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# Experimental study on tuned liquid damper performance in reducing the seismic response of structures including soil-structure interaction effect

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**Abstract.** In this paper, the performance of a tuned liquid damper (TLD) in suppressing the seismic response of buildings is investigated with shake table testing of a four-story steel frame model that rests on pile foundation. The model tests were performed in three phases with the steel frame structure alone, the soil and pile foundation system, and the soil-foundation-structure system, respectively. The test results from different phases were compared to study the effect of soil-structure interaction on the efficiency of a TLD in reducing the peak response of the structure. The influence of a TLD on the dynamic response of the pile foundation was investigated as well. Three types of earthquake excitations were considered with different frequency characteristics. Test results indicated that TLD can suppress the peak response of the structure up to 20% regardless of the presence of soils. TLD is also effective in reducing the dynamic responses of pile foundation.

**Keywords:** tuned liquid damper; vibration control; soil-structure interaction; shaking table model test.

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## 1. Introduction

Tuned liquid damper (TLD) is a passive control device used to suppress the dynamic response of structures. Typically it consists of a rigid tank and the liquid (water) inside the tank. When the tank is subjected to horizontal motion, the liquid experiences sloshing motion. Due to its simplicity, ease in installation, and low maintenance, TLD had been studied extensively with successful engineering applications (Fujii *et al.* 1990, Wakahara *et al.* 1991, Koh *et al.* 1994, Housner *et al.* 1997, Reed *et al.* 1998, Banerji *et al.* 2000, Modi *et al.* 2002). These investigations have shown that TLD is an effective controlling device to reduce both the wind- and earthquake-induced responses of structures. However, almost all of the studies assumed that the structure to be controlled is supported on a rigid base, and the effect of soil-structure interaction (SSI) was seldom investigated in analysis and design of TLD devices. In reality, many buildings are supported on pile foundation. In this case, the interaction between soil, pile foundation and structure changes the dynamic characteristics of the soil and foundation system under consideration and, as such, the design of a TLD depends upon the soil condition of the pile foundation.

Since ten years ago, the authors of this paper have launched a series of theoretical and experimental studies on the response reduction of soil-foundation-structure systems with passive, semi-active and active control. Their studies clearly indicated that SSI has significant influences on the effectiveness of various structure control means (Lou and Wu 1997, Cheng *et al.* 1999, Chen *et al.* 2000), especially Tuned Mass Damper devices for suppressing the seismic responses of structures (Wu and Lou 1997, Lou and Wang 2004). However, SSI effects on the seismic performance of TLD devices have never been investigated. Furthermore, the effect of TLD on the dynamic responses of pile foundation was ignored in previous studies. Pile foundation is sometimes subjected to local damage under seismic excitations. Damage in pile foundation is hidden under the ground and can not be repaired easily. It will eventually threaten the safety of the supported structure. Considering the advantages of TLD devices and the above issues, the objectives of this study are to investigate the SSI effects on the TLD performance in peak response reduction of the structure by shaking table model tests, and the TLD effect on the behavior of pile foundation.

## 2. SSI system model and test facility

The scale of a physical model must be sufficiently large to make the test results representative to its prototype structure. In general, the larger the model is, the more representative the results of shaking table tests are. However, the scale of a model is often controlled by the capacity of the shaking table and physical dimension of the test facility. In the design and shake table testing of a soil-foundation-structure system model, several challenges arise. First of all, the "box effect" of a finite soil model on the SSI system performance must be taken into account. This effect can typically be minimized or completely eliminated by using a horizontal laminar shear box when the soil box is subjected to a horizontal seismic excitation only (Wu *et al.* 2002). Secondly, the material properties and geometries of soils need to be properly simulated according to the model similarity. Thirdly and lastly, the structure portion of the system model is significantly smaller than the traditional model of a structure alone as the larger and heavier soil body occupies much of the space available and uses most of the capacity of the testing facility. As a result, the fundamental frequency of the model structure alone is relatively high, which is inconsistent with the low frequency

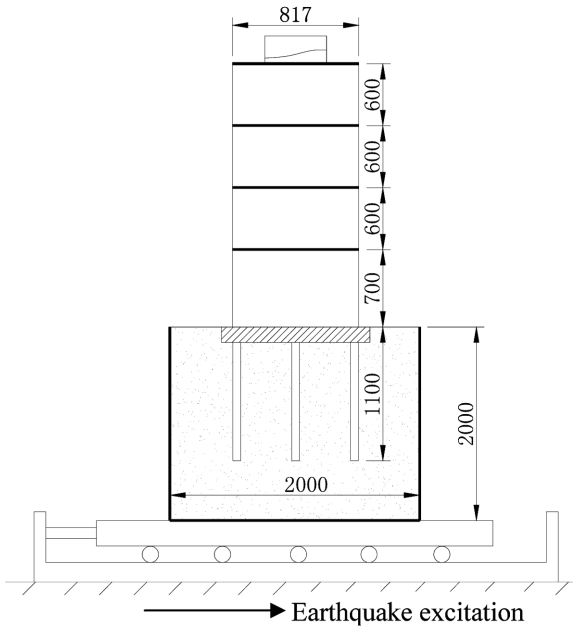



Fig. 1 Overview of the system model (all units in mm)

requirement to make a TLD more efficient. This last challenge is new and presents some difficulties to the model design and test of a soil-foundation-structure-TLD system. In this study, an emphasis has been placed on how to best select the fundamental frequencies of the structural component, TLD devices, and the finite soil body. Much of the efforts were made to reduce the fundamental frequencies of the structural and soil components.

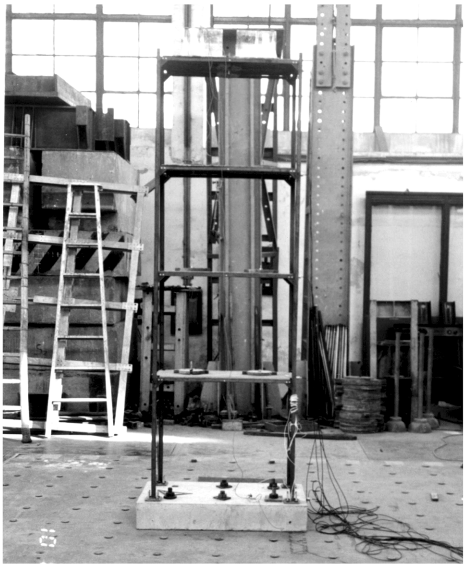
The schematic view of the soil-foundation-structure-TLD model used in this study is shown in Fig. 1. The system consists of four parts, including the building structure component, the TLD device fixed on the top floor of the building, the pile foundation, and the simulated soil body. Each part of the system is described in detail for its dimension and material properties as follows.

