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THE ROLE OF RUBBER BEARINGS OF THE BRIDGES DURING THE 1999 TAIWAN CHI-CHI EARTHQUAKE

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ABSTRACT

Investigations on the 1999 Taiwan Chi-Chi earthquake indicate that most of the bridge columns experienced none to-minor damages except for those bridges directly crossed by the ruptured faults. Studies show that the functions of the bearing system, including non-bolted rubber bearings, shear keys and restrainers, plays an important role for the performance of the bridges during the earthquake. One of the reason for this unexpected performance is the way of bridge bearing construction in Taiwan. This paper aims at understanding the effect of bridge bearing systems and providing a simplified method to estimate the maximum displacement demand. Experimental studies on friction coefficients of rubber bearing on non-shrink cement mortar or concrete surface were first carried out. A SDOF bridge system with rubber bearings were also studied under pseudo-dynamic tests and verified by a numerical model. Test results show that, in a quasi-static state, the friction coefficient of rubber bearing is about 0.2 on three different contact surfaces. The numerical model is adequate to obtain the global displacement demand when the rubber bearing is simulated by a friction-pendulum element with 15-20% reduced shear stiffness during large shear deformation. Based on the experimental results, this study proposes a simplified ATC-40 method considering the equivalent friction damping to determine performance point. The numerical result of a SDOF bridge predicts the maximum displacement of the bridge deck well when compared with the mean value from 14 nonlinear time-history dynamic analyses. Results of this study help to understand the damage that may occur to the rubber bearings and bridges columns under major earthquake ground motions.

Introduction

A devastating earthquake with the magnitude of ML = 7.6 struck the central region of Taiwan in the early morning on September 21, 1999. It was known as the 921 or Chi-chi earthquake (EERI 2001). There are approximately 1,100 highway bridges spread on the provincial and county routes in the regions with major catastrophe especially in Taichung and

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Nantou counties. About 90 percent of the bridges escaped from serious damage. The extents of bridge damages are relatively minor when compared to those observed in the 1994 Northridge earthquake (EERI 1995a) and 1995 Kobe earthquake (EERI 1995b). It was observed that the friction-sliding mechanism of rubber bearings played a critical role to limit the seismic load passing to the bridge columns. Most of the bridge damage appeared to be the movement of superstructure and separation of thermal expansion joints due to sliding or failure at the bearings, with the exception of seven bridges collapsed due to large fault displacements indirectly crossed the bridges. It was also observed that the number of bridge column damage was surprisingly small. Chang et.al (Chang et.al 2004a) developed a bridge model to simulate slide-friction at rubber bearing, impact effect between shear key and girder, and hinge on the column, which well simulated a bridge damaged in the Chi-Chi Earthquake. Since most of the bridges in the damaged area of Chi-Chi earthquake were designed without ductile detailing, it may be in contrast to the current seismic design concept emphasizing the design of plastic hinge. This paper summaries the study on the effect of bridge bearing systems and proposing a simplified method to estimate the maximum displacement demand of the bridges with non-bolted rubber bearings.

Experimental Study

Two seriess of experimental programs (Chang. Et al 2004b) are carried out to understand the static and dynamic behaviors of rubber bearings. Friction coefficient test is conducted first and followed by the SDOF pseudo-dynamic test.

Friction Coefficient Test

Test Setup, Material and Procedure

Fig. 1 shows the setup of the friction coefficient test. Based on the 17th version of the Standard Specifications for Highway Bridges of AASHTO (AASHTO 2002), the size of Steel-reinforced Elastomeric Bearing specimen is determined to be 250mm×250mm×38mm (some with 46mm for different thickness of the steel layer), satisfying the requirements of compression stress, compression displacement, shear strain, and stability. The Hardness IRHD of the rubber material is 60, and shape factor is 6.1, respectively. The yielding strength of the steel layer is 245MPa. To understand the effect of roughness on different contact surfaces, three common materials used as bearing pad, such as concrete, non-shrink cement mortar, and steel are chosen to be tested the friction coefficient again the rubber material. Table 1 shows the parameters of the test specimens. Total of 24 cases of the specimens are divided into two groups: Group1(the experimental group) of 9 sets with constant speed equals to 1.27mm/sec; Group2, the control group of 15 cases with the same type of inner steel layer and constant displacement equals to 150mm. The friction coefficient test was carried out according to the prEN-1337-5(prEN 1996). The specimens are subjected to preloaded axial force for one hour before the friction test. Two vertical hydraulic actuators provide 556kN axial forces upon the two specimens; one horizontal hydraulic pushes the bearings to the specified cyclic displacement and measures the friction force. One side of the bearing is bolted on the bottom flange of the strong beam and the other side is moved along the substrate surface as shown in the Fig. 2.

