>
<td>0.070</td>
</tr>
</tbody>
</table>

*Note: Isolation efficiency is defined as the ratio between the equipment acceleration and PGA.

5.2 Comparison with traditional isolation system

In order to demonstrate the advantages of the IVIS, the seismic responses of the IVIS measured in the test are compared with the simulated responses of a counterpart traditional isolation system. To have the same basis for comparison, in the simulation, the parameters \( M, c, k \) and \( u_f \) of the traditional system are taken to be the same as those of the IVIS as shown in Table 1. As a result, the traditional system has an isolation frequency of 0.78 Hz. The time histories of the isolation displacement and equipment accelerations of the two systems subjected to the El Centro and Kobe (JMA) earthquakes are compared in Figures 8 and 9, respectively, while peak-responses of the isolation systems due to the four earthquakes are summarized and compared in Table 2. Notably, the PGA for each vertical ground motion shown in Table 2 is the maximum value that could be achieved by the shaking table. As shown in Figure 8, the isolation displacements of the IVIS are much less than those in the traditional system for the earthquakes with either far-field (Figure 8(a)) or near-fault characteristics (Figure 8(b)). The fifth column of Table 2 indicates that the isolation displacements of the IVIS are reduced to around 30-40% those of the traditional system. Moreover, for the equipment acceleration response, Figure 9(b) shows that the IVIS has a lower acceleration response than the traditional system in the near-fault Kobe earthquakes. However, for the far-field El Centro earthquake, which has more high-frequency contents, Figure 9(a) shows that the IVIS is less effective in reducing the acceleration response. Nevertheless, the second row and the last column of Table 2 shows that the IVIS is still effective in reducing the acceleration response of the isolated equipment in the El Centro earthquake, as compared with the peak ground acceleration.

To evaluate the isolation efficiency under each of the four earthquakes, the ratios between the PGA and the peak accelerations of the IVIS and the traditional system are listed in the last two columns of Table 2, respectively. A lower value of the ratio means better isolation efficiency. Depending on the type of the
In order to overcome the conflict between the demand for static and dynamic stiffness in vertical seismic isolation, a novel inertia-type vertical isolation system (IVIS) is proposed and verified experimentally in this study. The IVIS is primarily composed of a leverage mechanism and a counterweight that produces an additional reactive force. As a result, the effective stiffness of the IVIS is shifted to a higher value statically and a lower value dynamically. This paper first derived the dynamic equation for simulating the seismic responses of the IVIS. Then, for experimental verification, a shaking table test was conducted on a prototype IVIS system subjected to four types of vertical ground motions. The following conclusions can be drawn from this work.

(1) A comparison between the frequency response functions of the IVIS and its counterpart traditional isolation system reveals that the traditional system will suffer from a resonance problem when subjected to a ground motion whose predominant frequency is close to the isolation period. The resonance problem can be effectively alleviated in the IVIS by the additional inertia force contributed by the counterweight.
The frequency response function of the IVIS is primarily determined by a key factor named the ground-motion influence factor $\alpha$, which has a suggested range of $0 < \alpha < 1$. In this range, a lower value of $\alpha$ will give the IVIS a better ability to mitigate the resonant response and to suppress the isolator displacement response; however, it will also result in a higher acceleration response for higher-frequency excitations. Therefore, it is not recommended to adopt an extreme low value of $\alpha$.

In the shaking table test, four vertical ground accelerations recorded from historic earthquakes were imposed on a prototype IVIS. The test results show that the measured displacement and acceleration responses match very well with the simulated results, especially for the acceleration responses. This proves that the seismic behavior of an IVIS system can be accurately predicted by the dynamic equation introduced in this work.

The experimental results also demonstrate that, as compared with a counterpart traditional isolation system, the isolator displacement demand of the IVIS is only about 30-40% that of the traditional system for earthquakes with either near-fault or far-field characteristics. As for reducing the equipment acceleration response, the IVIS is also more effective for near-fault earthquakes with strong long-period components. However, for the far-field earthquakes with more high-frequency contents, although the IVIS is still effective in reducing the acceleration response, it is not as good as the traditional system.

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