Scientia Iranica, Vol. 15, No. 3, pp 275–285
© Sharif University of Technology, June 2008

SCIENTIA
IRANICA

Strong Ground Motion Effects on Seismic Response Reduction by TLCDs

S.M. Zahrai[1] **and A. Kavand**[2]

Nowadays, various types of passive control systems are being used as an effective solution to reduce the seismic responses of structures. One type of these systems, the Tuned Liquid Column Damper (TLCD), suppresses the input seismic energy by a combined action, including the movement of liquid mass in the container, a restoring force on the liquid, due to gravity loads, and the damping, due to liquid movement through the orifices. In this paper, the possible effects of seismic excitation characteristics, such as frequency content and soil condition, on the seismic performance of TLCDs, are investigated, using nonlinear time-history analyses. For this purpose, a ten-story building was modeled as an elastic MDOF structure and used for numerical analyses. For the time-history analyses, among the past strong ground motion records of Iran, 16 records with different characteristics were selected. The results of this study show that these characteristics play a substantial role in the performance of TLCDs and they should be, accordingly, considered in the designing of TLCDs. In some cases, TLCD is able to reduce structural displacement up to 50%, while, in most cases, the effectiveness of TLCD in reducing structural acceleration is not significant. However, it should be mentioned that, in real applications, de-tuning may occur, due to the inelastic behavior of structures, which can reduce effectiveness. This study also shows that the displacement reduction capacity of TLCDs is highly dependent on excitation characteristics, while the acceleration reduction capacity is not that sensitive.

INTRODUCTION

As a passive energy-absorbing device, a Tuned Liquid Column Damper (TLCD) is able to suppress structural vibration by the motion of liquid in a column damper. Recently, TLCD has been used to reduce structural vibrations in many modern buildings. Figure 1 shows the 26-story Cosima Hotel in Japan and a schematic sectional view of the TLCD device [1].

There are a number of advantages in using this device. TLCDs are relatively easy to install in new and existing buildings. Despite other passive devices, they do not usually interfere with vertical and horizontal load paths. Adjustment of their frequencies is easy and they can be used as hybrid systems, when combined with active control devices. Moreover, TLCDs can dissipate energy in two directions, simultaneously, using a bi-directional U-tube [2]. However, it must be noted that the potential of liquid dampers in their passive state is not fully recognized, due to the dependence of their damping on motion amplitudes (or level of excitation) and their inability to respond quickly to suddenly applied loads, such as earthquake forces [3]. Therefore, semi-active systems were proposed to overcome some of the problems inherent in TLCDs [2,4,5].

In recent years, there have been several studies undertaken on the evaluation of TLCD performance in suppressing the vibration of structures. However, most of them are devoted to an evaluation of TLCD performance under wind excitations, and relatively few studies have been made on the seismic performance of TLCDs. Because of the complicated nonlinear behavior of TLCDs, their analysis and modeling have some difficulties, particularly under seismic excitations. This is one of the reasons for insufficient studies being carried out to assess the seismic performance of TLCDs [6]. In this paper, the effects of seismic excitation characteristics, such as frequency content and soil conditions, on the seismic performance of

---

1. *Corresponding Author, Center of Excellence for Engineering and Management of Infrastructures, School of Civil Engineering, University of Tehran, Tehran, Iran. E-mail: mzahrai@ut.ac.ir*
2. *Department of Civil Engineering, University of Tehran, Tehran, Iran.*

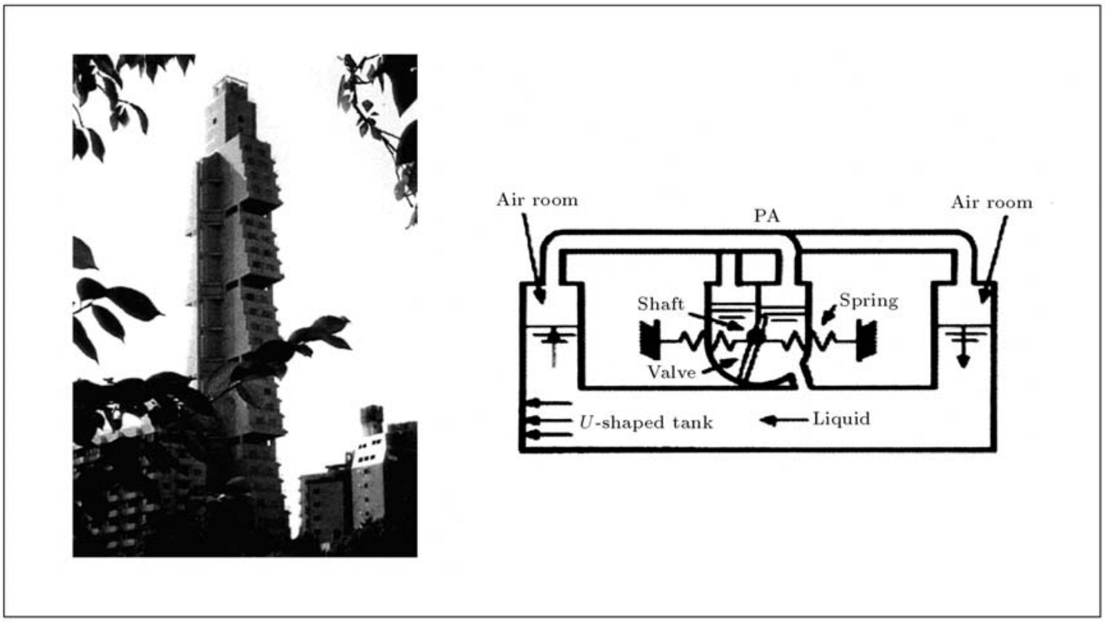


Figure 1. Cosima Hotel and sectional view of the TLCD device [7].

TLCDs are investigated. In this regard, among the past earthquake ground motion records of Iran, 16 records, with different excitation parameters, were selected and used for numerical analyses. A ten-story building with TLCD was modeled as a multi-degree of freedom and considered to demonstrate how the ground excitation characteristics could affect TLCD performance. The TLCD was simulated using a rigid mass attached to the structure with a spring and a nonlinear dashpot [7].

ANALYTICAL PROCEDURE

A model of a SDOF system with a tuned liquid column damper is shown in Figure 2. Assume the liquid density to be ρ and the TLCD to be a uniform U-shaped liquid column with a cross-sectional area, A, a horizontal length, B, and a total length, L. The equation of motion of the liquid column can be expressed as follows [6]:

$$\rho AL\ddot{y} + \frac{1}{2}\rho A\delta|\dot{y}|\dot{y} + 2\rho Agy = -\rho AB\ddot{x}, \tag{1}$$

where y represents the elevation change of the liquid column and g is the acceleration of gravity; $\dot{y}$ and $\ddot{y}$ denote the first and second derivatives of y, with respect to time, respectively, and $\ddot{x}$ is the structure horizontal acceleration. The head loss coefficient, δ, depends on the orifice opening ratio (area of opening to cross-sectional area of tube) where $\delta = 0$ corresponds to a full orifice opening and $\delta = \infty$ corresponds to a full orifice closure.

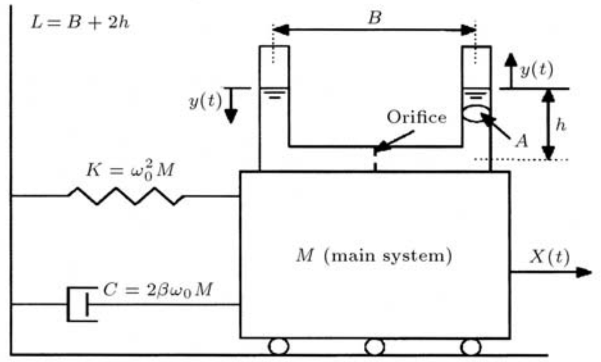


Figure 2. A single-degree-of-freedom structure with an attached tuned liquid column damper [6].

The equation of motion for a tuned mass damper, subjected to ground acceleration, $\ddot{x}_g$, is considered as follows [6]:

$$\ddot{Z} + 2\xi\omega_T\dot{Z} + \omega_T^2 Z = -\ddot{x}_g, \tag{2}$$

where Z is the horizontal displacement, ξ is the damping ratio and ω_T is the natural frequency of the TMD. By comparing with Equation 1, it can be shown that a tuned liquid column damper can be considered as a tuned mass damper with a natural frequency, ω_T, given by:

$$\omega_T = \sqrt{\frac{2g}{L}}, \tag{3}$$

and a velocity-dependent damping ratio, ξ, expressed as:

$$\xi = \frac{\delta}{4\sqrt{2gL}}|\dot{y}|. \tag{4}$$

The equation of motion governing a TLCD-SDOF structural system, subjected to ground excitation, in matrix form, can be shown as follows [6]:

$$\begin{bmatrix} M+\rho AL & \rho A\alpha L \\ \rho A\alpha L & \rho AL \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{y} \end{Bmatrix} + \begin{bmatrix} 2M\omega_0\beta & 0 \\ 0 & \frac{1}{2}\rho A\delta|\dot{y}| \end{bmatrix} \begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix} + \begin{bmatrix} M\omega_0^2 & 0 \\ 0 & 2\rho Ag \end{bmatrix} \begin{Bmatrix} x \\ y \end{Bmatrix} = -\begin{Bmatrix} M+\rho AL \\ \rho A\alpha L \end{Bmatrix} \ddot{x}_g, \tag{5}$$

where M is the total mass of the SDOF structure, ω_0 is the natural frequency, β is the damping ratio and $\alpha = B/L$ is the ratio of the tube width to the liquid length.

Equations 1 and 5 have a nonlinear damping term, $|\dot{y}|$, indicating that the TLCDs have a nonlinear behavior. In some studies, the equivalent linearization technique has been used to solve the nonlinear equations [8]. It should be noted that, for a deterministic analysis, using earthquake accelerograms, the equivalent linearization technique cannot be used to solve Equation 5, because of the nonlinear characteristics of TLCD [6].

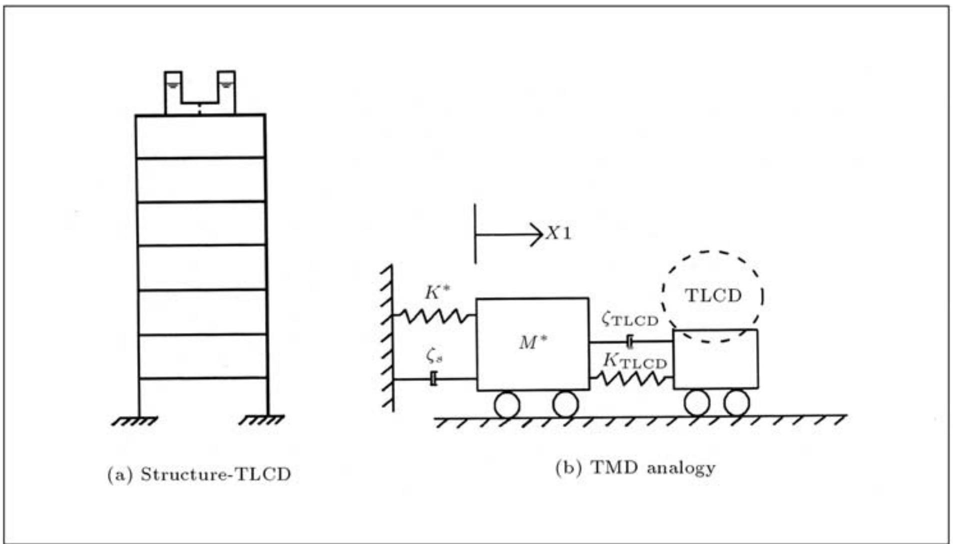
NUMERICAL STUDY

Considering the mentioned difficulties in analyses of TLCD, due to nonlinear behavior and because of the need to carry out several time history analyses of MDOF structures, numerical analyses were used in this study. In this regard, the TLCD was modeled as a TMD using Equations 3 and 4. A rigid mass, attached to the structure with a spring and a nonlinear dashpot, was used to simulate the TMD, such as that used by El Damatty [7] for simulating TLD. In order to examine the equivalent mass-spring system, Equation 1 was also subsequently solved, numerically, and the analytical results were compared with those of an equivalent system. Figure 3 shows the schematic of a building with TLCD attached.

Selection of Earthquake Accelerograms

In order to investigate the impact of seismic excitation characteristics on the seismic effectiveness of TLCDs, among past earthquake ground motion records of Iran [9], 16 records, with different excitation characteristics, were selected and used for time history analyses. The parameters studied include the frequency content of excitation and soil conditions. The classification of the accelerograms is done, based on these parameters. Characteristics of the selected earthquake records are presented in Table A1 in the Appendix.

Because earthquake records have different peak ground motions, they cannot be used on an absolute basis to show the effects of different parameters. So, the records were scaled to a peak ground acceleration of 0.35 g before they were imposed to the structure model. In order to get a better view of the frequency content of the records, the Fourier spectra of all records were also computed. This allowed an investigation of the effects of the frequency content of excitation on TLCD performance. Additionally, the response spectra of records were computed, because the peaks and valleys in the response spectrum of the records affect the response of the structure and, subsequently, the performance of TLCD.



(a) Structure-TLCD

(b) TMD analogy

Figure 3. Schematic of a building with TLCD and the corresponding mass-spring system.

Selection of Structural Model

A ten-story building, such as that used by Sadek et al. [6], was modeled as a MDOF structure and used for analysis. A schematic of the building model is shown in Figure 4. The building was assumed to have a damping ratio of 0.02 in the first mode and to be designed for a peak ground acceleration of 0.35g. The assumed story mass and column stiffness from top to bottom are: $\{98, 107, 116, 125, 134, 143, 152, 161, 170, 179\} \times 10^3$ kg and $\{34.31, 37.43, 40.55, 43.67, 46.79, 49.91, 53.02, 56.14, 59.26, 62.47\} \times 10^3$ kN/m, respectively. The fundamental natural period of the building is 2 sec. The building was analyzed twice, once with TLCD attached to the top floor and once without TLCD. The method proposed by Sadek et al. [6] was used to select the design parameters of TLCD. The liquid mass was considered as 44.36×10^3 kg, equal to about 0.03 of the total mass of the structure. For TLCD, 800 U-tubes, each with a liquid length of 2.2 m and a cross sectional area of 0.025 m^2 were used. Ultimately, by using Equations 2, 3 and 4, equivalent parameters of the mass-spring-dashpot system were obtained.

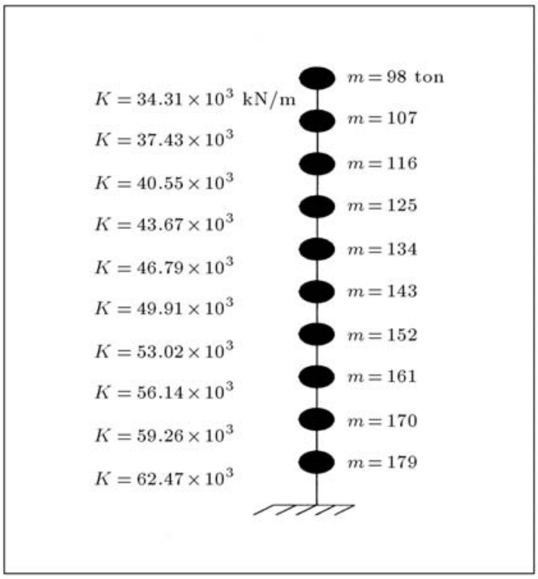


Figure 4. Equivalent simple mechanical building model used for analyses.

NUMERICAL RESULTS

For verifying the structural model and analysis procedure, the building, with and without TLCD, was subjected to the 90°component of the Capitola Fire Station accelerogram, from the Loma Prieta earthquake of October 17, 1989, and the analysis results were compared to those obtained by Sadek et al. [6]. Results of these comparisons are presented in Figure 5.

The effectiveness of the TLCD was quantified, using the following proposed ratios:

$$eff_d = \frac{x_0 - x_{\mathrm{TLCD}}}{x_0} \times 100\%, \qquad (6)$$

$$eff_a = \frac{\ddot{x}_0 - \ddot{x}_{\mathrm{TLCD}}}{\ddot{x}_0} \times 100\%, \qquad (7)$$

where x_{TLCD} and x_0 are the values of the structural displacements at the top floor, with and without dampers, respectively. Also, $\ddot{x}_{\mathrm{TLCD}}$ and $\ddot{x}_0$ are the values of the structural acceleration at the top floor, with and without dampers, respectively. The parameter eff_d, given in Equation 6, indicates the effectiveness of TLCD in reducing structural displacement, while eff_a, in Equation 7, indicates the effectiveness of TLCD in reducing structural acceleration.

The building, with and without TLCD, was analyzed using the selected acclerograms. The results of the analyses are summarized in Tables 1 and 2, which show that, for some records, the effectiveness of TLCD in reducing structural displacement is good, while, for some records, it is even negative. Also, for most

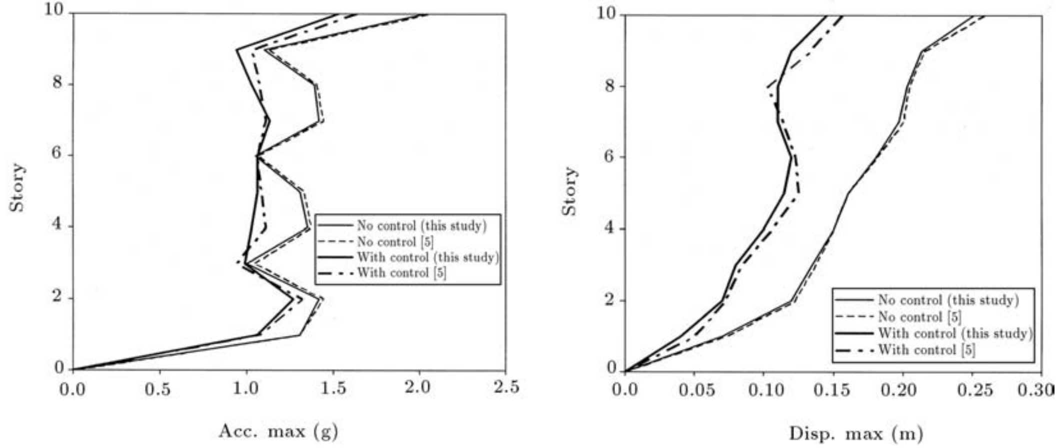


Figure 5. Comparison between results of the present study and those obtained by Sadek et al. [6].

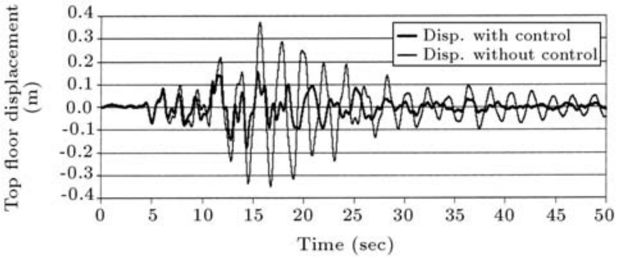
Table 1. Values of maximum structural displacement at top floor with and without passive control and corresponding TLCD effectiveness.

Earthquake (Year)	**Station (Record No.)**	**Disp. with Control (m)**	**Disp. Without Control (m)**	eff_d **(%)**
Sarkhoon (1975)	Bandar Abas (1006-1)	0.124	0.179	30.7
Naghan (1977)	Naghan (1054-1)	0.130	0.157	17.2
Tabas (1978)	Tabas (1084-1)	0.180	0.369	51.2
Tabas (1978)	Ferdos (1126)	0.103	0.118	13.1
Ghaen (1979)	Kashmar (1130-3)	0.394	0.627	37.2
Tabas (1980)	Tabas (1136-3)	0.163	0.249	34.5
Ghaen (1979)	Birjand (1137)	0.361	0.575	37.2
Ghaen (1979)	Ghaen (1139)	0.136	0.171	20.6
Manjil (1980)	Roodsar (1151)	0.055	0.087	36.6
Broujerd (1980)	Broujerd (1160)	0.061	0.066	7.8
Golbaf (1981)	Kerman (1174)	0.119	0.245	51.5
Golbaf (1981)	Golbaf (1183-1)	0.077	0.102	24.8
Golbaf (1981)	Golbaf (1183-8)	0.052	0.059	12.2
Ardal (1989)	Ardal (1341-1)	0.033	0.030	-10.0
Manjil (1990)	Tonkabon (1359)	0.420	0.826	49.1
Roodbar (1990)	Roodbar (1395-1)	0.060	0.053	-13.8

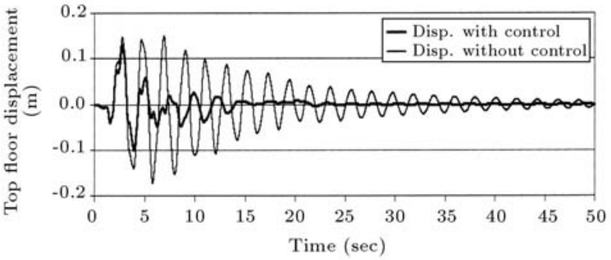
Table 2. Values of maximum structural acceleration at top floor and corresponding TLCD effectiveness.

Earthquake (Year)	**Station (Record No.)**	**Accel. with Control (m/s^2)**	**Accel. Without Control (m/s^2)**	eff_a **(%)**
Sarkhoon (1975)	Bandar Abas (1006-1)	7.365	7.358	-0.1
Naghan (1977)	Naghan (1054-1)	4.475	4.557	1.8
Tabas (1978)	Tabas (1084-1)	6.791	8.550	20.6
Tabas (1978)	Ferdos (1126)	6.295	6.157	-2.2
Ghaen (1979)	Kashmar (1130-3)	12.160	11.991	-1.4
Tabas (1980)	Tabas (1136-3)	4.339	4.533	4.3
Ghaen (1979)	Birjand (1137)	11.600	11.262	-3.0
Ghaen (1979)	Ghaen (1139)	4.886	5.455	10.4
Manjil (1980)	Roodsar (1151)	5.563	5.602	0.7
Broujerd (1980)	Broujerd (1160)	4.326	4.661	7.2
Golbaf (1981)	Kerman (1174)	6.041	6.389	5.4
Golbaf (1981)	Golbaf (1183-1)	2.173	3.127	30.5
Golbaf (1981)	Golbaf (1183-8)	3.244	3.192	-1.6
Ardal (1989)	Ardal (1341-1)	1.760	1.733	-1.6
Manjil (1990)	Tonkabon (1359)	12.370	18.265	32.3
Roodbar (1990)	Roodbar (1395-1)	1.258	1.323	4.9

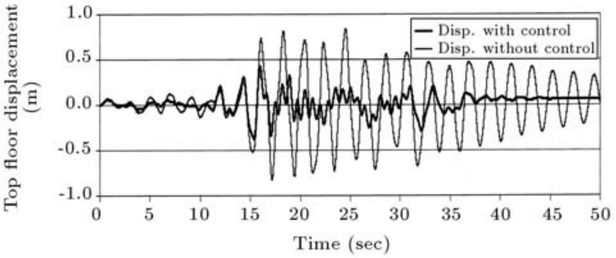
records, the effectiveness of TLCD in reducing structural acceleration is not very significant. This problem is important for acceleration sensitive components, such as nonstructural components. The results also show that the parameter, eff_d, significantly depends on the excitation characteristics, while the parameter, eff_a, is less sensitive to the excitation characteristics. For example, in Figure 6, top floor displacements, with and without control, are compared for three sample records. As shown in Figure 6, for record no. 1084-1



(a) Record no. 1084-1



(b) Record no. 1054-1



(c) Record no. 1359

Figure 6. Comparison of top floor displacement with and without control for three sample records.

and 1359, TLCD reduces structural displacements by about 51% and 49%, respectively. The reduction in top floor displacement is considerable when the structure is subjected to these two sample records. However, it is worth-mentioning that, in real applications, de-tuning may occur, due to the inelastic behavior of structures, which can reduce effectiveness. De-tuning, due to the inelastic behavior of building structures is not only a characteristic of TLCDs, but also of passive energy absorbing systems, which are sensitive to tuning ratios, i.e. tuned passive control systems.

In order to investigate the effects of soil condition on the performance of TLCD in reducing structural displacement, the analysis results are classified, with respect to the soil type of the earthquake record stations, and presented in Table 3. Soil types are based on soil classes defined in the Iranian code of practice for the seismic design of buildings [10]. The results show that, in most cases, for soil type I (stiff soil conditions), the effectiveness of TLCD is not significant and is even negative for two records, while, for soil type IV (soft soil conditions), the effectiveness is significant. As a matter of fact, the effectiveness of TLCD increases when the soil conditions change from type I to type II, III and IV. Considering that the fundamental period of the building with TLCD is about 2.36 seconds and that the predominant period of soil changes to higher amounts when the soil conditions change from stiff to soft, it can be concluded that the best performance of TLCD is achieved when the fundamental period of the building is matched with or close to both seismic excitation and soil predominant periods. In Figure 7, the effectiveness of TLCD, with respect to the mean period of records, is shown for each soil condition. According to Figure 7, the effectiveness of TLCD generally increases with increasing the mean period of seismic excitation. In general, it is concluded that the soil conditions play a substantial role in the performance of TLCDs and should be considered as a significant parameter in their design.

To investigate the effects of the frequency content of seismic excitation on TLCD performance, the Fourier spectra of all records were computed. Some of the calculated spectra are presented in Figure 8. By comparing the presented Fourier spectra, it can be observed that, in the records of the 1979 Ghaen earthquake (Birjand station, record no.1137) and the 1990 Manjil earthquake (Tonkabon station, record no.1359) belonging to soil type IV, the peaks of the spectra are located in short frequencies (less that 1 Hz.), which resulted in a better performance of TLCD. On the other hand, in the record of the 1990 Roodbar earthquake (Roodbar station, record no.1395-1), the spectrum shows two distinct peaks, meaning that this record predominantly consists of two sinusoidal like excitations, none of which are matched or close to the structural period with TLCD, so the performance of TLCD in reducing the structural response is the worst.

This is because the design parameters of TLCD were not selected properly, showing that in selecting the design parameters of TLCDs, seismic excitation characteristics should be considered. One way to solve this problem is by considering the subsoil conditions of the site in the determination of design ground motions, i.e. using site-specific design ground motions as earthquake characteristics, such as frequency content or mean period of earthquake records considered in this paper.

Another reason for reductions in the response being observed for some records but not for others can be the peaks and valleys in the response spectrum of the records [6]. Addition of the TLCD introduces one more degree of freedom and shifts the fundamental structural period (without TLCD) of 2.0 sec to periods of 2.36 and 1.80 sec, for the first and second modes (with TLCD), respectively. To investigate this issue, velocity response spectra for all of the selected records have been obtained and presented in Figure A1 in Appendix

Table 3. TLCD effectiveness in reducing structural displacement regarding soil conditions.

Earthquake (Year)	Station (Record No.)	Disp. with Control (m)	Disp. Without Control (m)	eff_d (%)	Soil Type
Ardal (1989)	Ardal (1341-1)	0.033	0.030	-10.0	I
Roodbar (1990)	Roodbar (1395-1)	0.060	0.053	-13.8	I
Naghan (1977)	Naghan (1054-1)	0.130	0.157	17.2	I
Ghaen (1979)	Ghaen (1139)	0.136	0.171	20.6	I
Broujerd (1980)	Broujerd (1160)	0.060	0.066	7.8	I
Tabas (1980)	Tabas (1136-3)	0.163	0.249	34.5	II
Golbaf (1981)	Golbaf (1183-1)	0.077	0.102	24.8	II
Tabas (1978)	Tabas (1084-1)	0.180	0.369	51.2	II
Tabas (1978)	Ferdos (1126)	0.103	0.118	13.1	II
Golbaf (1981)	Golbaf (1183-8)	0.052	0.059	12.2	II
Manjil (1980)	Roodsar (1151)	0.055	0.087	36.6	III
Sarkhoon (1975)	Bandar Abas (1006-1)	0.124	0.179	30.7	III
Ghaen (1979)	Kashmar (1130-3)	0.394	0.627	37.2	III
Golbaf (1981)	Kerman (1174)	0.119	0.245	51.5	III
Ghaen (1979)	Birjand (1137)	0.361	0.575	37.2	IV
Manjil (1990)	Tonkabon (1359)	0.420	0.826	49.1	IV

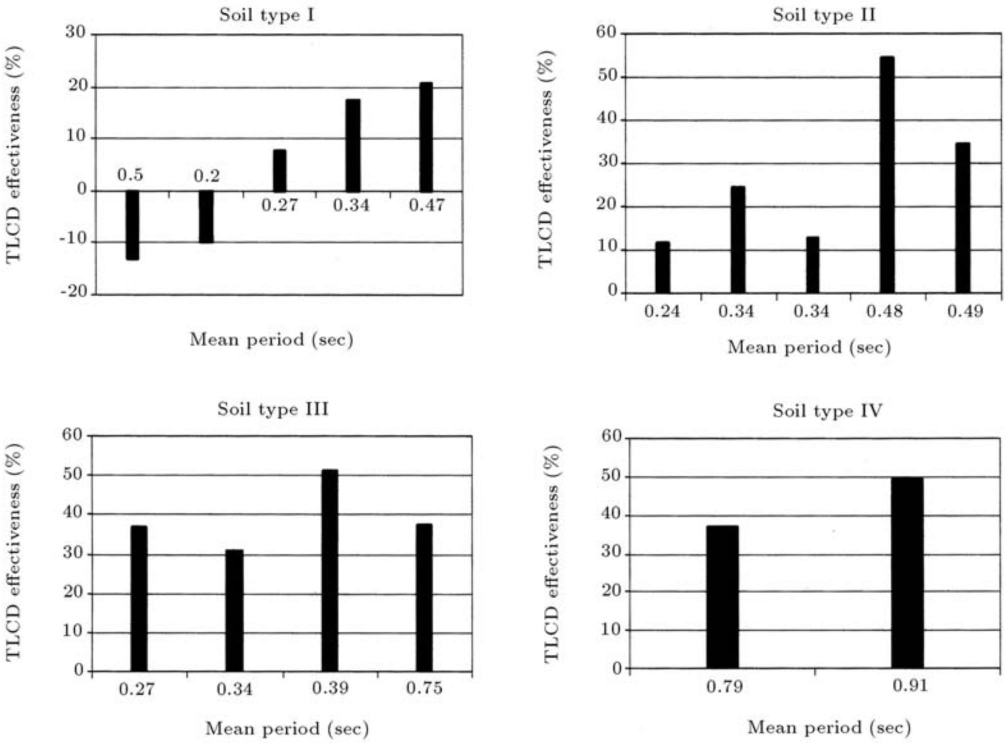


Figure 7. The effectiveness of TLCD with respect to the mean period of records for each soil condition.

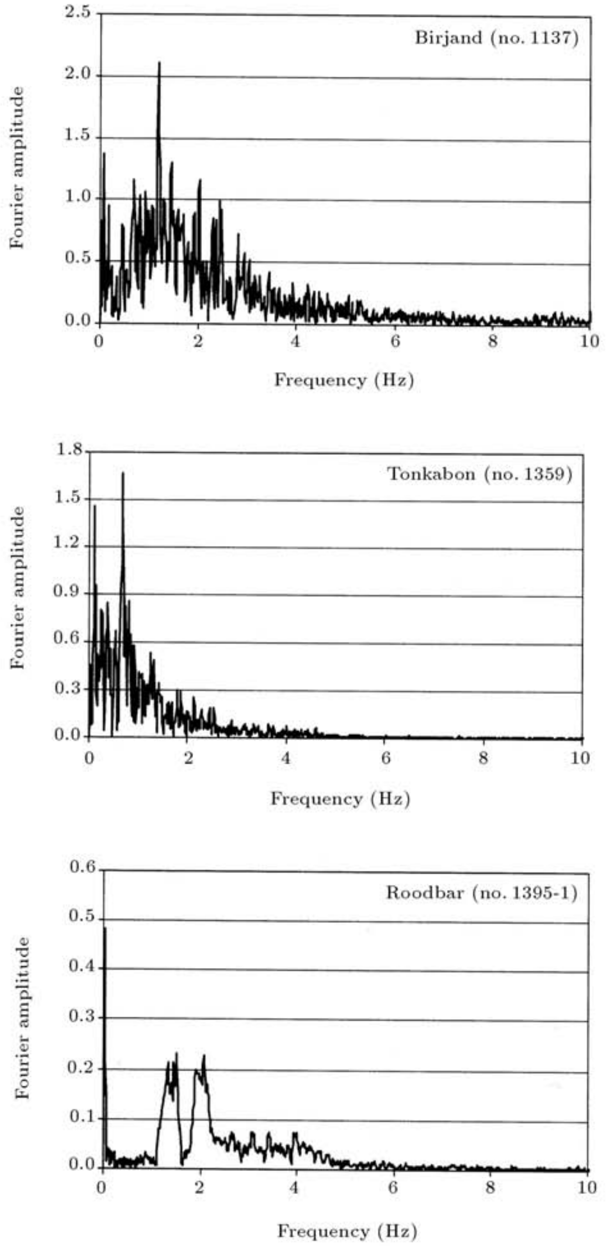


Figure 8. Sample Fourier spectra of the Birjand, Tonkabon and Roodbar earthquake records.

II. For instance, the velocity response spectra for the records of the 1990 Roodbar earthquake (Roodbar station, record no. 1395-1) and the 1981 Golbaf earthquake (Kerman station, record no. 1174) are presented in Figure 9. An examination of the spectra for the Kerman earthquake record shows that the responses at 2.36 and 1.80 sec are smaller than the response at 2.0 sec (structure without TLCD), resulting in a significant reduction in structural response. However, for the Roodbar earthquake record, the responses at both 2.36 and 1.80 sec are significantly greater than the response at 2.0 sec. This increases the structural response, leading to a negative performance of TLCD.

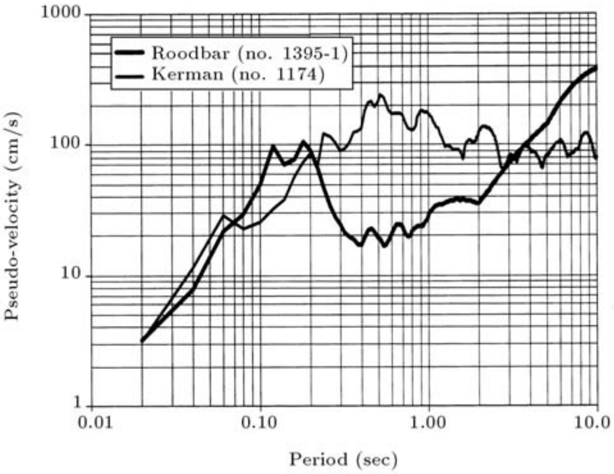


Figure 9. Response spectra for Roodbar and Kerman earthquake records with a damping ratio of 5%.

CONCLUSIONS

This paper was devoted to determining how seismic excitation characteristics would affect the effectiveness of tuned liquid column dampers. The study shows that the displacement reduction capacity of the TLCD is highly dependent on excitation characteristics, while the acceleration reduction capacity is not that sensitive. TLCD is able to reduce structural displacement even up to 50%, in some cases, while the effectiveness of TLCD in reducing structural acceleration is not significant. It was observed that soil conditions play a substantial role in the performance of TLCD. The best performance of TLCD is achieved when the soil predominant period is equal, or near, to the fundamental period of the structure with TLCD, mostly because of the effect of soil conditions on the frequency content of excitations. The frequency content of seismic excitation was also observed to greatly affect the performance of TLCD. When the predominant frequency range of seismic excitation is near to the natural frequency of the structure with TLCD, the performance of TLCD could be the best. As a result, the seismic excitation parameters, particularly soil conditions, should be considered in designing TLCDs and in optimizing their design parameters. Generally, this study shows that the performance of TLCDs, like all passive control systems, is influenced by the frequency of the structure, the soil condition and the frequency content of the excitation, which can underscore the performance of the TLCD systems.

REFERENCES

1. Shimizu, K. and Teramura, A. "Development of vibration control system using U-shaped tank", *Proceedings of the 1st International Workshop and Seminar on Be-*

havior of Steel Structures in Seismic Areas, Timisoara, Romania, pp 7.25-7.34 (1994).

2. Kareem, A. "The next generation of tuned liquid dampers", *1st World Conference on Structural Control*, 3-5 August, Los Angeles, CA, USA, pp FP5-19-FP5-28 (1994).
3. Yalla, S.K. and Kareem, A. "Semiactive tuned liquid dampers: Experimental study", *Journal of Structural Engineering, ASCE*, pp 960-971 (July 2003).
4. Haroun, M.A. and Piers, J.A. "Active orifice control in hybrid liquid column dampers", *1st World Conference on Structural Control*, 3-5 August, Los Angeles, CA, USA, **I**, pp FA1-69-FA1-78 (1994).
5. Abe, M., Kimura, S. and Fujino, Y. "Control laws for semiactive tuned liquid column damper with variable orifice opening", *2nd Int. Workshop on Structural Control*, Hong Kong (1996).
6. Sadek, F., Moheraz, B. and Lew, H.S. "Single and multiple tuned liquid column dampers for seismic applications", *Earthquake Eng. and Structural Dynamics*, **27**, pp 439-463 (1998).
7. El Damatty, A.A. "Studies on the application of tuned liquid dampers (TLD) to up-grade the seismic resistance of structures", *ICLR Research*, Paper Series-No. 17, Department of Civil and Environmental Engineering, University of Western Ontario (April 2002).
8. Kwok, K.C.S., Xu, Y.L. and Samali, B. "Control of wind-induced vibrations of tall structures by optimized tuned liquid column dampers", in *Computational Mechanics*, Y.K. Cheung, J.H.W. Lee and A.Y.T. Leung, Eds., pp 249-254, Balkena, Rotterdam (1991).
9. *Earthquake Records of Iran*, Building and Housing Research Centre (BHRC) of Iran; website: http://www.bhrc.ac.ir/ISMN.
10. *Iranian Code of Practice for Seismic Resistant Design of Buildings*, Standard No.2800, Building and Housing Research Center (2003).
11. Mir Ahsani, V. "Seismic design response spectra for Iran", *Building and Housing Research Center, Research Report*, Publication No. R-355 (2001) (in Persian).

APPENDIX

Table A1. Characteristics of the selected earthquake records used in analyses. All records were selected from the past strong ground motion records of Iran [9,11].

Earthquake (Year)	Station	Record No.	Magnitude Ms	Mb	Peak Accel. (gal) T	V	L	Soil Type	Source Distance (Km)
Ardal (1989)	Ardal	1341-1	-	4.6	82	68	143	I	16
Broujerd (1980)	Broujerd	1160	3.8	4.6	75	59	70	I	28
Roodbar (1990)	Roodbar	1395-1	-	4.7	91	50	45	I	53
Naghan (1977)	Naghan	1054-1	6.1	5.4	518	-	700	I	5
Ghaen (1979)	Ghaen	1139	7.1	6.1	117	96	186	I	54
Tabas (1980)	Tabas	1136-3	5.8	5.3	204	84	150	II	31
Golbaf (1981)	Golbaf	1183-1	4.0	4.8	68	50	99	II	17
Tabas (1978)	Tabas	1084-1	7.3	6.7	849	522	832	II	28
Tabas (1978)	Ferdos	1126	7.3	6.7	99	51	76	II	118
Golbaf (1981)	Golbaf	1183-8	-	4.6	98	22	61	II	60
Manjil (1980)	Roodsar	1151	5.1	5.3	93	63	84	III	30
Sarkhoon (1975)	Bandar Abas	1006-1	6.1	5.9	124	43	83	III	33
Ghaen (1979)	Kashmar	1130-3	7.1	6.1	67	34	70	III	171
Golbaf (1981)	Kerman	1174	7.0	5.9	76	50	98	III	56
Ghaen (1979)	Birjand	1137	7.1	6.1	28	19	32	IV	42
Manjil (1990)	Tonkabon	1359	7.7	6.4	85	33	130	IV	131

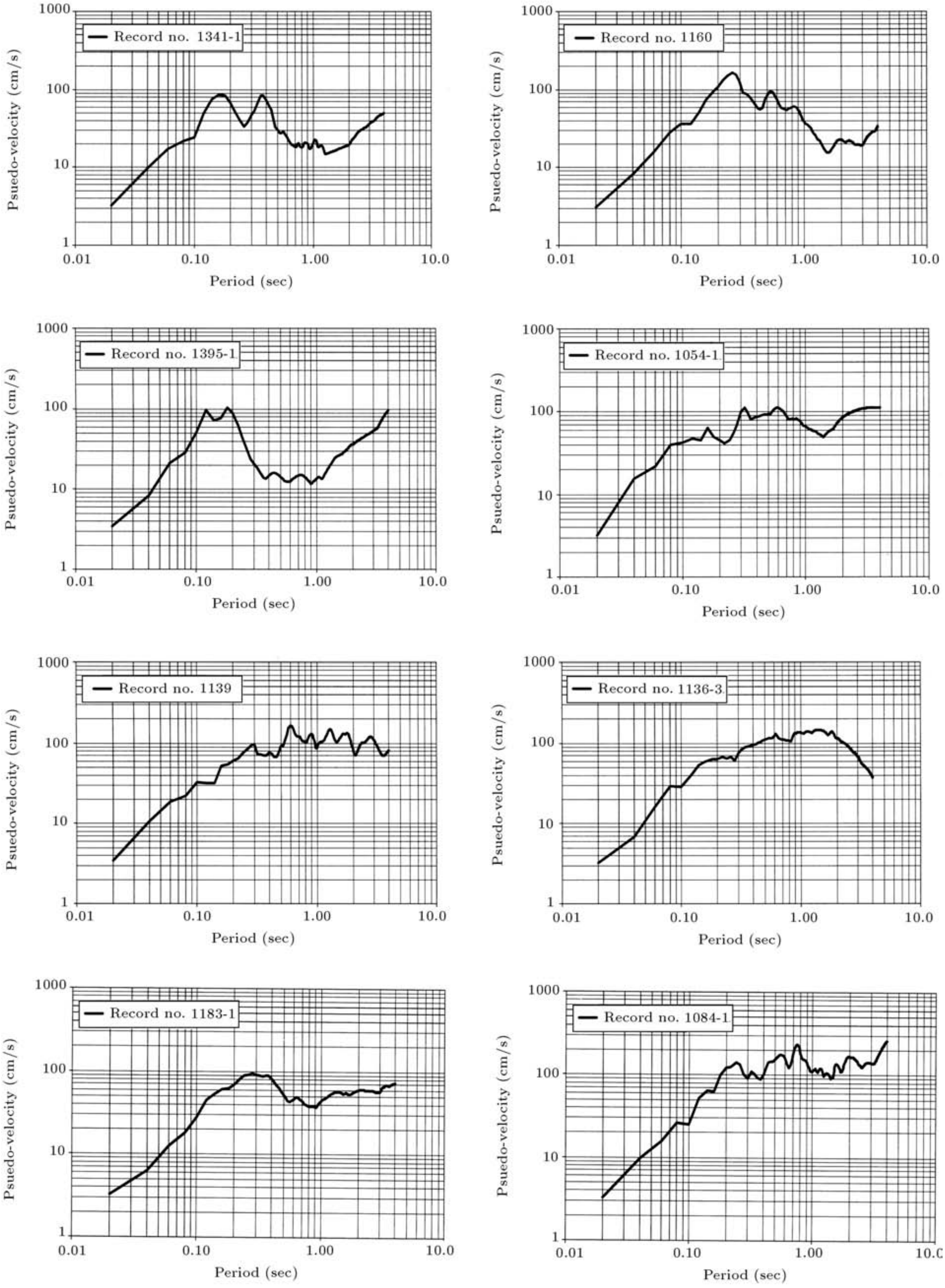


Figure A1. Velocity response spectra for all selected earthquake records. As mentioned before, the reason that reductions in response are observed for some records but not for others can be the peaks and valleys in the response spectrum of the records.

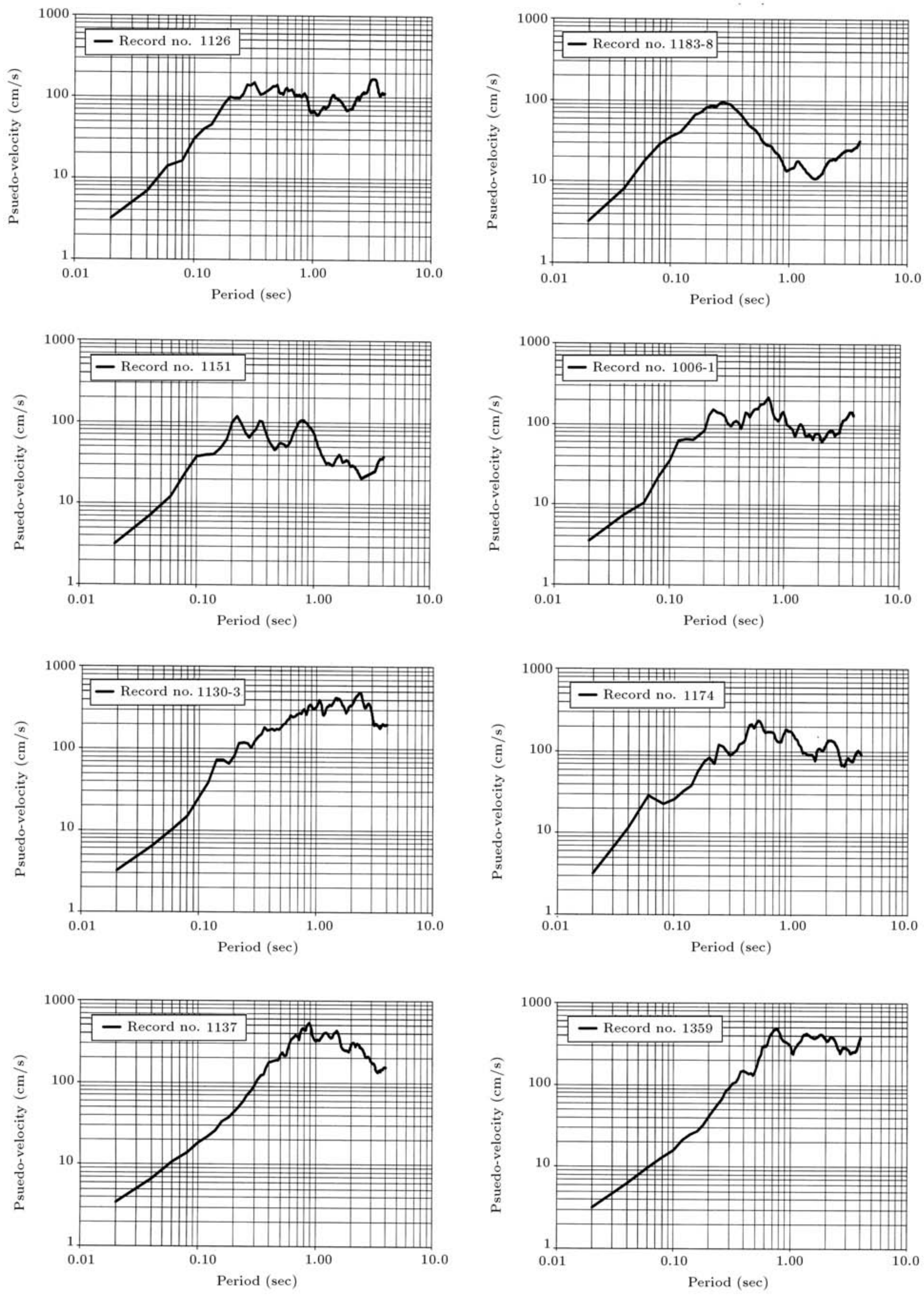


Figure A1. Countinued.