Test Results

Fig. 3 shows the hysteresis curves of test No. 2, 5, 8 in group1; 10, 11 and No.12 in group 2, respectively. From Fig. 3(a) to 3(c), the parallelogram shape of the hysteresis curve is more obvious when bearings slide a longer distance. The friction force is decreasing slightly from first to final cycle due to wearing on the cover of the bearing. From Fig. 3(d) to 3(f), some jumps can be found in the first cycle for those specimens with higher speed. The friction force decreases quickly with increasing cycles due to the high temperature induced by the movement. The friction coefficient is defined as the normal force divided by the peak horizontal force. Fig. 4 shows the trend of friction coefficient in group1 under different cycles. Among three substrates, the coefficient on concrete surface is the biggest. Table 1 summarizes the friction coefficient of 24 sets, giving an average value of 0.26, or 0.22 only for 6 sets with non-shrink cement mortar. Both values are larger than the basic requirement, 0.15, for a roller-end adapting rubber bearing in the seismic design code for highway bridge structures. In addition, based on the test results in Group 2, the regression equations of friction coefficient on three substrates can be determined as a function of velocity as shown from Eq. 1 to Eq. 3. In the quasi-static state, the value is about 0.2. It is suggested that more tests data be obtained to recommend proper friction coefficients for seismic evaluation of bridges with moveable non-bolted elastomeric bearings.

$$\mu = 0.0044v^2 - 0.0221v + 0.2408 \quad \text{for concrete surface} \quad (1)$$

$$\mu = 6^{-6}v^4 - 0.0002v^3 + 0.0022v^2 + 0.0085v + 0.1969 \quad \text{for non-shrink cement mortar surface} \quad (2)$$

$$\mu = 3^{-6}v^4 + 9^{-5}v^3 - 0.0039v^2 + 0.0341v + 0.2025 \quad \text{for steel surface} \quad (3)$$

Pseudo dynamic Test

Test Setup, Material and Procedure

A pseudo dynamic test is performed to understand the bearing behavior. The same test frame used for friction coefficient test (Fig. 1) is taken as a single degree of freedom (SDOF) system with mass, {M}, transmitted from vertical loads of two hydraulic jackets, and restoring force, {R}, measured from one horizontal hydraulic jacket during the test. For the damping force, it is assumed to be zero at first, and then got through the analytical simulation. Newmark explicit integration algorithm is adapted to solve the equation of motion of this SDOF system. The input acceleration is selected at one strong-motion station TCU070 in Chi-Chi Earthquake, as shown in Fig. 5, and the corresponding peak ground acceleration (PGA) is adjusted into three levels: 0.08g, 0.33g, and 0.4g, respectively. To simulate the construction practices in most existing PCI-girder bridges in Taiwan, the test is divided by the boundary conditions: first one for bearings with two-side-free, placed directly between two substrate blocks without any bolts on the upper or bottom face of the bearing, compared to the second one with one-side-free condition, as had in the friction coefficient test. Total of six cases are shown in Table 2.

Test Results and Numerical Analysis

The test results are compared with the simulated results from an analytical model shown in the Fig. 5. In this model, the only nonlinear behavior is at the bearing in the horizontal direction when friction force is encountered, before that, it is linear to represent the elastic stiffness of the rubber. The mass and weight are assigned at the top node to reflect the real ones from the superstructure. Fig. 6 shows the comparison among test and analytical results. Obviously, only a few differences exist between these two boundary conditions. Therefore, the friction coefficient used in the analytical model can be obtained directly from the friction coefficient test by determining the velocity in Eq.1 to Eq.3 based on the duration and displacement in each test case. By this approach, the friction coefficient is 0.205, 0.207, and 0.208, respectively, corresponding to the peak ground acceleration equals to 0.1g, 0.33g, and 0.4g. In addition, the bearings appear to be warped while undergoing large shear deformation. The effective area is less than the original one. A factor, R, is induced to account for this effect by reducing 15% to 20% of the horizontal stiffness in the nonlinear region. From Fig. 7, the analytical results well predict the behavior after sliding, and get the peak displacement, though the residue displacements are improved-needed in the case with larger PGA.

