

A COMPREHENSIVE EVALUATION OF TUNED VERTICAL ISOLATION SYSTEM FOR SEISMIC RISK MITIGATION

S. Babaei ^a, F. Karimi Ghaleh Jough ^{a,*}

^a Faculty of Engineering, Department of Civil Engineering, Final International University, Via Mersin 10, AS 128, Kyrenia, North Cyprus, Turkey; E-mails: sasan.babaei@final.edu.tr, *fooad.karimi@final.edu.tr

Received: 05.02.2024 / Accepted: 22.02.2024 / Revised: 02.04.2024 / Available online: 31.05.2024

DOI: [10.2478/jaes-2024-0004](https://doi.org/10.2478/jaes-2024-0004)

KEY WORDS: vertical isolation, tuned mass damper, response spectrum analysis, time history analysis, structural control.

ABSTRACT:

Vertical isolation by dividing the building into two soft and stiff sub-systems benefits from the period shifts and the damping mechanism across the height. However, the displacement demand imposed on the soft sub-system is less applicable in congested urban areas. As a result, in this study, a hybrid system of vertical isolation system benefiting from a tuned soft subsystem divided into upper and lower portions is investigated. A parametric linear 3-Degree of Freedom (DoF) model of the system incorporating mass and frequency ratio of the sub-systems was introduced and analyzed by response spectrum in MATLAB. A closed-form solution for the system frequency and mode shapes was also established. Response spectrum analysis indicates increasing the Tuned Mass Damper (TMD)'s fundamental period to 2.5 times the soft sub-system's, reduces its displacement to more than 40 percent. The Multi Degree of Freedom (MDoF) model of the system is parametrically generated in MATLAB. Time history analysis of the building subjected to 40 records with 2 and 10 percent probabilities of exceedance in 50 years compared with conventional vertical isolation reveals the lower soft sub-system displacement can be reduced up to 45 percent by shifting drift to upper stories. The innovative tuned vertical isolation by demonstrating superior control performance as comprises lower floors' drift may be an applicable solution for adjacent high- and low-rise buildings.

1. INTRODUCTION

Urbanization rate growth demands higher pressure to build in already densely populated areas. It is expected by 2050, 66 percent of the world's population live in cities where some are prone to natural hazards (United Nations Department of Economic and Social Affairs, 2014). Yet in the first half of 2023, \$110 billion worldwide estimated losses from natural catastrophes were mostly due to earthquakes in Turkey and Syria (World Bank, 2023). Such lower-income countries are less resilient and are at an intensifying risk (Bündnis Entwicklung Hilft, 2023). To this end, seismic-resistant methods should satisfy the construction budget and be applicable to prevailing techniques in the region.

Vibration isolation is one of these seismic resistant techniques which by shifting the predominant period of the building evade the dominant frequency content of the projected seismic hazard at the region. Lower-cost passive isolations requiring no control systems can be conventional base or recent vertical isolations. Base isolations are less effective in high-rise buildings due to the accumulation of high gravitational load at the isolation layer and the isolator movement under strong wind excitations and the uplift in the isolation bearings. To avoid pounding economically infeasible gaps should be designed in the vicinity of buildings located in densely urban areas (C. S. Tsai, 2006).

To offset this hindrance damping mechanism at the isolation layer was initially introduced which is less effective in strong motions due to the activation of higher modes. Hybrid controls such as tuned dampers added to the lateral load-resisting already isolated system were also investigated and found more effective in reducing the gap displacement. These two strategies simply utilize additional components to directly manipulate the dynamic characteristics of the system. Design manipulation was the second approach in implementing the isolation in the system (Babaei Sasan et al., 2020; Jough & Şensoy, 2016; Wang et al., 2022).

Pakpour et al proposed a low-cost seismic isolation platform containing simple flat sliding isolation bearings for mass implementation. This method requires no significant change to current construction practices and isolates several commonly designed buildings in one base (Pakpour, 2019). Such an approach can be affordable in densely low-rise built environments like central Asia. Mid and multi-story isolations were also an alternative design transformation to shift the isolation displacement to upper stories. As a result, mid-story isolated high-rise buildings can safely be built across the low-rise buildings (Skandalos et al., 2020).