### *2.1 Structural component*

The structure component was a four-storey steel frame as shown in Fig. 2(a). The members of the frame were connected with bolts. To ensure the frame can only vibrate in the direction of seismic excitation during each test, the frame was diagonally braced in each story along the direction perpendicular to the seismic excitation. The overall dimensions of the steel frame were 0.817 m in length along the excitation direction, 0.417 m in width, and 2.50 m in height. From the bottom to the top, the height of each storey was 0.7, 0.6, 0.6 and 0.6 m, respectively. The average weight of each storey was approximately 21.1 kg.

### *2.2 TLD device*

The TLD device used in this study consisted of two identical cubic containers filling with water that was dyed into red with artificial colors. Each container was made of acryl glass and was



(a) Steel frame

(b) TLD device

(c) Pile


(d) Laminar shear box

Fig. 2 Four components of the experimental model

mounted on the top floor of the steel frame as shown in Fig. 2(b). To meet the similitude requirements for the cases with and without the SSI effect, two types of containers (two in each type) with a different width of 0.20 m and 0.10 m were designed. The other dimensions of all containers were 0.30 m in length and 0.15 m in height. The weight of each container without the water for both types was 2 kg.

### *2.3 Pile foundation*

The pile foundation designed for this study was composed of a reinforced concrete (RC) pile cap and six square RC piles as shown in Fig. 2(c). Both the cap and piles were reinforced with iron wires. The pile cap was designed with sufficient rigidity. Three piles were arranged along the earthquake (longitudinal) direction and two piles were along the other (transverse) direction. The pile cap weighed 226 kg and it had a dimension of 0.96 m in length, 0.56 m in width, and 0.10 m in height. Each pile was 1.0 m long and it had a cross section of 0.05 m × 0.05 m. Weighing 6.25 kg, each pile was designed to provide sufficient strength against cracking during the entire test period.

### *2.4 Soil container and materials*

The laminar shear box shown in Fig. 2(d) was used in the experiment. The box can simulate reasonably the horizontal shearing deformation of the soil layers inside the box. The overall dimensions of the box are 2.0 m in length, 1.5 m in width, and 2.0 m in height (Wu *et al.* 2002). To minimize the fundamental frequency of the materials filling in the box as much as possible, a mixture of saw dusts (2 mm or finer), fine sands, and water was used to simulate the soil materials. The new mixture of the soil materials was characterized to determine its dynamic characteristics. It was shown from these experiments that the mixed materials had consistent properties and low shear modulus. The ingredients of the simulated soils used in the final system model included 450 kg fine sands with a moisture content of 3%, 135 kg saw dusts, and 315 kg water. The volume of the soil container is 6 $m^3$, and the density, the Young's modulus and shear wave velocity of the simulated soil are approximately 1055 $kg/m^3$, $7.98 \times 10^6$ Pa and 53.67 m/s, respectively.

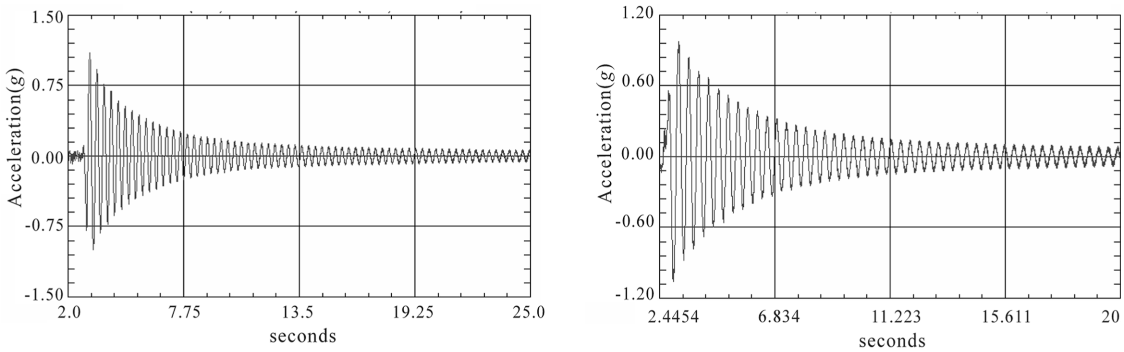
### *2.5 Shake table test facility*

Tests were conducted in the Structures Laboratory at Tongji University. An MTS shaking table with six degrees of freedom was used in this study to simulate earthquake excitations. The shaking table has a plan dimension of 4.0 m × 4.0 m, and can support a maximum payload of 25 tons. The working frequency of the table ranges from 0.1 to 50 Hz.

## 3. Dynamic characteristics of the frame and TLD device

### *3.1 Dynamic properties of the steel frame and soil-foundation-structure system*

The fundamental frequencies of the frame model supported on rigid foundation and the soil-foundation-structure system model must be identified first because these data will be used to design TLD devices. For this purpose, free vibration tests were conducted for the two models and the acceleration time histories at the top floor of the frame were plotted in Fig. 3. From the decaying envelope curve in Fig. 3, the fundamental frequencies of the frame alone and the soil-foundation-




(a) Frame on rigid foundation (b) Soil-foundation-structure system

Fig. 3 Acceleration time histories at the top floor of the frame from free vibration tests

Table 1 Fundamental frequency of TLD devices and damping ratio of the frame

| Depth of water (cm) | Frequency (Hz) | Tuning ratio | Damping ratio |
|---|---|---|---|
| 0.0 | - | - | 0.0345 |
| 5.0 | 2.660 | 0.891 | 0.0534 |
| 6.0 | 2.764 | 0.926 | 0.0476 |
| 8.0 | 2.871 | 0.962 | 0.0410 |