Proposed Simplified Seismic Evaluation Method

A simplified seismic evaluation method to estimate maximum displacement on the girder is proposed in this paper based on the experiment results described above and Capacity-Spectrum Method (CSM) in ATC-40 (ATC 1996). The accuracy of the proposed method is also verified through the nonlinear dynamic analysis.

Seismic Demands

Total of seven ground acceleration records are chosen from Chi-Chi earthquake, and made them compatible with the design response spectrum with PGA equals to 0.28g and 0.36g, corresponding to design and maximum considerable earthquake (MCE) level, respectively, in the draft Seismic Design Provision and Commentary for Highway Bridges in Taiwan (MOTC 2004).

Structural Capacity

The pushover curve which combines the friction and hinge mechanism is generated first and is transferred to the capacity spectrum later. Fig. 8 shows the analytical bridge model, a two-degrees-of-freedom system, in which the bearing is moveable controlled by the friction force, and the column hinge follows the pivot hysteresis rule that defines the strength degradation, stiffness reduction, and pinching effect. Moreover, to find the maximum displacement, the bearing is sliding without the presence of any displacement-restrained device. The friction coefficient is assumed 0.2. The fundamental period of this model is 1.168sec. Because friction force is smaller than the column yielding force, the pushover curve tends to be an elastic-perfect-plastic curve.

Nonlinear Dynamic Analysis

Total of 14 cases in two PGA levels are analyzed. For each PGA level, the mean value shown in Table 3 about the maximum displacement on the girder from seven nonlinear cases is used as a reference to compare the results from proposed method.

Proposed Equivalent Friction Damping

Currently, the equivalent damping model in the CSM represents the energy dissipation ability resulted from the yielding of structure members. For rubber bearing, an approach is developed to determine equivalent friction damping β_{fri}. Once the pushover curve of the bridge is governed by the friction force, ideally, the base shear is unchanged as top displacement increasing. Therefore, according to the definition of equivalent damping, the expression can be simplified by taking a_y as a_{pi} in the Acceleration and Displacement Response Spectrum (ADRS) format, resulting in a equation which is only a displacement-related function. Fig. 9 shows the concept. The unknown variables are displacements at yielding d_y and performance point d_p. The total effective damping β_{eff} is sum of inherent damping β_{fri}, 5% for instance, and the friction damping in Eq. 4.

$$\beta_{fri} = \frac{1}{4\pi} \times \frac{W_D}{W_s} = \frac{1}{4\pi} \times \frac{4(d_p - d_y) \times a_y}{1/2 \times d_p \times a_y} = \frac{2}{\pi} \times \frac{(d_p - d_y)}{d_p} \quad (4)$$

$$\beta_{eff} = \beta_i + \beta_{fri} \quad (5)$$

Estimation of the Performance Point

Fig. 10 and Table 3 show the numerical results by the proposed simplified seismic evaluation method and nonlinear dynamic analysis. The propose method predicts the displacement demand with good accuracy, of which the difference in smaller than 5%. It is useful to determine the unseating length for the superstructure.

Conclusions

This paper aims at understanding the friction mechanism of the bridge bearing system and providing a simplified method to estimate the maximum displacement demand. Based on the experiences learned from Chi-Chi earthquake, two kinds of experimental programs are carried out on the rubber bearings to determine the friction coefficient and understand dynamic behaviors from pseudo dynamic tests. The friction coefficient of rubber bearing is 0.2, either on concrete, non-shrink cement mortar, or steel surface. The numerical simulation shows 15-20% reduction on the horizontal stiffness is needed to reflect the warping effect under large shear deformation. In addition, this study proposes a simplified ATC-40 method considering the equivalent friction damping to determine the performance point. The numerical result of a SDOF bridge well predicts the maximum displacement on the bridge deck in comparison with the mean value from 14 nonlinear time-history dynamic analyses. Results of this study helps to understand the damage level at rubber bearings and columns.