Becker and Ezazi's study revealed that double-layer isolation by increasing upper-story displacement by 19% can reduce the

* Corresponding author: Foad Karimi Ghaleh Jough, Associate professor, Faculty of Engineering, Department of Civil Engineering, Final International University, Via Mersin 10, AS 128, Kyrenia, North Cyprus, Turkey. Email: fooad.karimi@final.edu.tr

relative displacement of the first story by 48% (Becker & Ezazi, 2016. Kim and Kang at a mid-story isolated tall building controlled by MR damper used multi-objective optimization to decrease the inter-story drifts (Kim & Kang, 2019). In the realm of seismic behavior and risk assessment, providing second layer of control to the system also leads to a significant stride in addressing uncertainties inherent in seismic events (Karimi Ghaleh Jough & Ghasemzadeh, 2023). The dynamic and unpredictable nature of seismic behavior necessitates a nuanced understanding of uncertainties, a focal point explored in many researches (Babaei & Zarfam, 2019; Karimi Ghaleh Jough & Beheshti Aval, 2018; Karimi Ghaleh Jough & Şensoy, 2020; Karimi Ghaleh Jough et al., 2021; Dithurson et al. 2023).

To reduce the design complexity at the base, vertical isolation was introduced. In this technique structure within the height divides into stiff with less mass and soft with most of the system mass to benefit from the period shift effect (Ziyaeifar et al., 2012). This method is more applicable than conventional base isolations as the isolation layer is not subjected to high gravitational load, and the damping mechanism may be distributed across the height. Nonetheless, soft subsystem displacement similar to traditional base isolation leads to overall higher drift in the system (Milanchian et al., 2019). To address this issue, this study introduces the Tuned Vertical Isolation (TVI) system in which the soft subsystem is horizontally isolated in the middle. The lower soft subsystem is vertically joined to the stiff subsystem with viscous dampers. The upper portion of the soft subsystem above the horizontal isolation can benefit from the TMD's behavior in lateral response reduction. The 3DoF analytical model of the system was generated and analyzed with the response spectrum analysis. The MDoF model of the system was then introduced and regarding its subcomponents frequency and mass ratio was parametrically subjected to two series of 20 records with 10 and 2 percent probability of exceedance in 50 years. The flowchart of the proposed design method is delineated in Figure 1.

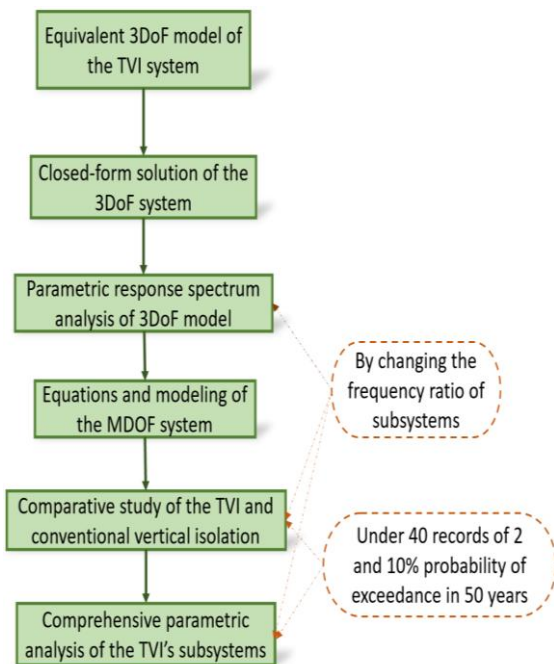


Figure 1. The flowchart of the proposed design method

The results indicate TVI can reduce the lower portion displacement to half in comparison to traditional vertical isolation. Such a reduction in the lower stories can lead to an increase in displacement in the upper portions. This, in the case of two adjacent high and low-rise buildings poses no implementation barrier.

2. EQUATION OF MOTION FOR TUNED VERTICAL ISOLATION SYSTEM

The 3 DoF model of the investigated system is shown in Figure 2. a and consists of soft, stiff, and TMD as its subcomponents. Schematic representation at b portrays spring and damping mechanism orientations in the system. In this figure, m_1 , m_2 , and m_3 represent the stiff, soft substructures and TMD's mass.

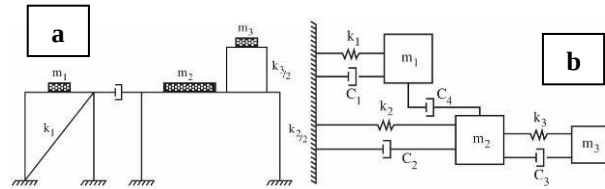


Figure 2. Simplified tuned vertical isolation model
(a. 3DOF model, b. schematic representation)

As a result, based on Naeim-Kelly classic linear isolation theory the equation of the motion, (Farzad Naeim, 1999) by taking relative displacement into consideration can be written as follows:

$$m_1 \ddot{u}_1 + c_1 \dot{u}_1 + c_4 (\dot{u}_1 - \dot{u}_2) + k_1 u_1 = -m \ddot{g} \quad (1)$$

$$m_2 \ddot{u}_2 + c_2 \dot{u}_2 + c_4 (\dot{u}_2 - \dot{u}_1) + c_3 (\dot{u}_2 - \dot{u}_3) + k_2 u_2 + k_3 (u_2 - u_3) = -m_2 \ddot{u}_g \quad (2)$$

$$m_3 \ddot{u}_3 + c_3 (\dot{u}_3 - \dot{u}_2) + k_3 (u_2 - u_3) = -m_3 \ddot{u}_g \quad (3)$$