Table 2 Fundamental frequency of TLD devices and damping ratio of the system

| Depth of water (cm) | Frequency (Hz) | Tuning ratio | Damping ratio |
|---|---|---|---|
| 0.0 | - | - | 0.0711 |
| 5.7 | 2.5205 | 0.910 | 0.0863 |
| 7.0 | 2.5734 | 0.929 | 0.0768 |
| 9.0 | 2.6056 | 0.941 | 0.0797 |

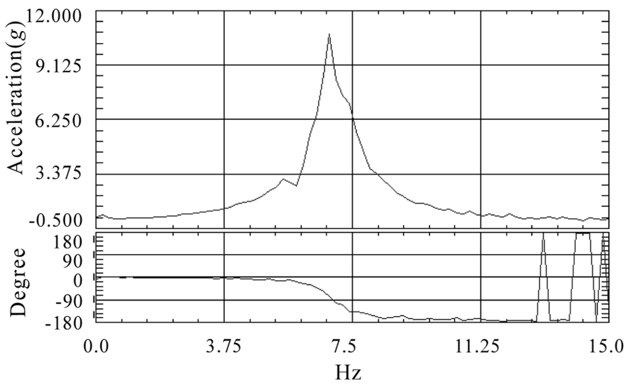



Fig. 4 Transfer functions

structure system can be identified to be 2.986 Hz and 2.772 Hz, respectively. Their corresponding damping ratios are 0.0345 and 0.0711.

### *3.2 Parameters of the TLD device*

The fundamental frequencies of one type of TLD devices for peak response reduction of the frame alone are given in Table 1 when filled with water of different depths. The tuning frequency ratio between each TLD and the frame structure and damping ratio of the frame structure are also included in Table 1. For the soil-foundation-structure system, the fundamental frequencies of the other type of TLD devices, the tuning frequency ratio between each TLD and the system, and damping ratio of the system are presented in Table 2.

### *3.3 Parameters of the simulated soil materials*

To identify the dynamic properties of the soil materials, shake table tests of the soil body inside the shear box were conducted under the excitation of white noise. The ground acceleration at the center point of the soil body and the shake table acceleration were recorded and their Fourier Spectra were performed, respectively. The ratio between the two spectra or transfer function in terms of amplitude and phase angle is shown in Fig. 4. From the transfer function, the fundamental frequency of the simulated soil body can be identified to be 6.836 Hz and its corresponding damping ratio is 0.0472. At the peak of the transfer function, the phase angle of the top-floor acceleration is approximately 90$^o$.

## 4. Procedure of shaking table model tests

### *4.1 Earthquake excitations*

Three time histories of modified seismic waves were used as the excitations of various shaking table tests. As shown in Fig. 5, these seismic waves are the S00E component of the 1940 El Centro earthquake record (EC Wave), the spectrum-compatible simulated wave at bedrock (SHJ Wave) in Shanghai, China, and the spectrum-compatible wave at ground surface (SH Wave) in Shanghai, China. The Fourier spectra of these time histories are also shown in Fig. 5. It can be seen from these Fourier spectra that the predominant frequency of the three excitations is in the range of 3-9 Hz, 8-20 Hz, and 1-5 Hz, respectively.

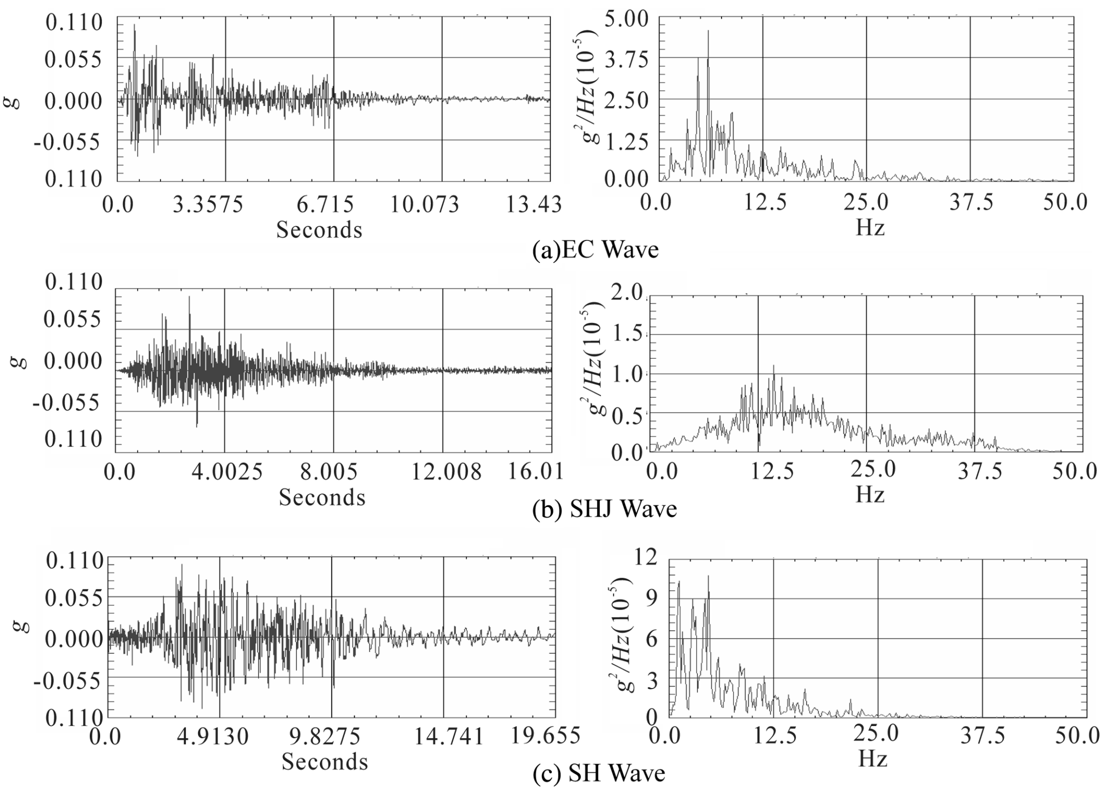
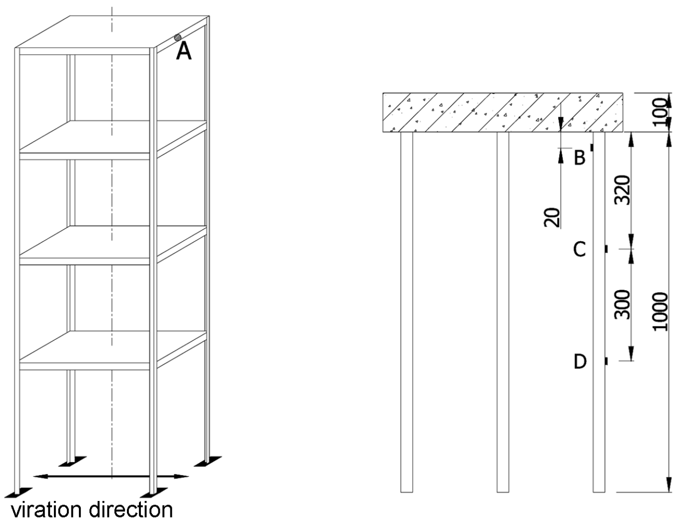