Acknowledgments

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Table 1. Experiment cases in the friction coefficient test

<table>
<tr><th>Group</th><th>No.</th><th>Friction substrate material</th><th>Bearing size (mm)</th><th>Inner steel plate type</th><th>Steel plate thickness (mm)</th><th>Horizontal velocity (mm/sec)</th><th>Horizontal displacement</th><th>cycles</th><th>Friction coefficient</th></tr>
<tr><td rowspan="9">1</td><td>1</td><td rowspan="3">Non-shrink cement mortar</td><td>250×250×38</td><td>SL304*</td><td>1</td><td rowspan="9">1.27</td><td>±90</td><td rowspan="24">15</td><td>0.1830</td></tr>
<tr><td>2</td><td>250×250×38</td><td>SS400</td><td>1</td><td>±90</td><td>0.2317</td></tr>
<tr><td>3</td><td>250×250×46</td><td>SS400</td><td>3</td><td>±90</td><td>0.2110</td></tr>
<tr><td>4</td><td rowspan="3">Concrete</td><td>250×250×38</td><td>SL304*</td><td>1</td><td>±60</td><td>0.2370</td></tr>
<tr><td>5</td><td>250×250×38</td><td>SS400</td><td>1</td><td>±60</td><td>0.2794</td></tr>
<tr><td>6</td><td>250×250×46</td><td>SS400</td><td>3</td><td>±60</td><td>0.2267</td></tr>
<tr><td>7</td><td rowspan="3">Steel</td><td>250×250×38</td><td>SL304*</td><td>1</td><td>±50</td><td>0.1944</td></tr>
<tr><td>8</td><td>250×250×38</td><td>SS400</td><td>1</td><td>±50</td><td>0.2165</td></tr>
<tr><td>9</td><td>250×250×46</td><td>SS400</td><td>3</td><td>±50</td><td>0.1969</td></tr>
<tr><td rowspan="15">2</td><td>10</td><td rowspan="5">Non-shrink cement mortar</td><td rowspan="15">250×250×38</td><td rowspan="15">SS400</td><td rowspan="15">1</td><td>1.27</td><td rowspan="15">±150</td><td>0.2068</td></tr>
<tr><td>11</td><td>5</td><td>0.2880</td></tr>
<tr><td>12</td><td>10</td><td>0.2671</td></tr>
<tr><td>13</td><td>15</td><td>0.2644</td></tr>
<tr><td>14</td><td>20</td><td>0.4431</td></tr>
<tr><td>15</td><td rowspan="5">Concrete</td><td>1.27</td><td>0.2381</td></tr>
<tr><td>16</td><td>5</td><td>0.2416</td></tr>
<tr><td>17</td><td>10</td><td>0.4048</td></tr>
<tr><td>18</td><td>15</td><td>-</td></tr>
<tr><td>19</td><td>20</td><td>-</td></tr>
<tr><td>20</td><td rowspan="5">Steel</td><td>1.27</td><td>0.1981</td></tr>
<tr><td>21</td><td>5</td><td>0.2706</td></tr>
<tr><td>22</td><td>10</td><td>0.3336</td></tr>
<tr><td>23</td><td>15</td><td>0.3407</td></tr>
<tr><td>24</td><td>20</td><td>0.3314</td></tr>
</table>

* SL means stainless steel

Table 2. Experiment cases in the pseudo dynamic test

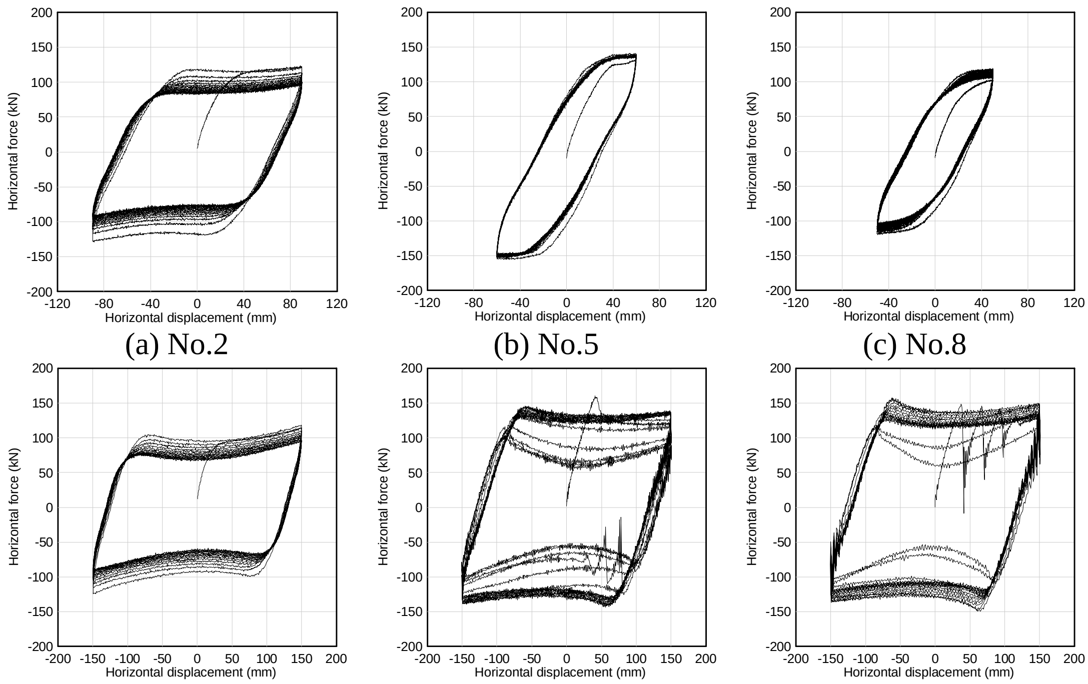
<table>
<tr><th>Boundary condition of rubber bearing</th><th>Case</th><th>Peak ground acceleration (g)</th></tr>
<tr><td rowspan="3">One-side-free</td><td>1</td><td>0.10</td></tr>
<tr><td>2</td><td>0.33</td></tr>
<tr><td>3</td><td>0.40</td></tr>
<tr><td rowspan="3">Two-side-free</td><td>4</td><td>0.10</td></tr>
<tr><td>5</td><td>0.33</td></tr>
<tr><td>6</td><td>0.40</td></tr>
</table>

Table 3. Analytical results from NDA and proposed method

<table>
<tr><th rowspan="3">Peak Ground Acceleration</th><th>Nonlinear dynamic analysis (NDA)</th><th colspan="4">Proposed method (friction coefficient = 0.2)</th></tr>
<tr><th>Displacement</th><th>Displacement</th><th>Difference</th><th>Difference percentage</th><th>Equivalent damping, β_{eff}</th></tr>
<tr><th>m</th><th>m</th><th>m</th><th>%</th><th>%</th></tr>
<tr><td>0.28g</td><td>0.1306</td><td>0.1307</td><td>0.0001</td><td>0.10</td><td>35.65</td></tr>
<tr><td>0.36g</td><td>0.1745</td><td>0.1659</td><td>-0.0086</td><td>-4.91</td><td>44.03</td></tr>
</table>

Figure 1. Test setup of the friction coefficient test

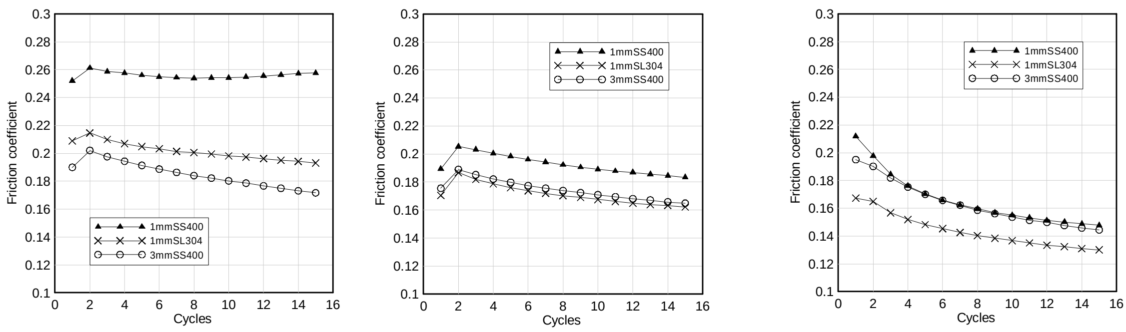
Figure 2. Friction and warping phenomenon



(a) No.2 (b) No.5 (c) No.8

(d) No.10 (e) No.11 (f) No.12

Figure 3. Hysteresis loops of the friction coefficient test



(a) No.5 (b) No.8 (c) No.2

Figure 4. Friction coefficient test results in Group1

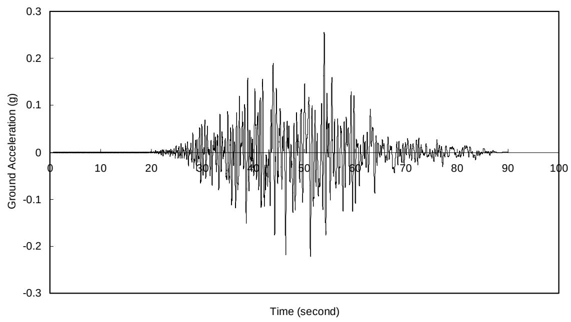


Figure 5. Input ground acceleration (TCU070)

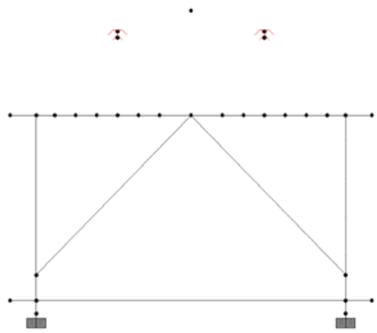
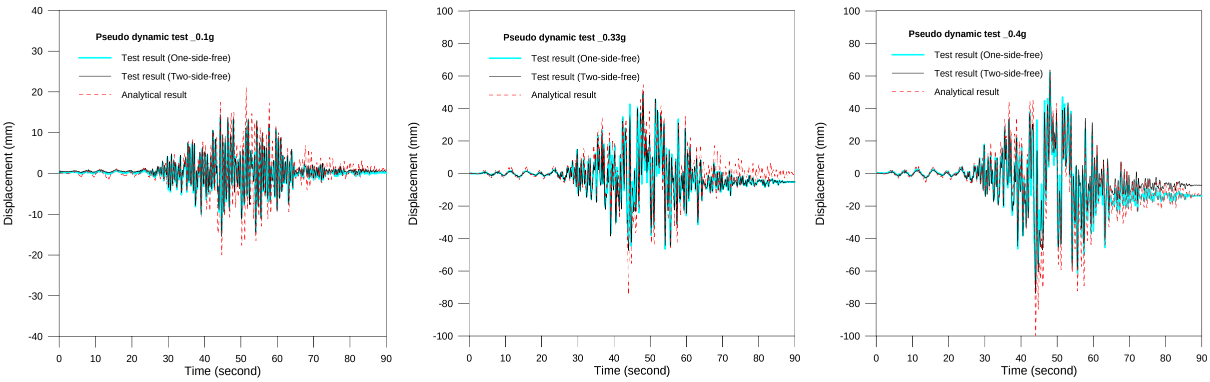


Figure 6. Analytical model



(a) 0.10g (b) 0.33g (c) 0.40g

Figure 7. Pseudo dynamic test and analytical results

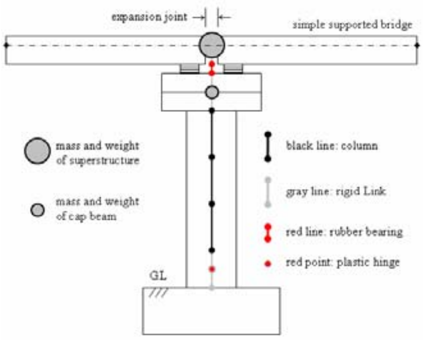


Figure 8. Analytical model for IDA

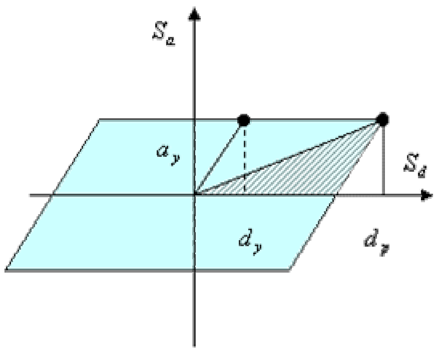


Figure 9. Concept of equivalent friction damping

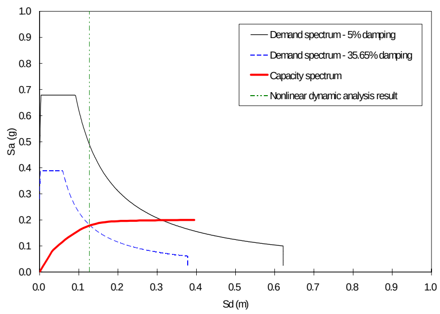


Figure 10.(a). Analytical result for PGA=0.28g

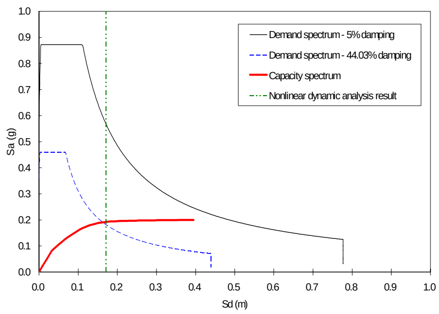


Figure 10.(b) Analytical result for PGA=0.36g