By introducing $\alpha_1 = m_1/m_s$ and $\alpha_d = m_3/m_s$ as the mass ratios where m_s is the total gross mass of the system, the mass matrix of the system is:

$$m = \begin{bmatrix} \alpha & & \\ & 1 - \alpha & \\ & & \alpha_d \end{bmatrix} m_s \quad (4)$$

The stiffness matrix of the system can be written as:

$$k = m_s \omega_s^2 \begin{bmatrix} \alpha \varepsilon_s^2 & & \\ & (1 - \alpha) + \alpha_d \varepsilon_d^2 & -\alpha_d \varepsilon_d^2 \\ & -\alpha_d \varepsilon_d^2 & \alpha_d \varepsilon_d^2 \end{bmatrix} \quad (5)$$

where $\varepsilon_s = \omega_1/\omega_2$ and $\varepsilon_d = \omega_3/\omega_2$ are the frequency ratios of the stiff and TMD to the soft substructure respectively. In which ω_1 , ω_2 and ω_3 are, the stiff, soft substructure, and TMD's frequencies respectively. The damping matrix is:

$$C = 2m_s \omega_s \begin{bmatrix} \zeta_1 \alpha \varepsilon_s + \zeta_4 \gamma & -\zeta_4 \gamma & 0 \\ -\zeta_4 \gamma & \zeta_2 (1 - \alpha) + \zeta_4 \gamma + \zeta_3 \alpha_d \varepsilon_d & -\zeta_3 \alpha_d \varepsilon_d \\ 0 & -\zeta_3 \alpha_d \varepsilon_d & \zeta_3 \alpha_d \varepsilon_d \end{bmatrix} \quad (6)$$

where ζ_1 , ζ_2 , ζ_3 , and ζ_d are the damping ratios of the stiff, soft substructure, the vertical damping system connecting the soft and stiff substructures and the TMD. The γ becomes:

$$\gamma = \sqrt{\alpha \varepsilon_s^2 + (1 - \alpha)} \quad (7)$$

The i^{th} modal frequency considering the mass and stiffness matrix is:

$$\omega_i^2 = \left\{ \omega_1^2, 0.5\omega_d^2(p \pm \sqrt{p^2 - 4}) \right\} \quad (8)$$

where p is equal to:

$$p = 1 + \varepsilon_d^{-2} + \frac{\alpha_d}{1 - \alpha} \quad (9)$$

The mode shapes are:

$$\phi = \{[1 \ 0 \ 0], [0 \ 1 \ (1 - 0.5(p \pm \sqrt{p^2 - 4}))^{-1}]\} \quad (10)$$

3. RESPONSE SPECTRUM

In this study, a 3DOF model comprising stiff, lower soft, and upper soft subsystems is analyzed for downtown Seattle under the ASCE 07-2016 provisions.

The design spectrum for downtown Seattle for soil class D for a residential building in risk-group 2 (47.6 longitude and -122.34 latitude) is obtained. The soft sub-structure period was 2.5 s and the ratio of the substructures to the isolation period was changed to examine the response spectrum of the system over a wide range. The damping ratio of vertical isolation was 15% and the Rayleigh damping was 2% for the system. Mass ratios α_1 and α_b were 0.2 and 0.05, respectively.

As presented in Figure 3, an increase in the period ratio of stiff to soft subsystems, as the two systems reach the same period the soft-system experiences a great displacement due to resonance. The graph also portrays increasing the period ratio of the soft sub-system to TMD leads to an increase of subsystem which is expected.

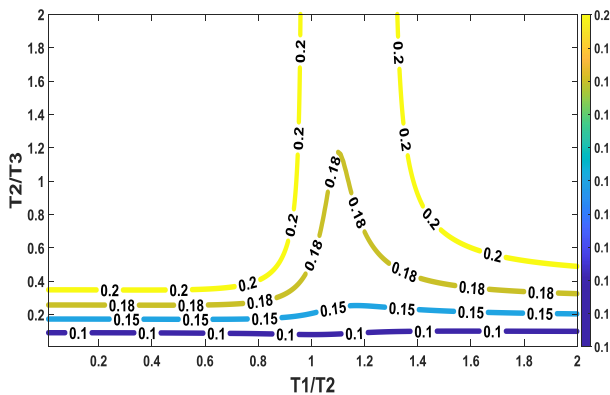


Figure 3. Variation of the soft substructure displacement in reference to the period ratio of the substructures

As the result for the TMD shows in Figure 4 the increase in the ratio of the stiff to soft subsystem decreases the displacement of the upper portion. Nonetheless, an increase in the TMD to soft substructure increases the TMD's displacement.