Fig. 5 Time histories and Fourier spectra of seismic excitations




(a) Accelerometers on the frame (b) Strain gauges on the pile

Fig. 6 Deployment of accelerometers and strain gauges

### *4.2 Test procedure*

Except for dynamic characterization of the two physical models, all tests consisted of three main stages. In the first stage, the frame structure with two TLD containers/devices was mounted directly on the shaking table, which represented that the structure to be controlled was fixed on rigid foundation. Four cases were considered with different depths of the water in the TLD containers. The depth of the water was selected as 0, 5, 6 and 8 cm, respectively. In each case, the frame structure was excited by the shaking table under the white noise wave, EC Wave, SHJ Wave, and SH Wave, respectively. For each seismic wave except the white noise, its peak acceleration increased from 0.1 g to 0.3 g by the interval of 0.1 g.

In the second stage, the laminar shear box containing the soil-foundation system was installed on the shaking table. The dynamic amplification factors of the system were measured under different seismic waves of various peak accelerations. In the third stage, the frame structure with two TLD containers was fixed on the pile cap. In this stage, SSI effects on the structural response were fully taken into account. The water depth in the TLD containers was selected as 0.0, 5.7, 7.0 and 9.0 cm, respectively. Similar to the first stage, the soil-foundation-structure system was excited with four seismic waves for different TLD water depths, respectively. For each seismic wave, two peak acceleration values were considered. For the frame structure, the peak acceleration at the top story was of interest in this experiment. During the first and the third test stages, the acceleration sensor at the top floor is labeled as ‘A’ in Fig. 6(a). To investigate the effect of TLD devices on the dynamic response of pile foundation during the third stage, three strain gauges ‘B’, ‘C’, ‘D’ were attached on the pile as shown in Fig. 6(b).

Table 3 Peak acceleration (g) of the frame and TLD control efficiency (no SSI, EC Wave)

| $\beta$ | 0.1 g | | | 0.2 g | | | 0.3 g | | |
|---|---|---|---|---|---|---|---|---|---|
| | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) |
| 0.891 | 0.1383 | 0.1446 | 4.36 | 0.2441 | 0.2707 | 9.83 | 0.3292 | 0.3946 | 16.57 |
| 0.926 | 0.1390 | 0.1401 | 0.79 | 0.2453 | 0.2741 | 10.51 | 0.3205 | 0.3962 | 19.11 |
| 0.962 | 0.1386 | 0.1414 | 9.05 | 0.2303 | 0.2720 | 15.33 | 0.3039 | 0.4012 | 24.25 |

Table 4 Peak acceleration (g) of the frame and TLD control efficiency (no SSI, SHJ Wave)

| $\beta$ | 0.1 g | | | 0.2 g | | | 0.3 g | | |
|---|---|---|---|---|---|---|---|---|---|
| | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) |
| 0.891 | 0.1863 | 0.1957 | 4.78 | 0.3460 | 0.3600 | 3.88 | 0.4440 | 0.4835 | 8.17 |
| 0.926 | 0.1825 | 0.1922 | 5.05 | 0.3479 | 0.3584 | 2.92 | 0.4464 | 0.4838 | 7.73 |
| 0.962 | 0.1884 | 0.1916 | 1.67 | 0.3348 | 0.3600 | 6.99 | 0.4383 | 0.4901 | 10.56 |

Table 5 Peak acceleration (g) of the frame and TLD control efficiency (no SSI, SH Wave)

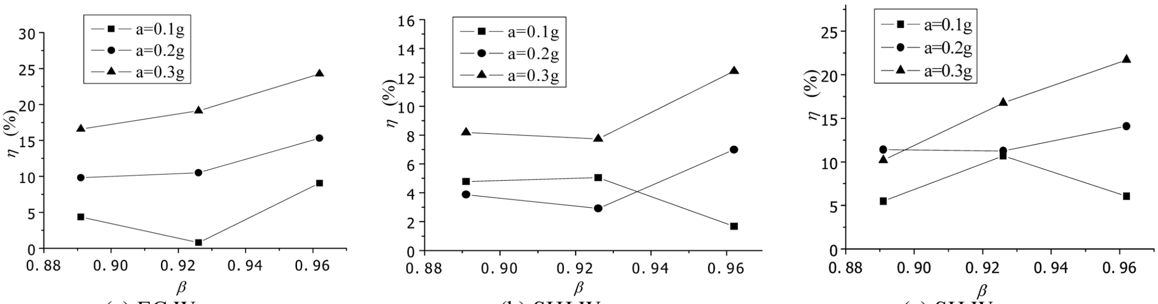
| $\beta$ | 0.1 g | | | 0.2 g | | | 0.3 g | | |
|---|---|---|---|---|---|---|---|---|---|
| | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) |
| 0.891 | 0.2777 | 0.2938 | 5.48 | 0.4255 | 0.4803 | 11.41 | 0.5492 | 0.6115 | 10.19 |
| 0.926 | 0.2729 | 0.3056 | 10.70 | 0.4161 | 0.4686 | 11.26 | 0.4450 | 0.5347 | 16.78 |
| 0.962 | 0.2186 | 0.2327 | 6.06 | 0.3684 | 0.4288 | 14.09 | 0.3828 | 0.4890 | 21.72 |

## 5. Test results and analysis

### *5.1 Responses of the frame structure without SSI effects*

Tables 3-5 give the maximum acceleration at the top floor of the frame that was supported on the rigid foundation. Among various test cases, the results measured from the accelerometers cannot be directly compared because the peak acceleration at the shake table may fluctuate from one to another case even though a closed-loop control system in the MTS shake table has been in place. Therefore, the direct measurements (raw data) from each test must be modified to represent the same level of excitations. The modified data for three seismic waves are listed in Tables 3, 4, and 5, respectively. In the top row of the tables, there are three levels of the modified peak acceleration values for each seismic input, such as 0.1 g, 0.2 g and 0.3 g. In the tables, the parameter $\beta$ is the ratio of the fundamental frequency of the TLD devices over the first modal frequency of the frame structure, and $g$ denotes the gravity acceleration. Based on the modified peak accelerations, the control efficiency $\eta$ of TLD devices is defined by the following equation:

$$\eta = \frac{A_s - A_{TLD}}{A_s} \times 100\% \quad (1)$$

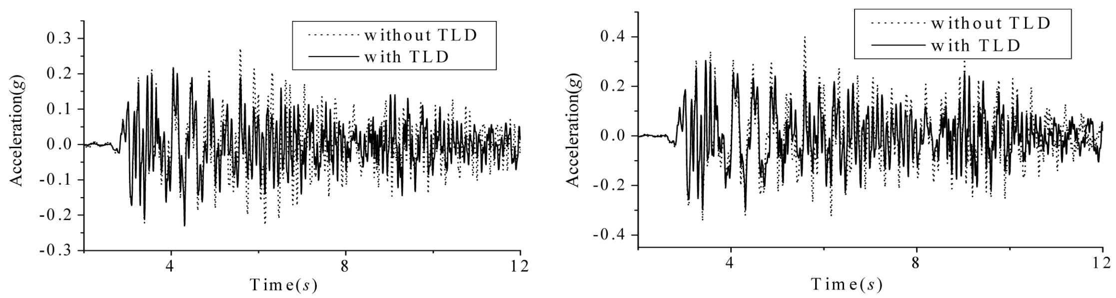



(a) EC Wave (b) SHJ Wave (c) SH Wave

Fig. 7 TLD control efficiency under various seismic excitations (no SSI)

in which $A_s$ and $A_{TLD}$ are the top-floor peak accelerations of the frame without and with presence of the TLD devices. The graphical representation of the control efficiency data in Tables 3-5 is given in Fig. 7 as a function of tuning frequency ratio ($\beta$) for the three seismic excitations with different peak acceleration values.

Several observations can be made from Tables 3-5 and Fig. 8. First of all, all of 27 data points in Fig. 7 show a positive reduction ratio of the acceleration at the top floor of the frame. These results indicate that the TLD devices can generally reduce the dynamic response of the structure. Secondly, in most cases, the control efficiency of TLD devices improves as $\beta$ increases, especially under strong seismic excitations when the peak acceleration is equal to 0.3 g. Seven out of nine curves in Fig. 7 indicate that the best performance of TLD devices can be achieved when the frequency of the TLD devices is approximately tuned into that of the structure. This result is consistent with the conclusions drawn from many numerical studies (Chen *et al.* 2000). Thirdly, test results have shown that more efficient control of the structural responses can be obtained by TLD devices as the peak acceleration of excitations increases. Fourthly and lastly, it can be seen from Tables 3-5 and Fig. 7 that the control efficiency of TLD devices under the SHJ Wave excitation is not as high as that under the El Centro Wave and SH Wave excitations. This result may be explained by using the Fourier spectra of the seismic waves shown in Fig. 5. The predominant frequency range of the SHJ Wave is far from the fundamental frequency of TLD devices and the frame structure. On the other hand, the predominant frequency range of other two seismic waves covers the fundamental frequency of both the TLD and the frame structure. Under the SH Wave and EC Wave excitations, the water in the TLD can slosh with a sufficiently higher elevation than that under the SHJ Wave excitation. As a result, the higher




(a) a=0.2g, $\beta = 0.962$ (b) a=0.3g, $\beta = 0.962$

Fig. 8 Representative time histories at the top floor of the frame (no SSI, EC Wave) control efficiency can be obtained for the former cases than the later. Therefore, the performance of TLD devices is significantly affected by the spectrum characteristics of seismic excitations.

Two typical acceleration time histories at the top floor of the frame under the EC Wave of two intensities (represented by the peak acceleration a) are compared in Fig. 8 to illustrate the effect of TLD devices on the time history feature of responses when SSI effects are not present. Fig. 8 indicates that the peak acceleration of the controlled and uncontrolled structure occurs at different time instants.

### *5.2 Responses of the frame structure with SSI effects*

Similarly, the results obtained in the third stage for the soil-foundation-structure-TLD system are shown in Tables 6-8. In the tables, two levels of the peak acceleration for each seismic wave/excitation at the shake table are listed in the first row. According to the peak accelerations of the seismic excitation and the dynamic amplification factors obtained in the second test stage, the peak accelerations of the free-field ground motion can be approximately determined as given in parentheses of the first row in Tables 6-8, corresponding to the two levels of excitations. The parameter $\beta$ is in this case defined as the ratio of the fundamental frequency of the TLD devices to the first modal frequency of the soil-foundation-structure system. The data in Tables 6-8 are reproduced in a graphical format in Fig. 9 to illustrate the change of the control efficiency $\eta$ of the TLD devices as a function of frequency ratio $\beta$.

Table 6 Peak acceleration (g) of the frame and TLD control efficiency (SSI included, EC Wave)

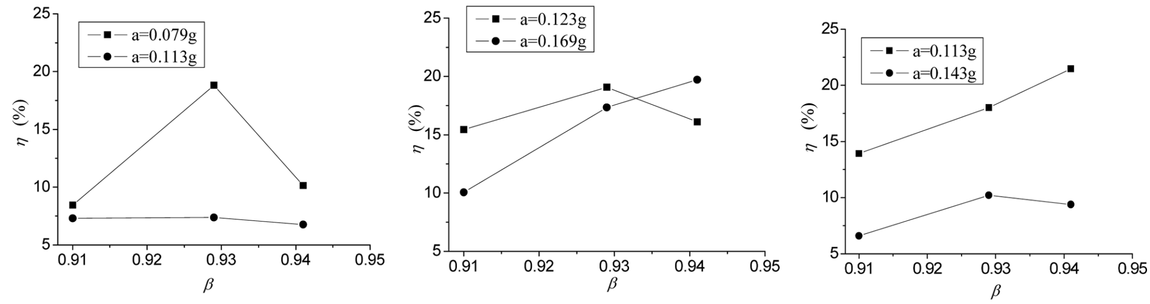
| $\beta$ | 0.079 g (0.202 g) | | | 0.113 g (0.285 g) | | |
|---|---|---|---|---|---|---|
| | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) |
| 0.910 | 0.2186 | 0.2387 | 8.44 | 0.2673 | 0.2884 | 7.31 |
| 0.929 | 0.1938 | 0.2387 | 18.81 | 0.2684 | 0.2898 | 7.37 |
| 0.941 | 0.2102 | 0.2339 | 10.14 | 0.2706 | 0.2898 | 6.76 |

Table 7 Peak acceleration (g) of the frame and TLD control efficiency (SSI included, SHJ Wave)

| $\beta$ | 0.123 g (0.215 g) | | | 0.169 g (0.261 g) | | |
|---|---|---|---|---|---|---|
| | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) |
| 0.910 | 0.2941 | 0.3478 | 15.44 | 0.3528 | 0.3920 | 10.05 |
| 0.929 | 0.2827 | 0.3493 | 19.07 | 0.3248 | 0.3930 | 17.34 |
| 0.941 | 0.2852 | 0.3399 | 16.10 | 0.3128 | 0.3964 | 19.72 |

Table 8 Peak acceleration (g) of the frame and TLD control efficiency (SSI included, SH Wave)

| $\beta$ | 0.113 g (0.208 g) | | | 0.143 g (0.251 g) | | |
|---|---|---|---|---|---|---|
| | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) |
| 0.910 | 0.3957 | 0.4597 | 13.92 | 0.4838 | 0.5179 | 6.59 |
| 0.929 | 0.3809 | 0.4646 | 18.02 | 0.4599 | 0.5122 | 10.21 |
| 0.941 | 0.3685 | 0.4692 | 20.00 | 0.4624 | 0.5122 | 9.38 |

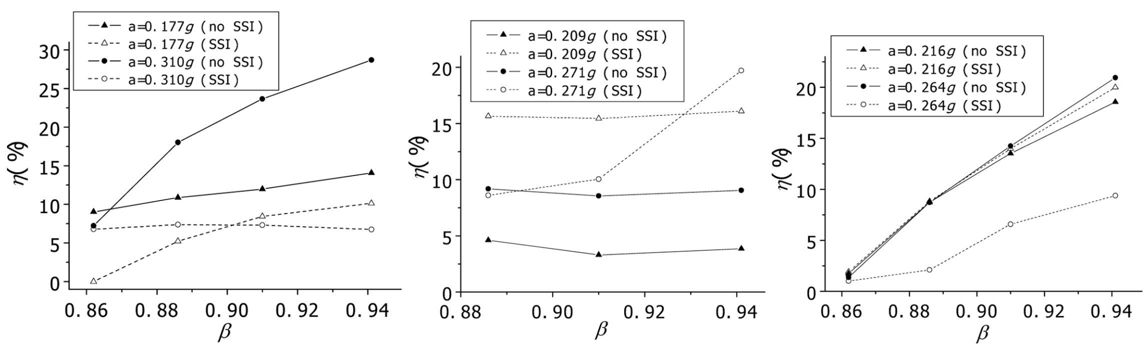



(a) EC Wave (b) SHJ Wave (c) SH Wave

Fig. 9 TLD control efficiency under various excitations with SSI effects

By comparing the data in Tables 6-8 and Fig. 9 with those in Tables 3-5 and Fig. 7, several observations can be made as follows. First of all, the data in Tables 6-8 and Fig. 9 indicate that the control efficiency of the TLD devices always increases as $\beta$ increases from 0.910 to 0.929. However, further increase of $\beta$ value from 0.929 to 0.941 degrades the efficiency of the TLD devices as indicated by four out of six lines in Fig. 9. Significantly different from that in Fig. 7, this result indicates that the optimum tuning frequency ratio of the TLD to the soil-foundation-structure system is smaller than that for a rigid-based structure, reflecting the reduction of the natural frequency of the system due to SSI effects. Secondly, as the seismic excitation increases, the TLD devices become less efficient in controlling the responses of the soil-foundation-structure system in most cases. This is due to the fact that the damping of the system increases when the nonlinearity of the soil becomes stronger at higher excitations. Thirdly, when TLD devices are used to reduce the seismic responses of the soil-foundation-structure system under approximately the same level of excitations, their control efficiency has been significantly influenced by soil-structure interaction. But the SSI effect on the control efficiency of the TLD devices is quite different.

In comparison with the no SSI case, the control efficiency of the TLD devices is improved under the SHJ Wave excitation, but decreases obviously under the SH Wave excitation and moderately under the EC Wave excitation. These changes can be seen in Fig. 10. In the Fig. 10, the peak accelerations at the base of the model structure are adjusted to same value according to model test results in both cases of considering SSI and no SSI under the excitation of the same seismic wave.

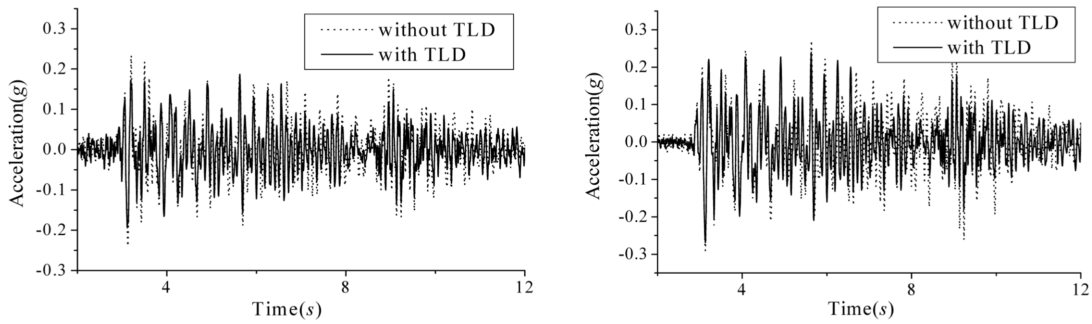



(a) EC Wave (b) SHJ Wave (c) SH Wave

Fig. 10 Comparison of the control efficiency of TLD devices between SSI system and structure only

These quite different influences indicate that the effect of the frequency spectrum of the seismic excitation on the performance of TLD devices seems decreasing when SSI is taken into account.

To see the characteristics in time domain, Fig. 11 shows the time histories of the horizontal acceleration at the top floor of the frame structure under the excitation of El Centro wave. Unlike the case without SSI effects in Fig. 7, the peak accelerations of both the controlled and uncontrolled structure occur corresponding to the first peak of the input acceleration. This result is likely attributable to the increase of damping of the soil-foundation-structure system due to SSI effects. In this situation, damping can more effectively reduce the structural responses after the first peak.




(a) a=0.079 g, $\beta$=0.929 (b) a=0.113 g, $\beta$=0.929

Fig. 11 Time histories of the top-floor acceleration of the frame structure (SSI included, EC Wave)

Table 9 Peak strain ($\times10^{-6}$) of the pile and TLD effects under the EC Wave

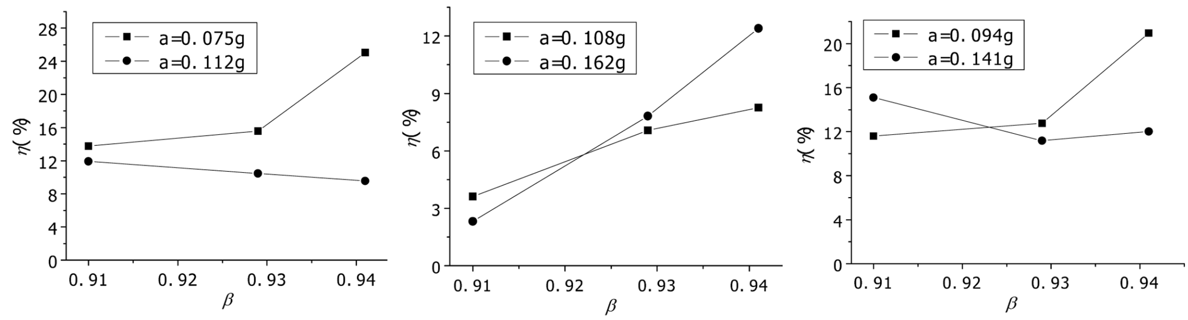
| $\beta$ | 0.079 g | | | 0.113 g | | |
|---|---|---|---|---|---|---|
| | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) |
| 0.910 | 37.8 | 43.8 | 13.75 | 49.0 | 55.64 | 11.93 |
| 0.929 | 37.0 | 43.8 | 15.58 | 50.1 | 55.9 | 10.45 |
| 0.941 | 31.8 | 42.43 | 25.05 | 50.6 | 55.9 | 9.56 |

Table 10 Peak strain ($\times10^{-6}$) of the pile and TLD effects under the SHJ Wave

| $\beta$ | 0.123 g | | | 0.169 g | | |
|---|---|---|---|---|---|---|
| | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) |
| 0.910 | 59.9 | 62.1 | 3.62 | 74.3 | 76.1 | 2.32 |
| 0.929 | 58.1 | 62.5 | 7.07 | 70.4 | 76.4 | 7.82 |
| 0.941 | 55.3 | 60.3 | 8.26 | 68.5 | 78.2 | 12.40 |

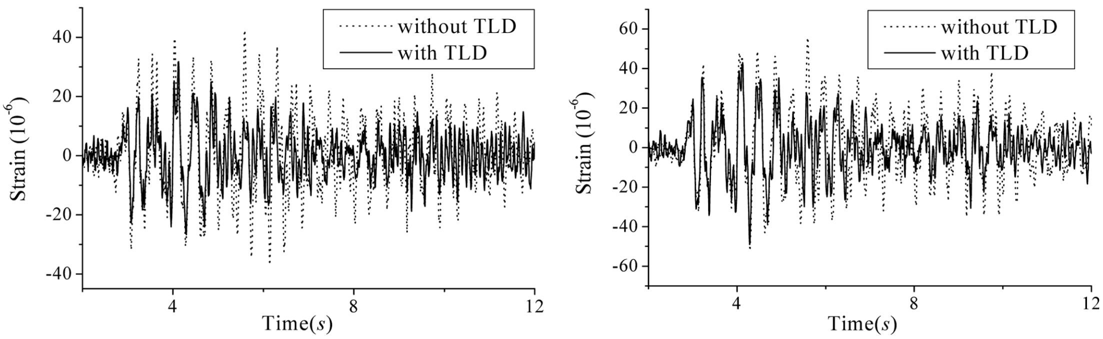
Table 11 Peak strain ($\times10^{-6}$) of the pile and TLD effects under the SH Wave

| $\beta$ | 0.113 g | | | 0.143 g | | |
|---|---|---|---|---|---|---|
| | With TLD | Without TLD | $\eta$ (%) | With TLD | Without TLD | $\eta$ (%) |
| 0.910 | 110 | 124 | 11.60 | 135 | 159 | 15.09 |
| 0.929 | 110 | 126 | 12.76 | 136 | 153 | 11.17 |
| 0.941 | 101 | 128 | 20.95 | 133 | 151 | 12.02 |



(a) EC Wave (b) SHJ Wave (c) SH Wave

Fig. 12 TLD control efficiency for pile response reduction with SSI effects



(a) a=0.079 g, β=0.941 (b) a=0.1139 g, β=0.910

Fig. 13 Strain time histories at the top of the pile under excitation of El Centro Wave

### *5.3 Responses of the piles*

When TLD is used to mitigate the seismic responses of the frame structure, it will also affect the dynamic responses of piles. The maximum stress and potential damage of each pile is generally located near the connection between the pile and its cap. Therefore, the strain readings at Point B in Fig. 6(b) were acquired in this study. Their peak values for different cases are listed in Tables 9-11. Eq. (1) was also used to measure the effect of the TLD devices on the dynamic strains of piles. The difference in this case lies in the use of strain instead of acceleration in Section 5.2 and 5.3. Fig. 12 shows the variation of the control efficiency $\eta$ with the increasing of $\beta$ under various excitations.

It can be clearly seen from Fig. 12 that all data points indicate the reduction of the dynamic strain of the pile by the TLD devices. Similar to the frame structure, the control efficiency $\eta$ for piles generally increases with $\beta$ and it reaches the maximum when the tuning frequency ratio is close to 1.0. The two exceptions in Fig. 12 are likely due to the small magnitude of strains and the complexity of a soil-foundation-structure system. Similar to the frame structure alone in Section 5.1, under the SHJ Wave excitation, the control efficiency of the pile is lower than that for the other two excitations. Therefore, it appears that the control efficiency of the TLD devices in reducing the pile's responses is significantly affected by the frequency characteristics of excitations.

The time histories of the longitudinal strain of one pile, Point B in Fig. 6(b), under the excitation of El Centro wave are shown in Fig. 13 to illustrate the TLD control efficiency in time domain. As one can see, the maxima/minima of the pile responses over the period of the excitation seems to be uniformly reduced, especially when $\beta = 0.941$. As the intensity of the seismic excitation increases from Fig. 13(a) to Fig. 13(b), the reduction in the first peak of the pile response becomes less effective. The effect of the TLD devices on the following peaks, however, is always significant as evidenced from Fig. 13.

## 6. Discussions

It is difficult to satisfy all of the scaling laws in shaking table model tests of the soil-structure-liquid interaction system due to limited capacity of the shaking table. Therefore, an emphasis of the tests in the paper is placed on studying the SSI influence on the performance of the TLD device or the dynamic behavior of the prototype structure controlled by TLD. In the model design, the main consideration was to coordinate the natural frequency of the model structure with the working frequency of TLD device and to reduce the natural frequency of the simulated soil to approach the natural frequency of the model structure as closely as possible. Thus, the scaling laws were not completely satisfied in the model design. Such as the physical property of the simulated soil is inconsistency with the data required by the scaling law. Meanwhile, the piles are designed stronger than the desired flexural stiffness to avoid the damage during the whole test process. It leads to small strains speared in the piles.

## 7. Conclusions

Based on extensive tests and result analyses of the building frame structure alone, the pile foundation in soil layers, and the soil-foundation-structure system, several conclusions can be drawn from this study:

1. TLD is an effective passive control device in mitigating the seismic response of the building structure regardless of soil-structure interaction effects. Over 20% reduction can be achieved with the installation of two TLD devices on the top floor of the building model that was tested on the shake table in this study.
2. The control efficiency of TLD devices is significantly affected by the frequency tuning ratio. In general, it increases with the frequency tuning ratio and reaches the highest when the fundamental frequency of the TLD devices is approximately equal to that of the dynamic system to be controlled, e.g., the structure or the soil-foundation-structure system.
3. The intensity of seismic excitations affects the performance of TLD devices that are installed on the building. A higher control efficiency of TLD devices can generally be obtained when the building was subjected to stronger seismic loads.
4. The behavior of TLD devices is influenced by the frequency characteristics of seismic excitations. For the structure supported on rigid foundation, a higher control efficiency of TLD devices can be achieved when the dominant frequency range of excitations spans over the fundamental frequency of the structure and/or the TLD devices. For the soil-foundation-structure system with significant SSI, the control efficiency seems less dependent upon the frequency characteristics of excitations since the structure perceives the input motion at the elevation of pile cap after different seismic excitations have been filtered by the same soil layers.

5. TLD devices can also reduce the seismic responses of piles. The interrelation of their control efficiency with structural and loading parameters is similar to the response of the building structure. SSI must be taken into account in the design of TLD devices for peak response reduction of both the structure supported on pile foundation and the piles.

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## References

Banerji, P., Murudi, M., Shah, A.H. and Popplewell, N. (2000), "Tuned liquid dampers for controlling earthquake response of structures", *Earthq. Eng. Struct. Dyn.*, **29**, 587-602.

Chen, G., Wu, J., Chen, C. and Lou, M. (2000), "Recent development in structural control including soil-structure interaction effect", *Proc. of the 7th Annual Int. Symposium on Smart Structures and Materials*, New Port Beach, USA.

Cheng, F.Y., Jiang, H. and Lou, M. (1999), "State-of-the-art of control systems and SSI effect on active control structures with embedded foundation", *ASCE Structural Congress: Structural Engineering in 21st Century,* 61-65.

Fujii, K., Tamura, Y., Sato, T. and Wakahara, T. (1990), "Wind induced vibrations of tower and practical applications of tuned sloshing dampers", *J. Wind Eng. Indu. Aerodyn.*, **33**, 263-272.

Housner, G.W., Bergman, L.A. and Caughey, T.K. *et al.* (1997), "Structural control: past, present, and future", *J. Eng. Mech.*, ASCE, **123**(9), 897-971.

Koh, C.G., Mahatma, S. and Wang, C.M. (1994), "Theoretical and experimental studies on rectangular liquid dampers under arbitrary excitations", *Earthq. Eng. Struct. Dyn.*, **23**, 17-31.

Lou, M. and Wu, J. (1997), "Effect of soil-structure interaction on structural control", *Dynamic Soil-Structure Interaction* (ED. By Zhang, C. and Wolf, J.D.), International Academic Publisher, 188-201.

Lou, M. and Wang, W. (2004), "Study on soil-pile-structure-TMD interaction system by shaking table model test", *Earthq. Eng. Eng. Vib.*, **3**, 127-137.

Modi, V.J. and Akinturk, A. (2002), "An efficient liquid sloshing damper for control of wind-induced instabilities", *J. Wind Eng. Indu. Aerodyn.*, **90**, 1907-1918.

Reed, D., Yu, J., Yeh, H. and Gardarsson, S. (1998), "Investigation of tuned liquid dampers under large amplitude excitation", *J. Eng. Mech.*, ASCE, **124**, 405-413.

Wakahara, T., Ohyama, T. and Fujii, K. (1991), "Wind response analysis of TLD-structure system considering nonlinearity of liquid motion", *J. Struct. Const. Eng.*, **426**, 78-88.

Wu, J. and Lou, M. (1997), "Influence of soil-structure interaction on tuned mass damper control for high-rise buildings", *J. of Tongji University,* **25**, 515-520. (in Chinese)

Wu, X., Sun, L., Hu, S. and Fan, L. (2002), "Development of laminar shear box used in shaking table test", *J. of Tongji University,* **30**, 781-785. (in Chinese)