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Καινοτόμο Σύστημα Σεισμικής Προστασίας Πολυωρόφου Κτιρίου μέσω πλωτών/σεισμικά-μονωμένων πλακών

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ΠΕΡΙΛΗΨΗ

Στην εργασία αυτή εξετάζεται η χρήση πλωτών πλακών, δηλαδή πλακών που έχουν μονωθεί σεισμικά από τον υπόλοιπο φέροντα οργανισμό, ως σύστημα ελέγχου της σεισμικής απόκρισης της κατασκευής. Ο σκοπός αυτών των πλωτών πλακών, εξαρτώμενος της περιόδου τους, είναι διττός: αφενός παρέχουν σεισμική μόνωση στα σώματα που βρίσκονται επάνω τους, αφετέρου δρουν ως αποσβεστήρας συντονισμένης μάζας (Tuned Mass Damper, TMD) για τη συνολική απόκριση της κατασκευής. Οι αναλύσεις βασίζονται σε αρκετές μελέτες περιπτώσεων με διαφορετικούς συνδυασμούς πλωτών / κανονικών πλακών κατά την έννοια του ύψους της κατασκευής, καθώς και για διάφορα χαρακτηριστικά των εφεδράνων. Η απόδοση κάθε περίπτωσης εξετάζεται με βάση ένα τεχνητό σεισμογράφημα, που παράχθηκε με το λογισμικό SIMQKE-II [1] το οποίο ακολουθεί ένα συγκεκριμένο φάσμα απόκρισης του Ευρωκώδικα 8. Τα αριθμητικά αποτελέσματα επιβεβαιώνουν ότι για τιμές της περιόδου της σεισμικής μόνωσης κοντά στη θεμελιώδη ιδιοπερίοδο της κατασκευής, το σύστημα των πλωτών πλακών δρα ως TMD με το πλεονέκτημα της μεγαλύτερης μάζας. Επιπλέον, για μεγαλύτερες τιμές της περιόδου (~1.5s και άνω) το σύστημα των πλωτών πλακών μειώνει την ενεργό σεισμική μάζα της κατασκευής, δρώντας και πάλι ευεργετικά στην απόκρισή της.

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Innovative Seismic Protection System for Multistory Buildings using Floating Slabs

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ABSTRACT

The use of floating slabs, i.e. slabs that have been seismically isolated from the skeleton of the structure, as structural control system is investigated herein. Depending on their period, the purpose of these slabs is twofold; on one hand they act as mass-damping system for the overall response of the structure and on the other hand they provide seismic isolation to their contents. The analyses are based on several case studies with different combinations of floating/normal slabs along the height of the structure, as well as seismic isolation characteristics. The performance of each structural configuration is tested under an artificial seismic motion, generated using the SIMQKE-II software [1] and matching a particular EC8 response spectrum. The numerical results confirm that for isolation periods close to the fundamental eigenperiod of the structure, the floating slabs act as tuned mass dampers (TMD), with the additional advantage of the larger mass. For large isolation periods (~1.5s or more), the floating slab system reduces the effective seismic mass of the structure, again having a beneficial effect regarding its response.

1 INTRODUCTION

The construction industry has recently witnessed an explosive increase in the size of structures that are feasible, following the wide use of high-strength materials with extraordinary properties. Consequently, dynamic effects such as earthquake- and wind-induced vibrations have become an important design factor. Modern structural design employs several techniques to mitigate these effects, yet the problem is anything but solved.

Regarding earthquake engineering, the most popular method of protection is base isolation, where the superstructure is isolated from its foundation by means of flexible elements. The aim is to reduce the seismic forces imposed to the structure, rather than increase its bearing capacity. This

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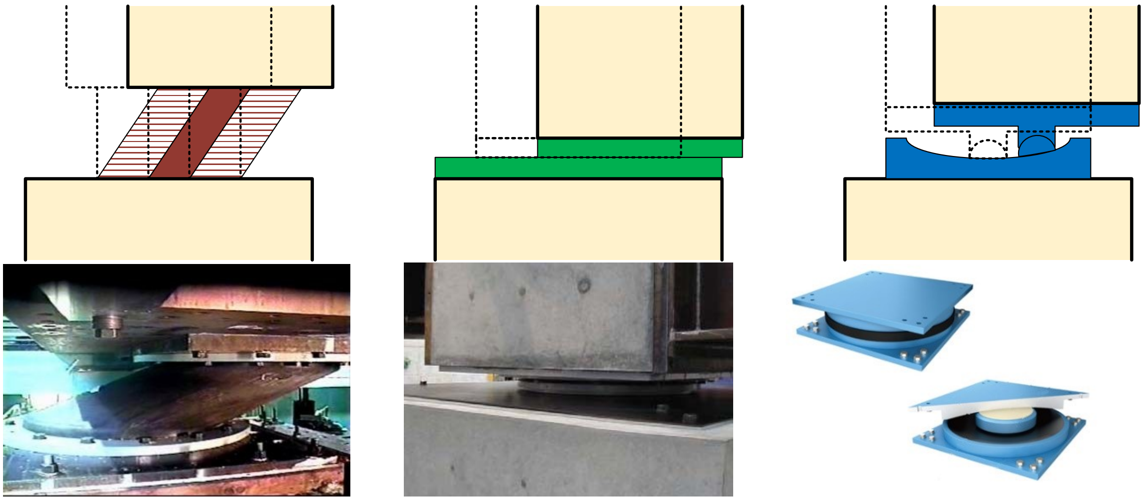
method has been used at least as early as circa 550 BC, when the Mausoleum of Cyrus the Great was built on top of six layers of smoothed blocks of stones.

Nowadays, base isolation is accomplished by installing special devices in the foundation of the structure. A popular choice is the Lead Rubber Bearing (LRB) which provides both damping properties and restoring force. Sliding Bearings use friction on a flat surface to provide frequency-independent damping, but they do not provide any restoring force. This drawback is addressed by Friction Pendulum Bearings, which use the curvature of spherical interfaces to provide a restoring force (Figure 1).



(a) (b) (c)

Figure 1. (a) Lead rubber bearing (b) Sliding bearing (c) Friction pendulum bearing.

The aforementioned systems are passive in the sense that they do not alter their properties dynamically. Being passive, they possess the important advantage of low cost in installation and maintenance. Other structural control systems may be semi-active (i.e., controllable passive devices which do not add mechanical energy to the structural system), active, or hybrid [2].

Base isolation is straightforward in new structures, where the bases of columns and shear walls are either placed directly on top of isolation devices, or through rigidity diaphragms. It can also be used in seismic retrofit, which may require creating rigidity diaphragms and moats around the structure, at a certain cost. Finally, base isolation can also be implemented in small-scale, to protect expensive equipment or artifacts of artistic or monumental significance.

Base isolation is not panacea. The reduction of seismic forces is achieved by increasing the rigid body mode period of the isolated structure so that the spectral acceleration becomes small. In general, the optimum value of the period is between 2 and 4 seconds for a wide range of parameters. Higher values are rarely used, as they have significant drawbacks due to the reduced stiffness in the isolation elements; namely, large displacements (which may lead to impact with adjacent structures, or failure of the bearings) and unwanted wind-induced movement (which may lead to occupant discomfort). Thus, base isolation is more suitable for relatively stiff structures on stiff foundations. Higher structures tend to have large fundamental periods by nature, so the seismic forces are small. In these cases, wind-induced vibrations are more important and another device, called the Tuned Mass Damper (TMD), is often utilized to alleviate these effects.

A TMD, sometimes referred to as a dynamic vibration absorber, is a classical engineering device consisting of a mass, a spring and a viscous damper. The device is attached to the superstructure and uses the inertia of its mass to absorb unwanted vibrations mainly from wind. The basic principal of the TMD is the mitigation of the dynamic response of the system through energy transfer to an attachment, installed at a suitable position within the structure. The TMD consists of an additional mass and a stiffness element in combination with an artificial damper. The parameters that concern the design of such devices are determined with the resonance of the frequency of the device with the fundamental eigenfrequency of the primary system. As a result, a significant portion of the vibration energy of the structure, due to a seismic or other vibratory excitation, is transferred to the mass of the device and then dissipated through the damper. Probably the first implementation of a TMD, in the form of internal open-surface tuned liquid dampers (TLD) to mitigate the roll of sea vessels, was proposed as early as 1883 by Watts [3]. The TMD concept was first patented by Frahm [4] who also designed an improved version of Watt's stabilizing tanks called the U-tube [5]. A detailed discussion of optimal tuning and damping parameters of TMD appears in Den Hartog [6]. These devices have found various applications in the field of Civil Engineering [7–10]. The use of TMDs in MDOF systems, as well the use of multiple small TMDs (MTMD), has also been investigated [11,12]. There exist passive, semi-active or even active implementations of TMDs [13,14].

Despite the fact that TMDs are known for their effectiveness, they possess certain important drawbacks. First, environmental influences and other external parameters may alter their properties, causing detuning phenomena which reduce their performance [15]. Second, and most important, a large oscillating mass is generally required in order to achieve significant vibration reduction [16]. Since the TMD is usually installed at the top of the structure, tuned in resonance with the primary mode of the primary structure [11], even small mass ratios in the order of 5% render its construction and placement rather difficult.

In light of the above, in this paper the use of floating slabs, i.e. slabs that are detached from the skeleton of low- or high-rise buildings on certain, or even all of their floors, are investigated as means of both structural control and mass damping.

2 DYNAMICS OF STRUCTURES FEATURING FLOATING SLABS

2.1 General considerations

By using their seismically excited dead and live weight, floating slabs provide vastly more mass for vibration than the traditional TMD. By examination of real-life high-rise structures, it is found that the mass of such a floating slab may easily account for 50% of the mass of the whole floor. More importantly, this mass is not additional to the mass of the structure; it exists anyway. Note that, in the literature, the mass ratio μ which is usually considered for TMDs accounts for up to

5% of the total mass. Since the TMD is usually installed in the top of the structure, tuned in resonance with the primary mode of the primary structure [11], even this mass ratio poses significant challenges regarding its safe installation and usage. As multiple floors can have their slabs seismically isolated from the skeleton of the structure, it is clear that the total mass that can potentially be used as damper is many times larger than that in the case of a traditional TMD. This is significant as parametric analyses indicate that, in general, the performance of the TMD in reducing structural vibration increases with higher values of the mass ratio [16].

The equations of motion of an *N*-degree-of-freedom shear building under seismic excitation are written as

$$\mathbf{M}\ddot{\ } \qquad \dot{\ } \qquad \ddot{\ } \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ are the mass, damping and stiffness square matrices of order N, respectively, $\mathbf{u}(t)$ is the vector of the structural lateral displacements with respect to the ground, $\mathbf{1}$ is a vector of order N with each element equal to unity, and $\ddot{\ }$ is the ground acceleration. The $\mathbf{M}$, $\mathbf{K}$ matrices and the $\mathbf{u}(t)$ vector for a N degree-of-freedom lumped-mass system are given as

$$\mathbf{M} = \begin{bmatrix} M_1+m_1 & & & & \\ & M_2+m_2 & & & \\ & & \dots & & \\ & & & M_{N-1}+m_{N-1} & \\ & & & & M_N+m_N \end{bmatrix} \tag{2}$$

$$\mathbf{K} = \begin{bmatrix} k_1+k_2 & -k_2 & & & \\ -k_2 & k_2+k_3 & -k_3 & & \\ & \dots & \dots & \dots & \\ & & -k_{N-1} & k_N+k_{N-1} & -k_N \\ & & & -k_N & k_N \end{bmatrix} \tag{3}$$

$$\mathbf{u}(t) = \begin{bmatrix} u_1 & u_2 & u_3 & \dots & u_N \end{bmatrix}^T \tag{4}$$

where M_i, m_i, k_i, u_i are the slab mass, node mass, stiffness and lateral displacement of the *i*th story of the shear building ($i = 1,2,\dots N$). Note that, in a lumped-mass system the total mass of the *i*th floor is equal to the sum of the slab mass and the node mass. Moreover, a classical damping matrix from modal damping ratios is adopted herein, which is given as

$$\mathbf{C} = \mathbf{M}\left(\sum_{i=1}^{N} \frac{2\xi_i\omega_i}{M_i+m_i}\phi_i\,\phi_i^T\right)\mathbf{M} \tag{5}$$

where ω_i, ϕ_i are the eigenvalues, and natural modes of the free undamped vibration problem, and ξ_i are the damping ratios of the ith mode.

2.2 Two-story structure

Detaching a significant mass from the skeleton of the structure drastically modifies its dynamic properties. For example, we consider a two-story structure (Figure 2). We proceed to detach the slab of the first floor which constitutes ~31.53% of the total mass by itself. The floating slab is installed on linear elastic bearings with total variable stiffness $k_3 = M_1(2\pi/T_{isol})^2$, depended on the selected isolation period T_{isol} of the floating slab.

For the two-story building of Figure 2b, to construct the equations of motion, with a single floating slab installed on the first floor. In this case, the slab mass is detached from the first floor and a new degree of freedom is formed with mass M_1 and stiffness k_3 which accounts for the total stiffness of the linear elastic bearings (Figure 2c).

For simplicity reasons, the new degree of freedom is placed at the end of the new matrices in the three-degree of system. Hence, the mass and stiffness matrices take the form

$$\mathbf{M} = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 + M_2 & 0 \\ 0 & 0 & M_1 \end{bmatrix} \tag{6}$$

$$\mathbf{K} = \begin{bmatrix} k_1 + k_2 + k_3 & -k_2 & -k_3 \\ -k_2 & k_2 & 0 \\ -k_3 & 0 & k_3 \end{bmatrix} \tag{7}$$

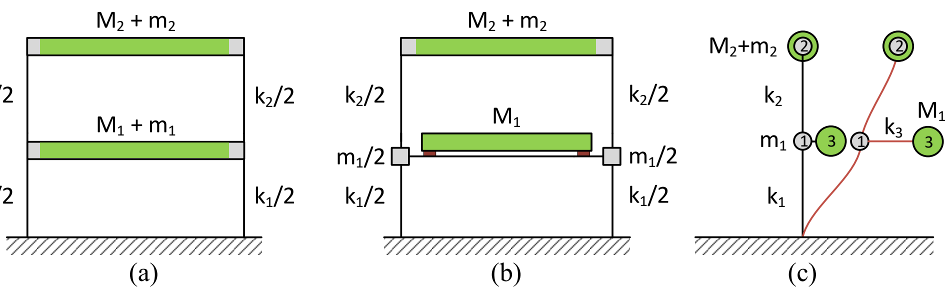


Figure 2. Sample two-story building (a) conventional structure (b) configuration with a floating slab on the first floor (c) equivalent 3-DOF system with m =node mass, M =slab mass.

Solving the eigenproblem for the undamped system we obtain the natural periods of the system as a function of T_{isol} (Figure 3). The mass-normalized mode shapes, corresponding periods and participation factors as a function of T_{isol} are shown in Figure 4. The small fundamental period is justified since the real-life plan view used in this example corresponds to a much higher structure.

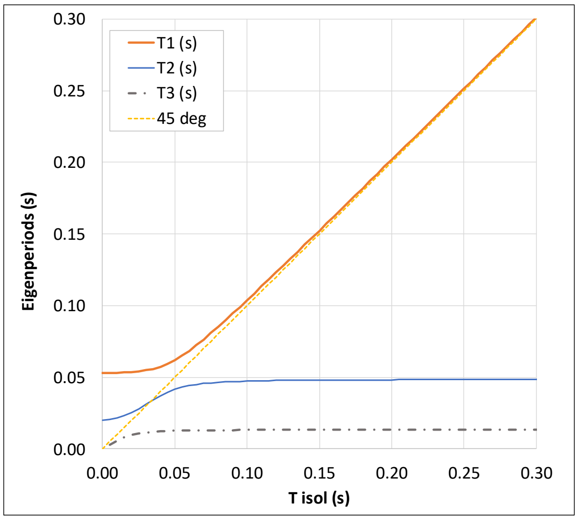


Figure 3. Eigenperiods of the structure as a function of the floating slab's isolation period.

The following observations can be made:

- For very small isolation periods, i.e. smaller than the periods of the conventional structure (see e.g. $T_{isol} = 0.016\ s$ in Figure 4), the participation factor of the third mode is very small. The two first modes are similar to those of the conventional structure.
- For intermediate isolation periods, the mode shapes change form and order. For $T_{isol} = 0.032\ s$ in Figure 4 it is observed that $T_2 \cong T_{isol}$ and the curve corresponding to T_2 crosses the 45° line in Figure 3. The second mode shape has almost no participation while its first DOF is suppressed, as the mode shape changes form.
- For very large isolation periods (see e.g. $T_{isol} = 5\ s$ in Figure 4), the modes are practically fully separated. The first mode refers to the vibration of the floating slab by itself, and the other two modes refer to the vibration of the building without the floating slab. Since the mode shapes are mass-normalized, the participation factor of the first mode (31.53%) is equal to the mass ratio of the floating slab with respect to the total mass. Consequently, the participation factors of the other two modes are significantly smaller.

We proceed to evaluate the response of the sample 2-story structure under an artificial seismic motion, generated using the SIMQKE-II software [1] and matching a particular EC8 response spectrum. Linear viscous damping with $\xi = 5\%$ for each mode has been used.

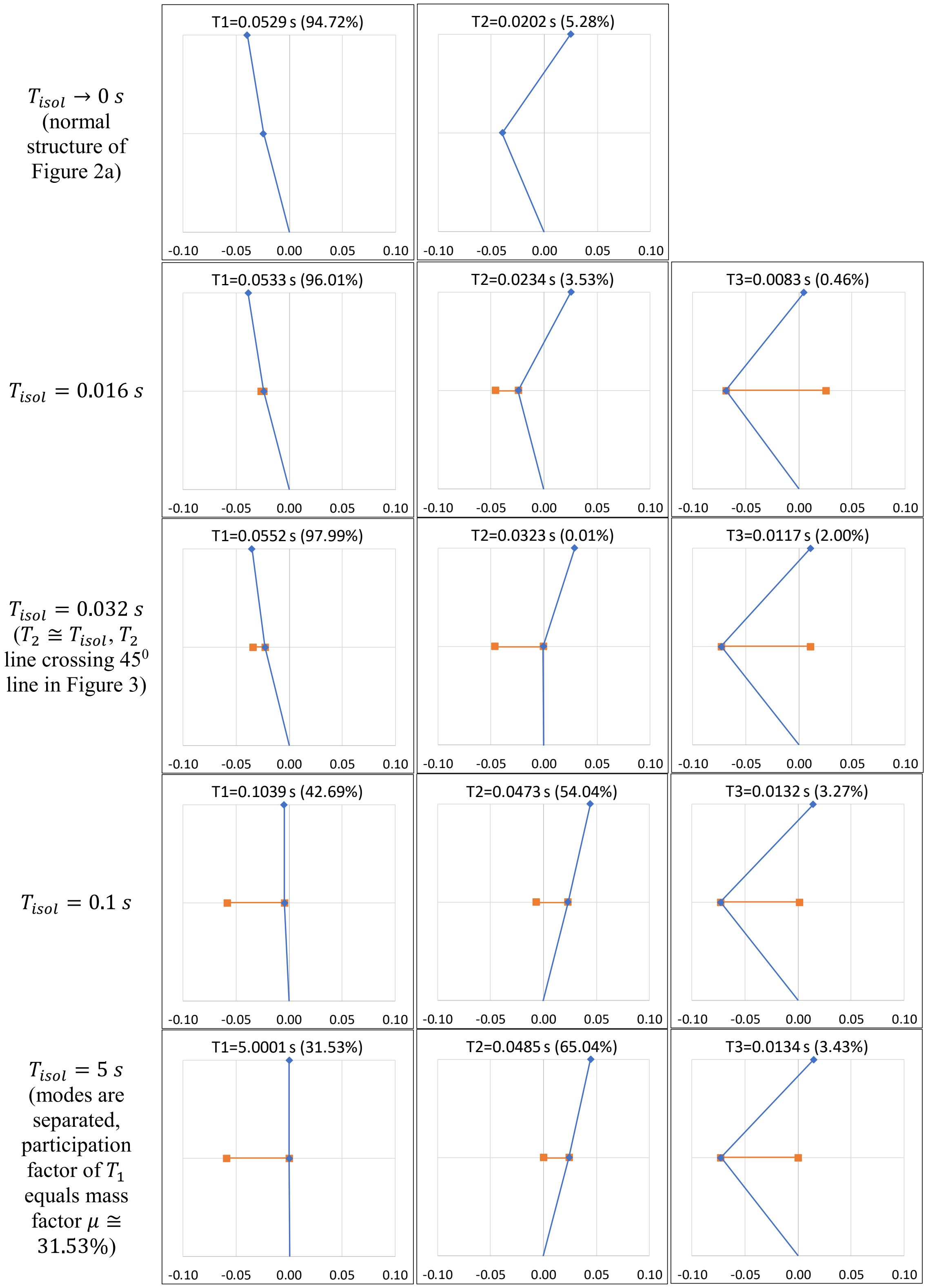


Figure 4. Mode shapes, corresponding periods and participation factors of two-story structure (Figure 2) for various isolation periods of the floating slab.

Figure 5 shows the total acceleration (i.e. including the ground) of the floating slab. It is evident that the accelerations are high for small values of T_{isol} and diminish for larger values. This confirms that local seismic isolation for the whole floor slab, or a small portion of it, is straightforward. Note that in usual base isolation, where the whole structure is separated from the foundation, very large isolation periods (>4 s) are rarely used. This is because the small stiffness leads to excessive displacements, while the unavoidable wind action results to incessant movement of the structure unless special frictional devices are used. In this case the slabs are located internally, so the wind action is irrelevant. In addition, a suitable bearing design using friction prevents the floating slab from swaying under small horizontal forces. This allows the potential use of large isolation periods, which diminish the accelerations observed on the floating slab.

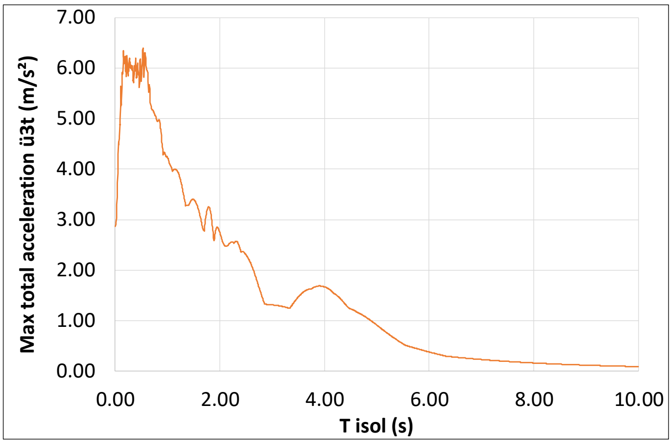


Figure 5. Maximum total acceleration of the floating slab of two-story structure (Figure 2) for various isolation periods of the floating slab.

Figure 6 shows the normalized displacements u_1, u_2 of first and top floor, respectively. Normalization is performed with respect to the corresponding values of the normal structural configuration, where the slabs are rigidly connected to the nodes; therefore, the curves initiate at 100% when $T_{isol} \to 0$. Interestingly, for small values of T_{isol} there is a lot of fluctuation, but one should bear in mind that a proper damping model needs to be utilized for the bearings of the floating slab, in order to dissipate energy effectively. For large values of T_{isol}, the curves become smooth into a much lower level than 100%. Contrary to the traditional base isolation, the fundamental period is not increased in order to reduce the spectral acceleration; in fact, it is slightly smaller (Figure 3). Thus the reduced response observed in Figure 6 is due to the sheer reduction of the seismic mass which participates in the second and third mode of vibration, as explained in Figure 4. The reduction is more prominent for the first floor where the floating slab is located. The gradual smoothing of the curves is explained by the gradual separation of the modes corresponding to the floating slab and the rest of the structure.

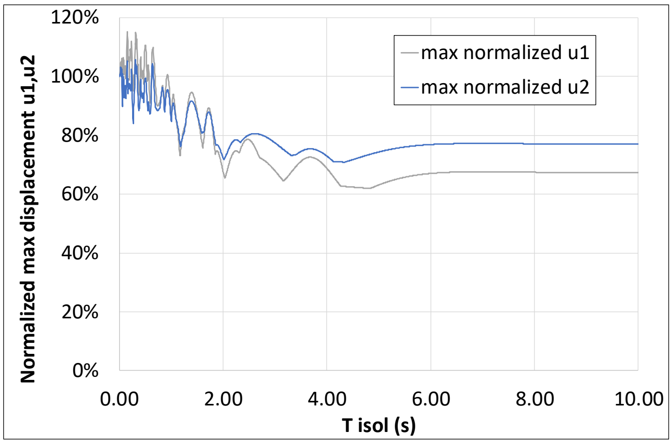
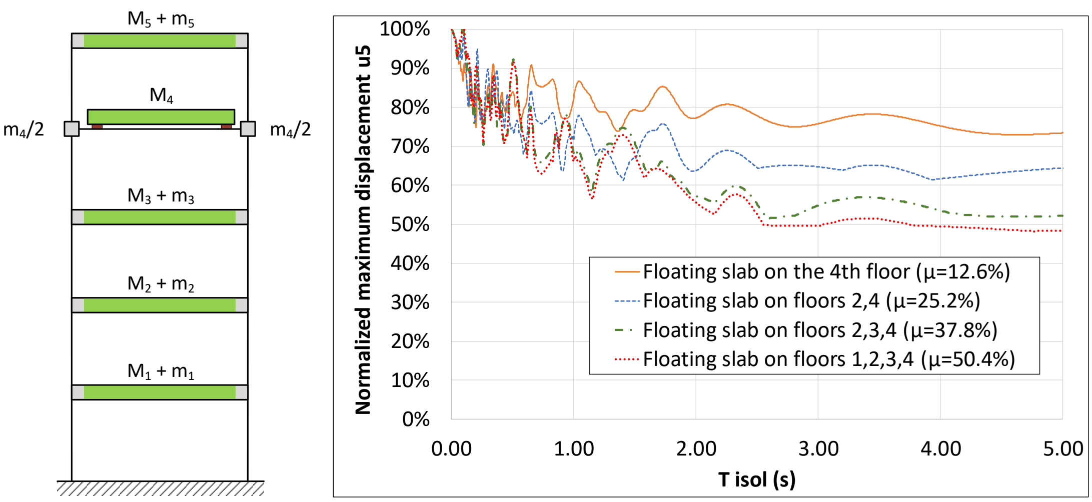


Figure 6. Normalized maximum displacements $\boldsymbol{u_1}$, $\boldsymbol{u_2}$ of two-story structure (Figure 2) for various isolation periods of the floating slab.

2.3 Five-story structure

The aforementioned conclusions are extended to higher structures, as well. Consider a 5-story building with the same plan view and certain configurations of floating slabs (Figure 7). Under an artificial seismic motion, we evaluate the maximum displacement of the top floor as a function of the isolation period T_{isol} of the floating slab(s). Plotting the percentage of this value with respect to the conventional structure (i.e., when $T_{isol} \to 0$), reveals a large decrease for both small periods (due to TMD action) and large periods (due to sheer reduction of the seismic mass), as shown in Figure 7b.



(a) (b)

Figure 7. (a) Five-story structure with a single floating slab on the 4th floor (b) normalized maximum displacement of the top floor as a function of the isolation period of the slab.

3 CONCLUSIONS

Floating slabs can be installed in multiple levels within a building, rendering the total reduction of the effective seismic mass significant. Floating slabs provide more mass for vibration than the traditional TMD. By examination of real-life high-rise structures, it is found that the mass of each floating slab may easily account for 50% of the mass of the whole floor. More importantly, this mass is not additional to the mass of the structure; it exists anyway. Obviously, these slabs will undergo significant accelerations to act as TMDs. For larger isolation periods the floating slabs act as seismic mass reduction system. In this case, the slab accelerations are decreased, and the floating slabs offer important advantages with respect to traditional base isolation. Sometimes base isolation is not feasible because of adjacency with other structures. However, in the floating slab system, the large displacements of the floating slabs are contained within the structural skeleton.

4 REFERENCES

1. Vanmarcke EH, Fenton GA, Heredia-Zavoni E. SIMQKE-II (User's manual version 2) 1997.
2. Housner GW, Bergman LA, Caughey TK, Chassiakos AG, Claus RO, Masri SF, *et al.* Structural Control: Past, Present, and Future. *Journal of Engineering Mechanics* 1997; **123**(9): 897–971. DOI: 10.1061/(ASCE)0733-9399(1997)123:9(897).
3. Watts P. On a method of reducing the rolling of ships at sea. *Transactions of the Institution of Naval Architects* 1883; **24**: 165–190.
4. Frahm H. Device for Damping Vibrations of Bodies. US #989958, 1909.
5. Frahm H. Results of trials of the anti-rolling tanks at sea. *Journal of the American Society for Naval Engineers* 1911; **23**: 571–597. DOI: 10.1111/j.1559-3584.1911.tb04595.x.
6. Hartog DJP. *Mechanical Vibrations*. New York: McGraw-Hill; 1956.
7. McNamara RJ. Tuned Mass Dampers for buildings 1977; **103**: 1785–1798.
8. Luft RW. Optimal Tuned Mass Dampers for Buildings. *Journal of the Structural Division* 1979; **105**(12): 2766–2772.
9. Debnath N, Deb SK, Dutta A. Multi-modal vibration control of truss bridges with tuned mass dampers under general loading. *Journal of Vibration and Control* 2016; **22**(20): 4121–4140. DOI: 10.1177/1077546315571172.
10. Qin L, Yan W, Li Y. Design of frictional pendulum TMD and its wind control effectiveness. *Journal of Earthquake Engineering and Engineering Vibration* 2009; **29**: 153–157.
11. Lee CL, Chen YT, Chung LL, Wang YP. Optimal design theories and applications of tuned mass dampers. *Engineering Structures* 2006; **28**(1): 43–53. DOI: 10.1016/J.ENGSTRUCT.2005.06.023.
12. Abé M, Fujino Y. Dynamic characterization of multiple tuned mass dampers and some design formulas. *Earthquake Engineering & Structural Dynamics* 1994; **23**(8): 813–835. DOI: 10.1002/eqe.4290230802.
13. Hrovat D, Barak P, Rabins M. Semi-Active versus Passive or Active Tuned Mass Dampers for Structural Control. *Journal of Engineering Mechanics* 1983; **109**(3): 691–705. DOI: 10.1061/(ASCE)0733-9399(1983)109:3(691).
14. Chang JCH, Soong TT. Structural Control Using Active Tuned Mass Dampers. *Journal of the Engineering Mechanics Division* 1980; **106**(6): 1091–1098.
15. Weber B, Feltrin G. Assessment of long-term behavior of tuned mass dampers by system identification. *Engineering Structures* 2010; **32**(11): 3670–3682. DOI: 10.1016/J.ENGSTRUCT.2010.08.011.
16. Bekdaş G, Nigdeli SM. Mass ratio factor for optimum tuned mass damper strategies. *International Journal of Mechanical Sciences* 2013; **71**: 68–84. DOI: 10.1016/J.IJMECSCI.2013.03.014.