This behaviour is expected; since the higher period has considerable displacement due to the spectrum response of the region.

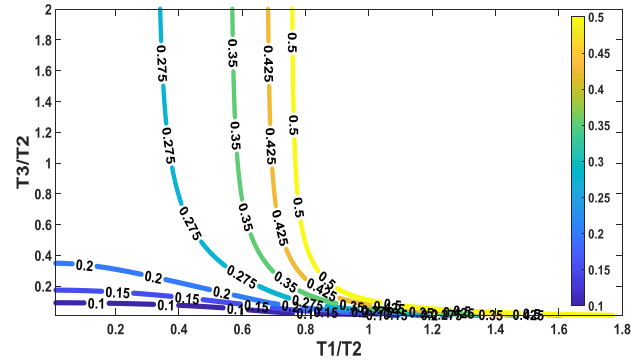


Figure 4. Variation of the TMD displacement in reference to the period ratio of the substructures

4. EQUATIONS AND MODELING OF MDOF SYSTEM

In this study, a tuned vertical isolation system is made up of stiff, lower, and upper soft subsystems and an isolation layer among soft structures. The MDOF system is presented in Figure 5. Linear- shear type model of the system comprises lumped mass at the centre and doesn't reflect the soil effect on the response. The seismic impact is considered unidirectional.

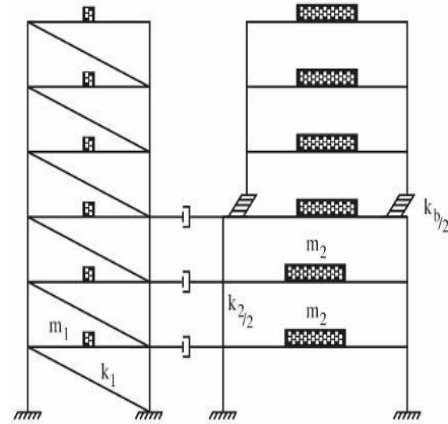


Figure 5. MDOF model of linear TVI

The mass, stiffness, and damping matrix of each substructure is constructed initially to form the dynamic matrix of the system. The mass of each floor including soft and stiff substructures remains constant along the height. α , α_b which are the mass ratio of the stiff, and isolation, were introduced to construct the mass matrix. The mass matrix can be obtained as:

$$M = m_s \begin{bmatrix} \alpha I_n & & \\ & (1 - \alpha) I_t & \\ & & \alpha_b \\ & & & (1 - \alpha) I_{n-t} \end{bmatrix} \quad (11)$$

Where I_b and I_{n-t} are the identity matrices. n , and t are the total story number, and number of isolated mass stories. The stiffness matrix of the system can be expressed as:

$$k = \begin{bmatrix} k_1 \times KI_n & & & \\ & k_2 \times KI_t & & \\ & & k_b & \\ & & & k_2 \times KI_{n-t} \end{bmatrix} + K_{1b2} \quad (12)$$

This matrix includes two matrices. The first is the diagonal stiffness matrix of the substructure and the second is the effect of the mid-isolation on the lower and upper soft substructure. In this equation, k_1 , and k_2 are the floor stiffness of the stiff, and soft sub-structures. k_1 and k_2 can be obtained by coding in MATLAB and are the results of the mass ratio, frequency ratio, and number of stories of these substructures. KI_t and KI_{n-t} are the stiffness matrix of t and $n-t$ -story frames with a stiffness equal to one. In symmetric matrix k_{1b2} , the $n+t$ row and column entry is equal to k_b , the $n+t+1$ row and $n+t$ column entry is equal to $-k_b$, the $n+t+1$ row and column entry is equal to k_2 and the $n+t+2$ row and $n+t+1$ column entry is equal to $-k_2$. The damping matrix of the system is expressed as:

$$C = \begin{bmatrix} C_1 & & & \\ & C_2(1:t, 1:t) & & \\ & & c_b & \\ & & & C_2(t+1:n, t+1:n) \end{bmatrix} \quad (13)$$

$+C_{1b2} + C_d$

where the C_1 , C_2 , and c_b are the damping matrix of the substructures obtained with 5% Rayleigh damping, and the damping of the isolation layer which is equal to 15%. In the symmetric matrix of C_{1b2} , the $n+t$ row and column entry is equal to c_b , the $n+t+1$ row and $n+t$ column entry is equal to $-c_b$, the $n+t+1$ row and column entry is equal to c_2 and the $n+t+2$ row and $n+t+1$ column entry is equal to $-c_2$. Where c_2 is the damping coefficient of the soft subsystems at each floor. The third matrix in this equation includes the effect of the viscous dampers connecting the floors at vertical isolation.

The viscous damping criteria introduced at the FEMA 356 is used to calculate the damping effect between two substructures (FEMA 356, 2000). The damping matrix of C_d can be calculated as:

$$C_d = \begin{bmatrix} C_{c1} & 0 & 0 \\ 0 & C_{ci} & 0 \\ 0 & 0 & C_{cn} \end{bmatrix} \quad (14)$$

Where C_{ci} is the damping coefficient between subsystems at floor level i , which is assumed to be equal at all floors, and is obtained by the following equation:

$$\beta = \frac{(\max\{T_{s1,1}, T_{s2,1}\}) \sum_j c_{cj} (\phi_{j,1} - \phi_{j,2})^2}{4\pi \sum_i m_i \phi_i^2} \quad (15)$$

Where $T_{s1,1}$, $T_{s2,1}$, $\phi_{j,1}$, and $\phi_{j,2}$ are the fundamental periods, and the first mode displacement at floor level j of soft and stiff subsystems respectively. m_i , and ϕ_i are the reactive mass, and the first mode displacement floor level i of the equivalent non-isolated system.

5. RESPONSE COMPRESSION OF DUAL ISOLATION WITH TRADITIONAL BASE ISOLATION

The seismic response of tuned vertical isolation is affected by the frequency ratios of its subsystems. Therefore, three individual models of the tuned vertical isolated system with lower to upper soft substructure period ratios of 0.1, 0.2, and 0.4, denoted as TVI0.1, TVI0.2, and TVI0.4, were parametrically introduced in MATLAB. Then a series of models for each of these three models and traditional vertical isolation were generated. These series were produced by incrementally altering the frequency ratio of the isolation layer to the structure in the range of 0.2 to 0.9. These 4 series of models were submitted to time history analysis of 40 records taken from the FEMA/SAC project. These records consist of two groups LA1-20 and LA21-40, corresponding to a hazard level of 2 and a 10% probability of exceedance in 50 years (Somerville 1997). Maximum average roof displacement of stiff lower soft and upper soft subsystems for series with tuned vertical isolation and roof displacement of stiff and soft substructure at traditional vertical isolation were calculated.

In this analysis, the fundamental period of the non-isolated building is equal to 0.9 s. Mass ratios α_1 and α_b in the structures was 0.4 and 0.02. The inherent and the isolation damping ratios were 0.05 and 0.15 respectively. The horizontal isolation at the soft substructure is placed in the middle. The average spectral displacement of the sub-systems for each model subjected to seismic records is presented in Figure 6, Figure 7, and Figure 8.

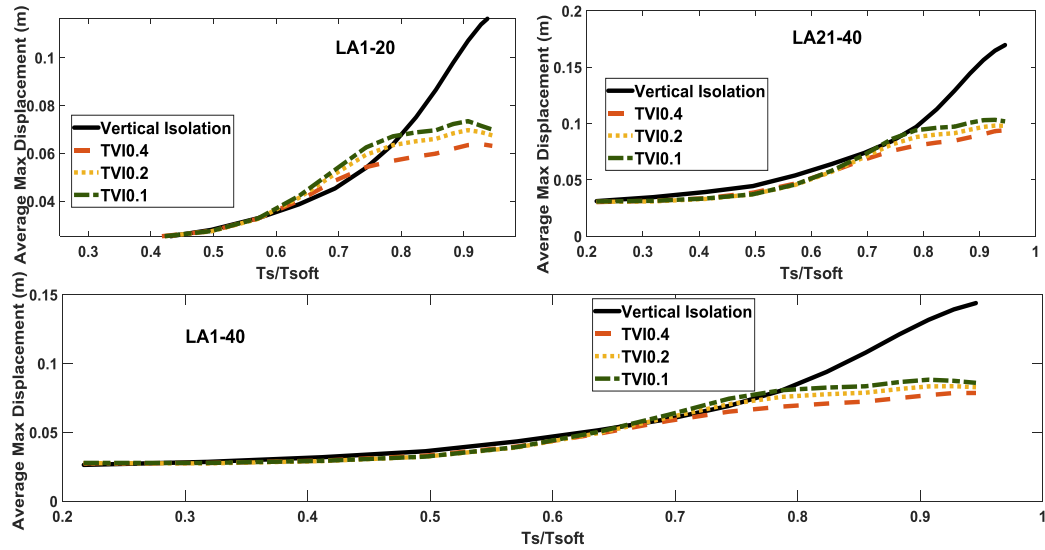


Figure 6. Maximum average displacement spectrum of the stiff substructure when subjected to series of ground motions (a) 20 records with 10% probabilities of exceedance in 50 years (b) 20 records with 2% probabilities of exceedance in 50 years (c) Average max displacement under 40 records

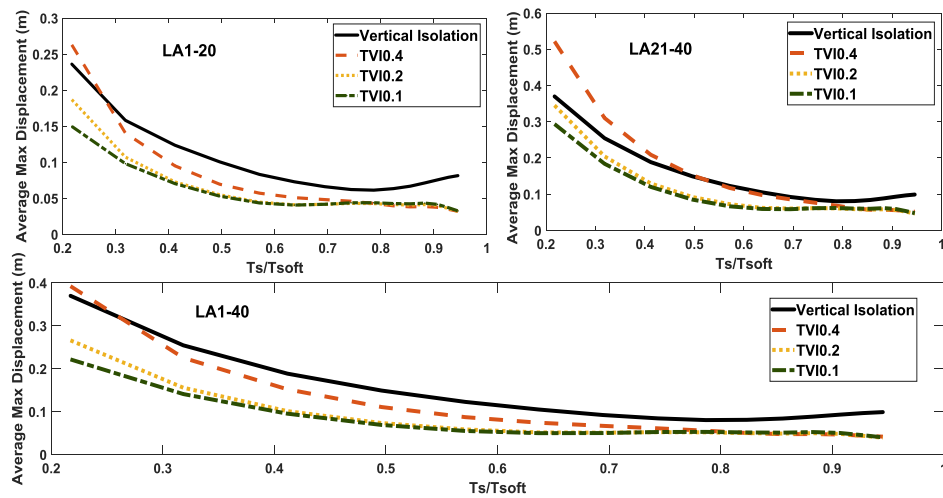


Figure 7. Maximum average displacement spectrum of the lower substructure when subjected to series of ground motions (a) 20 records with 10% probabilities of exceedance in 50 years (b) 20 records with 2% probabilities of exceedance in 50 years (c) Average max displacement under 40 records

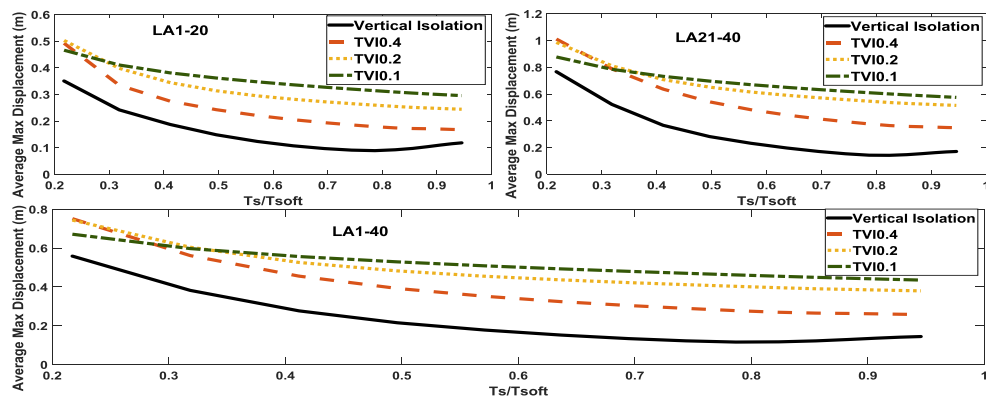


Figure 8. Maximum average displacement spectrum of the upper substructure when subjected to series of ground motions (a) 20 records with 10% probabilities of exceedance in 50 years (b) 20 records with 2% probabilities of exceedance in 50 years (c) Average max displacement under 40 records

Figure 6 delineates that the stiff substructure's displacement is less susceptible to the period ratio for a ratio of less than 0.6 for structure to soft. As expected, at this ratio the stiff substructure is much stiffer than the soft substructure. As this ratio reaches one the isolation effect becomes less active, therefore damping mechanism, would become more active in reducing the structure displacement. As a result, the TVI counterparts inherit better outcomes for the stiff substructure.

Figure 7 however shows in the period ratio of 0.1 of the lower to upper portion, the roof displacement of the lower portion is reduced to half. This reduction is more prominent for vertically isolated buildings of higher period ratio. The displacement demand reduction by increasing the period ratio to 0.2 is also as effective. On the other hand, as this period ratio reaches 0.4 the effect on the displacement reduction would decrease. This graph also implies the displacement reduction characteristics of this tuning are applicable at any vertically isolated building ratio of the structure to soft period.

Isolating the soft substructure decreases the displacement at the lower portion, However, this technique as Figure 8 shows leads to greater displacements at the upper portion of the substructure. This increase is less activated as the soft substructure inherits a lower period ratio of the structure to soft. On the contrary, as this ratio increases the displacement ratio of the roof of the upper TVI to vertical isolation becomes higher.

To portray a numerical comparison of the subsystem's response at three selected tuned vertical isolation systems to the traditional vertical isolation, at each graph average response of the selected subsystem divided to the traditional one at a period ratio of 0.3 to 0.6 of the structure to the subsystem is obtained and depicted in Table 1. It can be shown seismic response of the stiff sub-system at the TVI and vertical isolation is almost the same; however, TVI can reduce the response up to 10 percent in severe ground motions.

	TVI0.4	TVI0.2	TVI0.1
Records	Stiff-sub system		
LA1-20	1.00	1.04	1.07
LA 21-40	0.88	0.89	0.92
LA 1-40	0.92	0.95	0.97
Records	Lower soft-sub system		
LA1-20	0.72	0.61	0.60
LA 21-40	0.96	0.66	0.63
LA 1-40	0.84	0.63	0.62
Records	Upper soft-sub system		
LA1-20	1.84	2.52	2.98
LA 21-40	2.23	2.96	3.24
LA 1-40	2.09	2.80	3.14

Table 1. Average sub-system's displacement ratio to traditional vertical for each tuned vertical isolation system and each selected record in a period ratio of 0.3 to 0.7 of structure to the soft subsystem

Lower soft- subsystem shows prominent response reduction in TVI especially for TVI0.2 and TVI0.1 even to 45 percent on average. As previously discussed, this system has to endure a high drift demand at the upper soft sub-system, analysis shows for a moderate isolation approach this ratio can be limited to 2, and in a severe isolation this demand ratio reaches to 3.2.

The period ratio is the most critical parameter leading to subsystems displacement. Therefore, the period ratio of the subsystems changed simultaneously to obtain an average displacement response. The mesh result as the system is subjected to 40 records is depicted in Figure 9.

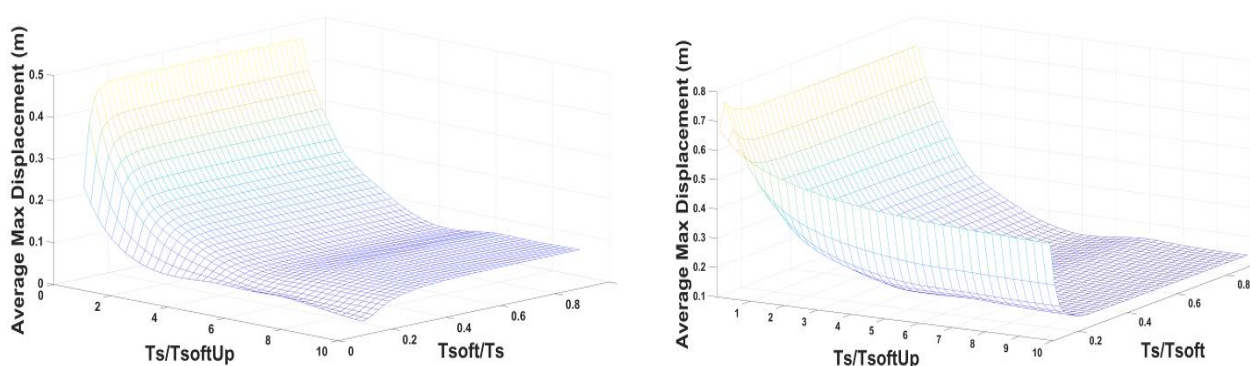


Figure 9. Maximum average displacement spectrum of the upper substructure when subjected to 40 ground motions (a) lower soft sub-structure (b) upper substructure

It portrays the lower and upper sub-system displacement. The lower and upper soft subsystem displacement is less susceptible to the soft system's period ratio to the stiff system. The lower and upper soft systems period ratio on the other hand affects dramatically the sub-system's response. The graph also reveals reducing the period ratio of the upper and lower subsystems to

half reduces the lower subsystem response severely however after that ratio the response reduction becomes almost negligible.

6. CONCLUSION

The conventional vertical isolation though effectively reduces the lateral displacement, leads to unacceptable drifts at the higher period soft subsystem. To address this drawback, especially at the lower stories of high-rise buildings in congested urban settings an innovative isolation technique was introduced and investigated.

Tuned vertical isolation by dividing the soft subsystem into two components with mid-story isolation reduced the lower story drift by shifting it to upper stories. Response spectrum analysis of a simplified 3DoF model and maximum average displacement spectrum obtained by time history analysis of a parametric MDoF model subjected to 40 ground motions reveals the TVI system benefits the vertical isolations merits and also can reduce the lower story displacements even to half in comparison to traditional vertical isolation. A detailed analysis comparing traditional and TVI shows response reduction for stiff sub-system is up to 10 percent, while the soft-subsystem response is reduced by 45 percent. Nonetheless, this reduction is more prominent as severe earthquakes are applied, almost 10 percent TVI system's response reduction increased as it experienced a series of earthquakes with a 2 percent probability of exceedance in comparison with 10 percent in 50 years.

The analysis also reveals higher soft sub-system might undergo a higher ratio of drift in a case 3 times in comparison to traditional vertical isolation, however for a high-rise building located near a low-rise one should not impose a design barrier.

References

- Babaei, S., & Zarfam, P (2019). Optimization of shape memory alloy braces for concentrically braced steel braced frames. *Open Engineering*, 9(1), 697-708. <https://doi.org/doi:10.1515/eng-2019-0084>
- Babaei Sasan, Zarfam Panam, & Abdolreza, S. M (2020). Probabilistic and Deterministic Semi-Active Control Strategies for Adjacent Buildings Connected by MR Dampers 17th World Conference on Earthquake Engineering,
- Becker, T. C., & Ezazi, A (2016). Enhanced performance through a dual isolation seismic protection system. *The Structural Design of Tall and Special Buildings*, 25(1), 72-89. <https://doi.org/10.1002/tal.1229>
- C. S. Tsai, W.-S. C., Bo-Jen Chen, Wen-Shen Pong (2006). Vertical distributions of lateral forces on base isolated structures considering higher mode effects. *Structural Engineering and Mechanics*. <https://doi.org/http://dx.doi.org/10.12989/sem.2006.23.5.543>
- Dithurson, T., C. Daniel, S. Vivekananda Sharma, G. Hemalatha, Shalini R. Nair, and A. Arun Solomon. "Experimental Investigation of High-Force-to-Volume Extrusion Damper Subjected to Cyclic and Time History Loading." *Journal of Applied Engineering Sciences* 13, no. 2 (2023): 183-88. <https://doi.org/doi:10.2478/jaes-2023-0023>. <https://doi.org/10.2478/jaes-2023-0023>.
- Farzad Naeim, J. M. K (1999). Design of Seismic Isolated Structures: From Theory to Practice.
- FEMA 356, A. S. o. C. E (2000). FEMA 356 Prestandard and Commentary for the Seismic Rehabilitation of Building. In Reston, Virginia, USA.
- Bündnis Entwicklung Hilft, Ruhr University Bochum – Institute for International Law of Peace and Armed Conflict (IFHV) (2023). WorldRiskReport 2023.
- Karimi Ghaleh Jough, F., & Beheshti Aval, S. B (2018). Uncertainty analysis through development of seismic fragility curve for an SMRF structure using an adaptive neuro-fuzzy inference system based on fuzzy C-means algorithm. *Scientia Iranica*, 25(6), 2938-2953. <https://doi.org/10.24200/sci.2017.4232>
- Karimi Ghaleh Jough, F., & Ghasemzadeh, B (2023). Uncertainty Interval Analysis of Steel Moment Frame by Development of 3D-Fragility Curves Towards Optimized Fuzzy Method. *Arabian Journal for Science and Engineering*. <https://doi.org/10.1007/s13369-023-08223-8>
- Karimi Ghaleh Jough, F., & Şensoy, S (2016). Prediction of seismic collapse risk of steel moment frame mid-rise structures by meta-heuristic algorithms. *Earthquake Engineering and Engineering Vibration*, 15(4), 743-757. <https://doi.org/10.1007/s11803-016-0362-9>
- Karimi Ghaleh Jough, F., & Şensoy, S (2020). Steel Moment-Resisting Frame Reliability via the Interval Analysis by FCM-PSO Approach considering Various Uncertainties. *Journal of Earthquake Engineering*, 24(1), 109-128. <https://doi.org/10.1080/13632469.2017.1401564>
- Karimi Ghaleh Jough, F., Veghar, M., & Beheshti-Aval, S. B (2021). Epistemic uncertainty treatment using group method of data handling algorithm in seismic collapse fragility. *Latin American Journal of Solids and Structures*, 18.
- Kim, H.-S., & Kang, J.-W (2019). Optimal Design of Smart Mid-Story Isolated Control System for a High-Rise Building. *International Journal of Steel Structures*, 19(6), 1988-1995. <https://doi.org/10.1007/s13296-019-00258-8>
- Milanchian, R. and Hosseini, M (2019), "Study of vertical seismic isolation technique with nonlinear viscous dampers for lateral response reduction", *J. Build. Eng.*, 23, 144-154. <https://doi.org/10.1016/j.jobee.2019.01.026>.
- P. G. Somerville, N. Smith, S. Punyarnurthula, and J. Sun, Development of Ground Motion Time Histories for Phase 2 of the FEMA/SAC Steel Project, SACBD-97/04, Sacramento, CA1997.
- Pakpour, F. A., Beigi, