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Experimental Study on Using Uniform Tuned Liquid Column Damper for Structural Control of Buildings Resting on Loose Soil

A. Sarlak, H. Saeedmonir*, C. Gheyratmand

Department of Civil Engineering, Faculty of Engineering, Urmia University, Urmia, Iran

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ABSTRACT

In this study, through series of shaking table tests and statistical analysis, the efficiency of Uniform Tuned Liquid Column Damper (UTLCD) in structures resting on loose soils, considering soil-structure interaction was investigated. The soil beneath the structure is loose sandy soil. The Laminar Shear Box (LSB) as a soil container was adopted and the scaled form of the prototype structure namely model structure using scaling laws was built. Applying selected earthquake record the top story displacement of the soil-structure model was obtained. In the rest of the tests, the soil-structure model was equipped with UTLCD and tested. 3 different in sizes of UTLCDs, each with different blocking ratio and frequencies was used. To implement tests, completely randomized factorial design, with factors of Blocking ratio, Frequency and Type of the UTLCD was adopted. Through statistical analysis of the experimental tests was demonstrated that the mentioned factors are effective in response of the structure. Using Response Surface Methodology (RSM), the optimum values of the factors to minimize the top story displacement has been found. In this study it was demonstrated that, due to low reduction in structural responses (in average 12 percent), the optimum UTLCD is not efficient enough in controlling structures resting on loose soils.

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1. INTRODUCTION[1]

Through developments in industrial societies, tendency in using slender and low frequency structures such as tall buildings or bridges with long span, is increasing. Displacements play an important role in the design process of this type structures. The experienced stress in structural members often lay in acceptable range, but the discomfort of the occupants due to high displacements is still annoying. Therefore, motion control devices look fascinating and attract engineers interest. Among the passive control devices Tuned Mass Damper (TMD), Tuned Liquid Damper (TLD) and Tuned Liquid Column Damper (TLCD) are the renowned ones. TLD is tank filled with a liquid (usually water) that absorbs energy via motion of the fluid inside the tank during an earthquake. TLCD and TLD have robust advantages among other control devices including low cost, easy installation and economic maintenance [1]. The Initial use of the TLD in structural engineering goes back to 1990. Fuji et al. [2] studied the efficiency of the TLD in two structures. The first one was the 42-meter airport control tower in Nagasaki and the second was the 101-meter marine tower in Yokohama. Fuji et al. [2] showed that increasing the mass ratio (the ratio of the mass of water inside the tank to the structures mass) would increase the efficiency of TLD. Koh et al. [3] studied the effect of multi TLD in structures. Their numerical model consisted of seismic behavior of the Golden gate bridge. Jin et al. [4] studied the efficiency of TLD through numerical modelling and a series of shaking table tests. The considered structure was a marine platform. They showed the optimal mass ratio for TLD is a value between 1 to 5 percent. In deep water TLD, the entire water didn't participate actively in damping mechanism. This defect could be resolved through TLCD [5]. In TLCD the tank of water is in U-shape. There is an orifice in horizontal part of the tank.

*Corresponding Author's Email: h.saeedmonir@urmia.ac.ir (H. Saeedmonir)

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During an earthquake by displacing water inside this tank and passing through the orifice the damping mechanism acts [6].

The idea of TLCD was first developed by Sakai et al. They showed the efficiency of TLCD for Citicorp Center tower in New York and also for Golden tower located in Japan. Balendra et al. [7] inspected numerically the efficiency of TLCD for towers with different frequencies, subjected to wind load. They showed that for best performance of TLCD the frequency of TLCD must be tuned to the frequency of the tower. Gao et al. [8] developed a new TLCD which was in V-shape. Through numerical studies they showed that the new TLCD is more efficient than the original TLCD. Gao et al. [8] showed that the optimal performance of this new TLCD is obtained when the angle between inclined part of TLCD and horizon were a value between 10 to 30 degrees. Xue et al. [9] for the first time studied the TLCD function in reducing the pitching motion in structures. Matteo et al. [10] through experimental tests, validated the pre-defined proposed formula for optimal performance of the TLCD. Their experimental model structure was a Single Degree of Freedom (SDF), one story 3D frame.

The process in which the response of the soil influences the motion of the structure and response of the structure influences the motion of the soil, is referred to as Soil-Structure Interaction (SSI) [11]. Due to the SSI phenomenon, the frequency of the structure and the structural responses will be different from fixed base responses [12]. Ignoring the SSI effects leads to unreal dynamic responses of the structures, thus the SSI effects in structural analysis, must be considered [13]. Sarlak et al. [14] inspected the dynamic SSI effects for low frequency structures rested on loose soils. Applying numerical modelling along with a series of shaking table tests, using Laminar Shear Box (LSB), Sarlak et al. [14] concluded that ignoring SSI will result in unsafe design of these structures.

Due to significance of the SSI in dynamic response of structures, it’s clear that efficiency of the control devices, especially in low frequency buildings depends on the SSI effects. Xu and Kwok [15] numerically, inspected the effect of TMD in decreasing dynamic response of high rise buildings subjected to the wind loads. Considering SSI in their numerical models, Xu and Kwok [15] concluded that as a soil beneath the structure becomes stiffer the dynamic responses decreases more, and therefore TMD works more efficient. But for loose soils the results showed that TMD was not efficient enough. Gosh and Basu [16] inspected numerically the efficiency of TMD, considering SSI effects for structures rested on loose soils. They showed that tuning the TMD frequency to the fundamental frequency of the fixed base structure will result in incorrect responses, and it will question the efficiency of the TMD. Wang and Lin [17] studied numerically the effect of multi TMD (MTMD) in structures rested on loose soils. Considering SSI in their numerical models, they showed MTMD is more efficient than single TMD for structures rested on loose soils. Implementing numerical models, Farshidianfar and Soheili [18] optimized the function of a TLCD for a high rise building rested on different soils. The result of their study showed that tuning the TLCD frequency to the fundamental frequency of the whole structure (structure and sub-structure) will result in optimal function of TLCD. Min et al. [19] studied the efficiency of TLCD for high rise buildings subjected to the wind loads. They applied numerical modelling and shaking table tests. The results of their studies showed that TLCD with a low blocking ratio has best performance in decreasing dynamic response of structures subjected to the wind loads. By inspecting the previous studies, it can be noticed that:

- Most of these studies were considered for wind loadings.
- There were no experimental studies in which SSI effects were considered.
- Most of the experimental tests were conducted on a (SDF) models.

The aim of this paper is experimental study of uniform TLCD (UTLCD) function, considering SSI effects. the main structure or prototype structure is a low frequency structure rested on loose soil. The framework of this paper is as follows:

At first part of this study using scaling law, the model structure has been built. The LSB as soil container was built as well. In this part using shaking table, soil-structure model was subjected to an earthquake record and top story displacement has been obtained. At the second part, 3 different UTLCD with different characteristics was built. This time the soil-structure model equipped with each UTLCD once again was subjected to the earthquake record. Implementing the output data, the statistical analysis is carried out. In this part. the effect of the UTLCD in structural response were inspected, and optimized UTLCD using Response Surface Methodology (RSM) [20] was obtained. At the last part of this study the efficiency of the optimized UTLCD is inspected through applying 3 earthquake record to the soil-structure model.

2. MATERIAL AND METHOD

2. 1. Scaling Laws Scaling law is a discipline which is used for experimental study of the SSI effects in structural responses. The characteristics of scaled form of the structure is obtained from characteristics of the prototype through some relations. These relations are called scaling laws. As a pioneer of this discipline implementing it in soil mechanic. Rocha [21] proposed the linear relation in stress and strain between model and prototype structure. Moncarz and Krawinkler [22] presented a well-known "Cauchy condition" (Equation (1)) as a requisite for holding scaling laws.

$$\frac{(V_s)_p}{(V_s)_m} = \sqrt{\lambda} \tag{1}$$

in which V_s is shear wave velocity, and subscription p and m denotes prototype and model respectively. λ is geometrical scaling factor; which is the ratio of length in the prototype structure to the model structure. Iai [23] developed a general form of the "Cauchy condition" as follows:

$$\lambda_\varepsilon = \frac{\lambda}{\left(\frac{(V_s)_p}{(V_s)_m}\right)^2} \tag{2}$$

Using Equation (2), Iai [23] presented the set of relations for the SSI problems. in which $\lambda_\varepsilon = \frac{\varepsilon_p}{\varepsilon_m}$.

Meymand [24] exhibited the sufficient conditions for empirical study of the SSI. Meymand suggested besides satisfying the Cauchy condition the value of the λ_ε must be unity. In this study Meymand [24] scaling law relations is adopted. In Table 1, Meymand scaling law relations are shown. In which for each parameter, the corresponding value is the ratio of the prototype to the model, for that specific parameter.

The prototype structure is an 8-story building. The mass of this building is 2263-ton and its frequency is 0.243 (Hz). the building is a steel frame structure and is rested on loose Firoozkouh sand (No.161), with shear wave velocity equal to 100 m/s. The characteristics of the prototype structure and the finite element model of this structure is shown in Figure 2. Rayhani and Naggar [25] outlined the dimension of the soil media in Finite Element Method (FEM) modelling. According to their study, a minimum dimensions of the soil media in earthquake direction must be 5 times of width of the structure and 30 meters as a maximum depth of the finite soil media. Applying Rayhani and Naggar [25] results in this study, therefore 60 meters as the dimension of the soil media in earthquake direction and 19.5 meters for the soil depth, in FEM model was adopted. The tests are carried out using shaking table of Urmia University. The shaking table of Urmia university has single degree of freedom and its platform has rectangular shape with 3m × 2m dimensions. Its payload capacity is 2200 kg. Scaling factor (λ) for this study was selected 30, according to Figure 2, soil mass dimensions of the prototype structure become 2m × 1m × 0.65m. Considering 1500 kg/m^3 as a density of dry sand, the mass of the soil will be 1950 kg. Since maximum payload of the shaking table is 2200 kg, by

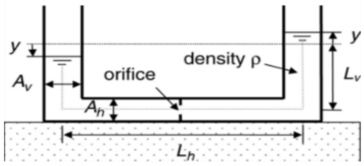

Figure 1. A typical TLCD

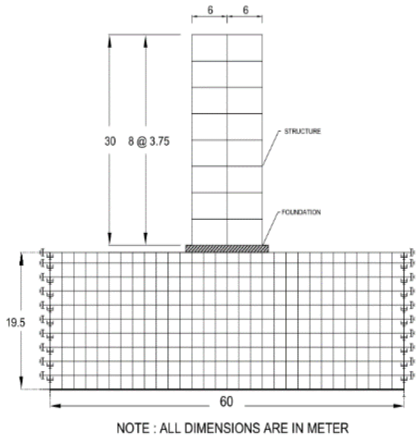

Figure 2. Finite element model of the prototype structure

decreasing the scale factor the total mass of the soil-structure prototype will become more than 2200 kg, which is not possible. And also by increasing the scale factor the accuracy of the output results will be decreased. Therefore, the selected scaling factor is the best choice. For experimental tests in current study, Laminar Shear Box (LSB) as a soil container was adopted. Through implementing Meymand scaling law relations, the characteristics of the model structure can be obtained. For instance, the ratio of period of the prototype structure to the model structure is equal to $\lambda^{1/2}$. Therefore, since the period of the prototype structure is equal to 4.115(s) (frequency is 0.243 (Hz)) we have:

$$\frac{T_p}{T_m} = \lambda^{1/2} \Rightarrow \frac{4.115}{T_m} = 30^{1/2} \Rightarrow T_m = 0.754(s)$$

Thus the frequency of the model structure is 1.327 (Hz). The characteristics of the model structure is summarized in Table 2. In Figure 3, the model structure is shown. The detailed discussion concerning to associated computations of the model structure and the LSB is elaborated in Sarlak et al [14] work.

2. 2. TLCD Damping mechanism of the TLCD is due to the motion of the water inside of the tank and passing through the orifice. The TLCD is suitable for controlling structures with low fundamental frequency [26]. A typical TLCD is shown in Figure 1. Wu et al. [6] show that the natural period of the TLCD can be obtained through Equation (3):

TABLE 1. Meymand scaling law relations [24]

Mass density	Force	Stiffness	Modulus	Acceleration	Shear wave velocity	Time	Frequency	Length	Stress	Strain	EI
1	λ^3	λ^2	λ	1	$\lambda^{1/2}$	$\lambda^{1/2}$	$\lambda^{-1/2}$	λ	λ	1	λ^5

TABLE 2. Model structure characteristics

Length (m)	Width (m)	Height (m)	Number of story	Mass (kg)	Frequency (Hz)
0.4	0.4	1	8	83.8	1.33

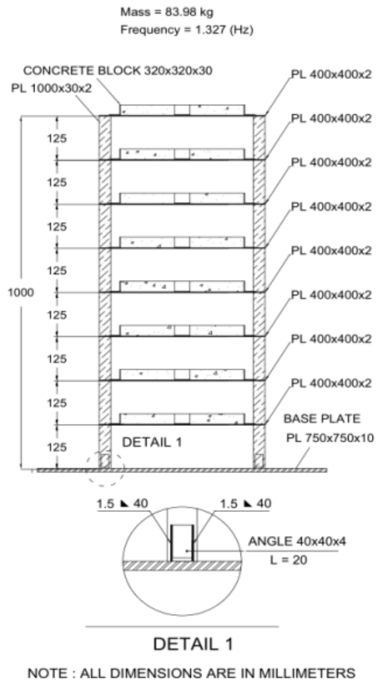

Figure 3. The model structure

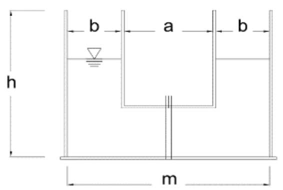

Figure 4. Outline of the UTLCD

$$T_d = 2\pi \sqrt{\frac{L_e}{2g}} \tag{3}$$

In above equation, $L_e = 2L_v + \nu L_h$ in which $\nu = \frac{A_v}{A_h}$. A_v and A_h are vertical and horizontal cross-section of the TLCD, respectively.

For uniform TLCD the vertical and horizontal cross sections are identical therefore, the ν is equal to 1. Using the uniform cross-section is always the best choice [6]. In this study, the uniform TLCD (UTLCD) has been considered. Ratio of the cross-section of the UTLCD at the orifice to other parts is called blocking ratio (Ψ). The main factors contribute in the performance of the given UTLCD are: natural period and head loss coefficient [18]. In this study 3 different in sizes UTLCD known as small, medium and large, were considered (Figure 8). In which the natural period and the blocking ratio is variable.

Figure 4 outlined the UTLCD. In Table 3, the dimensions of the UTLCDs is exhibited. From Equation (3) it's clear that L_e can be considered instead of the natural period. Head loss coefficient is directly related to the blocking ratio [19]. For each UTLCD 3 different orifice sizes corresponding to 3 different blocking ratios were considered.

These values are 0.25, 0.5 and 0.75, respectively (Figure 9). The control performance of building is less sensitive to small changes in the head loss coefficient [19]. Therefore, increasing in the number of the orifice sizes although will increase the total number of the tests, won't affect the results significantly.

2. 3. Numerical Modelling

Through numerical modelling The prototype structure and also soil-structure system is subjected to 3 selected earthquake records. The selected records are: Chi-chi, Kobe, Loma prieta. 4 factors involved in selection of the earthquake records, which are: magnitude, significant time duration, PGA and near and far fault earthquakes. All of the selected earthquake records must have magnitude greater than 6.5. The magnitude of Chi-chi, Kobe and Loma prieta earthquake records were 7.62, 6.9 and 6.93, respectively. The significant time duration of all of the selected records must be greater or equal than 10 seconds.

TABLE 3. Dimensions of different UTLCD (cm)

	A	b	m	H
Small	8	4	16	24
Medium	10	6	22	24
Large	12	8	28	24

The PGA of three selected records are different values in which, the differences between these values are notable. At least one of the selected records must be from a near fault earthquakes and one must be from far fault earthquakes. Chi-chi record is near fault earthquake and Kobe and Loma prieta, records are far fault earthquakes. The characteristics of the selected records are summarized in Table 4. The numerical models including fixed base model and flexible base model, were subjected to these earthquake records and fully nonlinear analyses method was applied. Detailed discussion concerning to adopted analytical model and analysis approach is presented in Sarlak et al. [14]. In Figure 5, the results of numerical modelling in terms of maximum displacement of the top story is presented. It can be noticed that SSI, has dominant influence on the response of the structure and therefore it shouldn't be ignored.

2. 4. TESTS In this part series of shaking table tests have been carried out. A model structure consists of a soil-structure model and the LSB which must be located on the shaking table. Using Meymand scaling law relations (Table 1) the mass density of the prototype soil and the model soil must be equal. Therefore, Firoozkouh sand (No.161) is used as a soil in soil-structure model. The LSB is consisted of several frames mounted on each other with negligible gap between each two successive frames. To prevent exiting soil through the gaps during the tests, a latex sheet is placed inside the LSB. After placing the latex sheet and pouring the desired sand inside the LSB, the soil-structure model is ready for tests. Through shaking table tests the top story displacement of the model structure as an output is obtained. To achieve this, a LVDT is used and it is attached to the tip of the model structure. Figure 10 show the overall soil-structure system on the shaking table ready for testing. In this study 3 selected earthquake records are implemented which are: Chi-chi, Kobe and Loma prieta. The scaled form of the original earthquake record must be used for shaking table tests. Implementing scaling laws, the scaled form of the earthquake records is obtained as follows: according to Meymand scaling law relations, only the time steps in an original record is changed and acceleration values are the same as the original one. According to Table 1, $\lambda^{1/2}$ is the ratio of the time step in original record to the scaled record. Therefore, time steps of Chi-chi and Loma prieta earthquake records which were 0.005 (s) will be change to 0.000912 (s). And the time steps of Kobe earthquake which were 0.01 (s) will be change to 0.001825 (s). Original and scaled records are shown in Figures 6a to 6f. For the first part of this study including tests and statistical analysis, The Chi-chi record was adopted. At last part besides Chi-chi the soil-structure model was subjected to Kobe and Loma prieta earthquake records.

TABLE 4. Selected earthquake records characteristics

Name	Country	Depth (km)	PGA(g)	Significant Duration (s)
Chi-chi	Taiwan	8	0.79	28.55
Kobe	Japan	17	0.67	10
Loma prieta	Italy	19	0.37	11

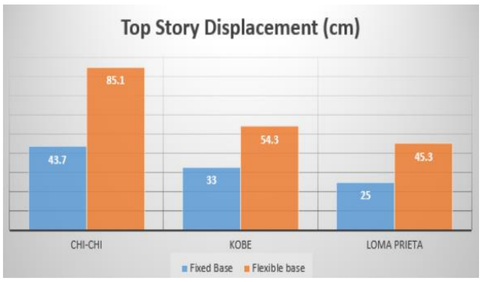

Figure 5. the results of numerical modelling

In the first tests the model structure without UTLCD is tested. In the rest of the tests the model structure is equipped with UTLCD. Each individual test was repeated for 3 times and the average of the values, was considered as the top story displacement. In the Figure 7 the results of first tests (without UTLCD) is exhibited. For flexible base models, the differences between numerical and the test results for Chi-chi, Kobe and Loma prieta records were 2.7, 3.9 and 2.8 percent, respectively. As it could be noticed the maximum discrepancies between numerical and test results are less than 5 percent. Therefore, due to this great accordance, the adopted boundary condition in the soil- structure models, namely LSB, is reliable. In the second type of tests the models are equipped with UTLCD. In each of these tests through changing the design parameters (natural period or Frequency, Blocking ratio and Type), the characteristics of the UTLCD is varied. Each individual test is repeated for 3 times. In the current study the ability of reducing the top story displacement of the soil-structure system, is considered as a main criterion for evaluating the efficiency of the UTLCD.

2. 5. Statistical Analysis In order to implement tests, completely randomized factorial design with factors of Blocking ratio, Frequency and Type (the type of the UTLCD which is small, medium or large) was applied. The first factor, Blocking ratio, is in three levels: 0.25, 0.5, 0.75. The second factor, Frequency, is in five levels: 1.33(Hz), 1.21(Hz), 1.11 (Hz), 1.04(Hz), 0.98(Hz).

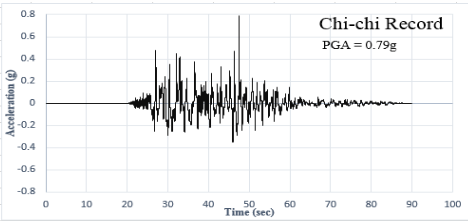

Figure 6a. Chi-chi acceleration record

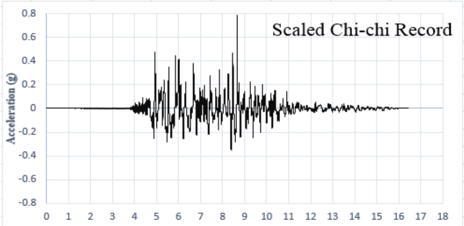

Figure 6b. Scaled chi-chi acceleration record

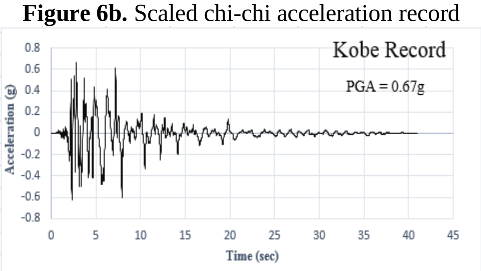

Figure 6c. Kobe acceleration record

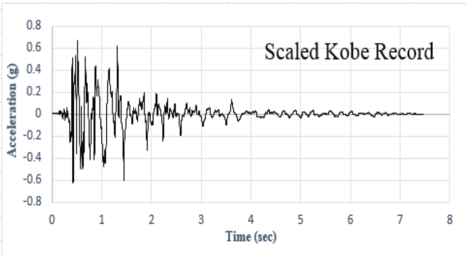

Figure 6d. Scaled Kobe acceleration record

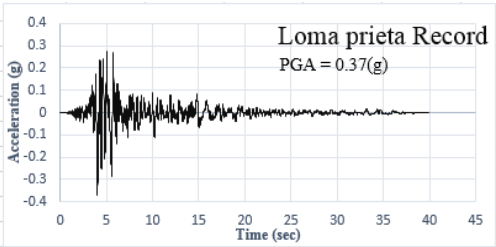

Figure 6e. Loma prieta acceleration record

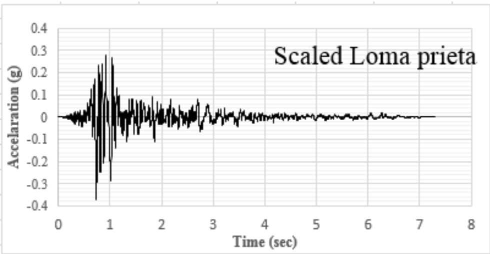

Figure 6f. Scaled Loma prieta acceleration record

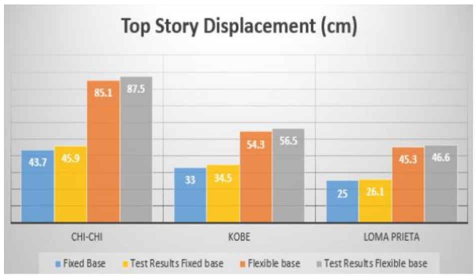

Figure 7. the results of numerical modelling

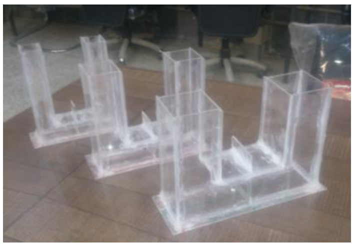

Figure 8. 3 types of UTLCD

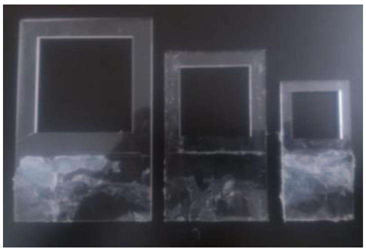

Figure 9. Blocking ratio equal to 0.5 for different UTLCDs

Figure 10. Soil-structure models ready for tests

Here are two important points. First the frequencies 1.33(Hz) and 1.11 (Hz) are the model structure frequencies respectively for fixed base and flexible base states. In fact, through numerical modelling, the fixed and flexible base frequency of the prototype structure is as follows: 0.243(Hz) and 0.203(Hz) [14].

Therefore, implementing Meymand scaling laws (Table. 1), and multiplying this values on $\lambda^{\frac{1}{2}}$ which is $\sqrt{30}$ the desired model structure frequency is obtained. Second important point is about the corresponding water length inside of each UTLCD. The five mentioned frequencies are corresponding to 28(cm), 34(cm), 40(cm), 46(cm) and 52(cm) of water length inside of each UTLCD. The last factor Type is in three levels: 0.0107, 0.0249 and 0.0458. these associated values are the mass of the water inside of each UTLCD. The factors T, B and F are the abbreviated of Type, Blocking ratio and Frequency, respectively. In order to find minimum value of the top story displacement and the corresponding design parameters of the UTLCD, the Response Surface Methodology (RSM) [20] was implemented. The RSM is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes [20].

3. RESULTS AND DISCUSSION

Statistical analysis was carried out using MINITAB software. The analysis of variance results is shown in Table 5. It can be noticed from this table that the corresponding P-value of the factors T, B and F are less than 0.01 which means that these factors are significant in 99 percent confidence level. Therefore, it is concluded that these factors are statistically significance in response of the structure (top story displacement). This result is in great accordance with the results of the numerical studies such as Farshidianfar and Soheili [18]. The regression function exhibited by RSM was in terms of T, B and F variables, and was in the form of full quadratic. Among the three options available in MINITAB to obtain the regression function using just effective terms, the Forward Selection option was chosen. In fact, there are 3 choices known as: Step Wise, Forward Selection, Backward Elimination. Coefficient of determination (R^2) for each of which is 57.23, 64.65 and 57.23, respectively. Therefore, using Forward Selection option, the associated regression function is shown in Equation (4):

$$D = 174.0 - 136.6\,T + 1.48\,B - 158.9\,F + 69.4\,F{*}F + 92.6\,T{*}B \tag{4}$$

Through using optimizer toolbox of the MINITAB, the minimum value of the top story displacement and the corresponding design parameters are as follows respectively:

$(T, B, F)_{optimum} = (0.0458, 0.25, 1.14)$

$(\text{Top story displacement})_{min} = 78.33$ cm

It can be concluded the best combination of the design parameters are $(T, B, F)_{best} = (0.0458, 0.25, 1.11)$. This reveals that the optimum UTLCD, is the largest UTLCD that could be situated in the top story and it has smallest blocking ratio. The frequency of this UTLCD must be tuned to the overall frequency of structure and sub-structure. From designing point of view the optimum UTLCD is implemented as follows:

In the design process of the structure the admissible top story displacement is increased by 10 percent, and then the structure is designed. After designing, the fundamental frequency of the soil-structure system is obtained. From architectural point of view, the largest UTLCD is implemented. This UTLCD with smallest blocking ratio is tuned to the fundamental frequency of the soil-structure system.

At the end of this part in order to inspect the efficiency of the UTLCD tuned with the best design parameters, obtained in this study, the model structure is subjected to 3 selected earthquake records. Once again, at the first step the model structure without UTLCD and at the second step the model structure equipped with UTLCD will be tested. The selected earthquake records are Chi-chi, Kobe and Loma prieta. As it can be noticed in Figure 11 the test results revealed that implementing tuned UTLCD leads to decrease in the top story displacements. This reduction is 13.1, 12.2 and 10.5 percent for Chi-chi, Kobe and Loma prieta records, respectively. This low amount of reduction (in average 12 percent) is due to the soil compactness beneath the structure. Actually due to the effects of the soil profile, the story displacements will be intensified. The looseness of the soil profile made the whole soil-structure system more flexible. In fact, the looseness of the soil profile and flexibility of the base, causes some rigid body movement of the whole building (super-structure). Thus because of this imposed rigid body movement, the efficiency of the UTLCD will be decreased. Therefore, the UTLCD is less effective device in mitigating dynamic response of structures resting on loose soils. One remedial solution in this cases, is increasing the stiffness and the damping of the structure, through using viscoelastic dampers. Due to existing interaction between the super-structure and the sub-structure, by increasing the stiffness and the damping of the structure, the super-structure become stiffer, as a result the deformation of the soil profile will be decreased.

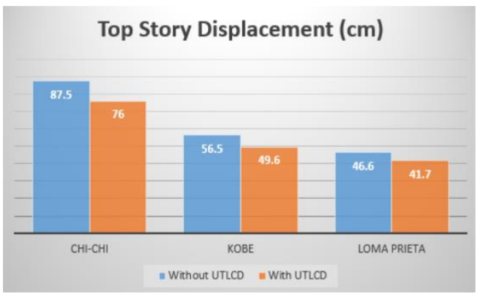

Figure 11. Top level displacement, the test results

TABLE 5. The table of variance analysis

Source	DF	Adj SS	Adj MM	F-Value	P-Value
Model	44	679.28	15.44	4.62	0.00
Linear	8	609.94	76.24	22.83	0.00
T	2	233.66	116.83	34.98	0.00
B	2	91.65	45.83	13.72	0.00
F	4	284.63	71.16	21.31	0.00
2-Way Interactions	20	64.8	3.24	0.97	0.51
T * B	4	13.11	3.28	0.98	0.42
T * F	8	34.7	4.34	1.3	0.25
B * F	8	16.98	2.12	0.64	0.75
3-Way Interactions	16	4.54	0.28	0.08	1.00
T * B * F	16	4.54	0.28	0.08	1.00
Error	90	300.56	3.34		
Total	134	979.83			

4. CONCLUSION

In this study the efficiency of the UTLCD for a low frequency structure rested on loose soil, through experimental tests and statistical analysis was investigated. The LSB as a soil container was used and model structure using scaling law was build. 3 different UTLCD in sizes, each of which with three different blocking ratio was built. There were five level of frequency associated to each UTLCD. Therefore, 45 different states for UTLCDs exist. Applying Chi-chi earthquake record via shaking table, to the soil-structure model, equipped with any of these UTLCDs, the top story displacement as output of each test was obtained. Each individual test was repeated for three times. Statistical analysis was carried out using MINITAB software. In this study statistical factorial design in shape of a completely randomized factorial design with factors of Blocking ratio, Frequency and Type (the type of UTLCD which is small, medium or large) was applied. By implementing RSM the mathematical model for the top story displacement was determined and using optimizer toolbox of the MINITAB, the minimum of the proposed model was obtained. Using shaking table tests, at the end part of this study, soil - structure model without the UTLCD and the soil - structure model equipped with the UTLCD tuned to the best design parameters, was subjected to three well-known earthquakes records. The results of this study were as follows:

1. It was demonstrated that the factors Blocking ratio, Frequency and Type are effective, in response of the structure (top story displacement).
2. It was shown that the best function of the UTLCD is obtained when the largest UTLCD with small blocking ratio is implemented. The frequency of this UTLCD is tuned to the whole structure (super-structure and sub-structure) fundamental frequency.
3. It was shown that for low frequency structures rested on loose soils, due to low reduction in structural responses (in average 12 percent), the UTLCD is not efficient enough in mitigating structural responses.

REFERENCES

1. Connor, J. and Laflamme, S., "Structural motion engineering, Springer, Vol. 493, (2014).
2. Fujii, K., Tamura, Y., Sato, T. and Wakahara, T., "Wind-induced vibration of tower and practical applications of tuned sloshing damper", ***Journal of Wind Engineering and Industrial Aerodynamics***, Vol. 33, No. 1-2, (1990), 263-272.
3. Koh, C., Mahatma, S. and Wang, C., "Reduction of structural vibrations by multiple-mode liquid dampers", ***Engineering Structures***, Vol. 17, No. 2, (1995), 122-128.
4. Jin, Q., Li, X., Sun, N., Zhou, J. and Guan, J., "Experimental and numerical study on tuned liquid dampers for controlling earthquake response of jacket offshore platform", ***Marine Structures***, Vol. 20, No. 4, (2007), 238-254.
5. Cammelli, S., Li, Y.F. and Mijorski, S., "Mitigation of wind-induced accelerations using tuned liquid column dampers: Experimental and numerical studies", ***Journal of Wind Engineering and Industrial Aerodynamics***, Vol. 155, (2016), 174-181.
6. Wu, J.-C., Shih, M.-H., Lin, Y.-Y. and Shen, Y.-C., "Design guidelines for tuned liquid column damper for structures responding to wind", ***Engineering Structures***, Vol. 27, No. 13, (2005), 1893-1905.

7. Balendra, T., Wang, C. and Cheong, H., "Effectiveness of tuned liquid column dampers for vibration control of towers", ***Engineering Structures***, Vol. 17, No. 9, (1995), 668-675.

8. Gao, H., Kwok, K. and Samali, B., "Optimization of tuned liquid column dampers", ***Engineering Structures***, Vol. 19, No. 6, (1997), 476-486.

9. Xue, S., Ko, J. and Xu, Y., "Tuned liquid column damper for suppressing pitching motion of structures", ***Engineering Structures***, Vol. 22, No. 11, (2000), 1538-1551.

10. Di Matteo, A., Iacono, F.L., Navarra, G. and Pirrotta, A., "Experimental validation of a direct pre-design formula for tlcd", ***Engineering Structures***, Vol. 75, (2014), 528-538.

11. Sarma, S., "Geotechnical earthquake engineering, IHE., (1996).

12. Gazetas, G., "Seismic soil-structure interaction: New evidence and emerging issues state of the art paper", in Geotechnical Earthquake Engineering and Soil Dynamics Geo-Institute ASCE Conference., (1998), 1119-1174.

13. Wolf, J.P. and Song, C., "Some cornerstones of dynamic soil–structure interaction", ***Engineering Structures***, Vol. 24, No. 1, (2002), 13-28.

14. Sarlak, A., Saeedmonir, H. and Gheyretmand, C., "Numerical and experimental study of soil-structure interaction in structures resting on loose soil using laminar shear box", ***International Journal of Engineering-Transactions B: Applications***, Vol. 30, No. 11, (2017), 1654-1663.

15. Xu, Y. and Kwok, K., "Wind-induced response of soil-structure-damper systems", ***Journal of Wind Engineering and Industrial Aerodynamics***, Vol. 43, No. 1-3, (1992), 2057-2068.

16. Ghosh, A. and Basu, B., "Effect of soil interaction on the performance of tuned mass dampers for seismic applications", ***Journal of Sound and Vibration***, Vol. 3, No. 274, (2004), 1079-1090.

17. Wang, J.-F. and Lin, C.-C., "Seismic performance of multiple tuned mass dampers for soil–irregular building interaction systems", ***International Journal of Solids and Structures***, Vol. 42, No. 20, (2005), 5536-5554.

18. Farshidianfar, A., "Optimized tuned liquid column dampers for earthquake oscillations of high-rise structures including soil effects", ***International Journal of Optimization in Civil Engineering***, Vol. 2, (2012), 221-234..

19. Min, K.-W., Kim, Y.-W. and Kim, J., "Analytical and experimental investigations on performance of tuned liquid column dampers with various orifices to wind-excited structural vibration", ***Journal of Wind Engineering and Industrial Aerodynamics***, Vol. 139, (2015), 62-69.

20. Myers, R.H., Montgomery, D.C. and Anderson-Cook, C.M., "Response surface methodology: Process and product optimization using designed experiments (wiley series in probability and statistics)", ***Applied Probability and Statistics***, (1995).

21. Rocha, M., "The possibility of solving soil mechanics problems by the use of models", in Proc. 4th Int. Conf. on SMFE. Vol. 22, (1957), 183-188.

22. Moncarz, P.D. and Krawinkler, H., "Theory and application of experimental model analysis in earthquake engineering, Stanford University California, Vol. 50, (1981).

23. Iai, S., "Similitude for shaking table tests on soil-structure-fluid model in 1g gravitational field", ***Soils and Foundations***, Vol. 29, No. 1, (1989), 105-118.

24. Meymand, P.J., "Shaking table scale model tests of nonlinear soil-pile-superstructure interaction in soft clay", (1998).

25. Rayhani, M. and El Naggar, M.H., "Numerical modeling of seismic response of rigid foundation on soft soil", ***International Journal of Geomechanics***, Vol. 8, No. 6, (2008), 336-346.

26. Zhu, F., Wang, J.-T., Jin, F. and Lu, L.-Q., "Seismic performance of tuned liquid column dampers for structural control using real-time hybrid simulation", ***Journal of Earthquake Engineering***, Vol. 20, No. 8, (2016), 1370-1390.

Experimental Study on Using Uniform Tuned Liquid Column Damper for Structural Control of Buildings Resting on Loose Soil

A. Sarlak, H. Saeedmonir, C. Gheyratmand

Department of Civil Engineering, Faculty of Engineering, Urmia University, Urmia, Iran

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چکیده

در این پژوهش با استفاده از آزمایشات میز لرزه و بهره گیری از تحلیل آماری، کارایی میراگر مایعی تنظیم شونده با مقطع یکنواخت در سازه‌هایی که بر روی خاک سست قرار دارند، با منظور کردن اثر اندر کنش خاک و سازه ،مورد بررسی قرار گرفته است. خاک بستر سازه خاک ماسه‌ای شل می‌باشد. از جعبه برشی لایه‌ای به عنوان مخزن جهت نگه داری خاک استفاده شد. مدل مقیاس شده سازه واقعی بر اساس قوانین حاکم بر مقیاس بندی ساخته شد. از طریق آزمایش میز لرزه سازه مدل آزمایشگاهی تحت یک رکورد زلزله منتخب قرار گرفت و جابه‌جایی نوک سازه اندازه گیری شد. در مابقی آزمایشات، سازه مدل آزمایشگاهی که مجهز به میراگر مد نظر بود، مجددا تحت همان بارگذاری قرار گرفت. از سه اندازه متفاوت از میراگر مدنظر که هریک قطر روزنه وفرکانس تنظیمی متفاوت دارند، استفاده شد. به منظور انجام آزمایشات یک طرح فاکتوریل کاملا تصادفی با فاکتورهای قطر روزنه، فرکانس و اندازه میراگراستفاده شد. نتایج تحلیل های آماری موید تاثیرگذاربودن این فاکتورها در پاسخ‌های سازه می‌باشند. از روش رویه‌های پاسخ به منظور پیدا کردن مقادیر بهینه فاکتورهای تاثیرگذارکه منجر به کمینه شدن جابه‌جایی نوک سازه می‌شود استفاده شد. در این تحقیق نشان داده شد با توجه به اینکه میراگر مدنظربه میزان کمی (به طور متوسط 12 درصد) باعث کاهش پاسخ‌های سازه می‌گردد درنتیجه به عنوان یک ابزار کنترل کارا در سازه‌هایی که روی خاک سست قرار دارند تلقی نمی‌شود.

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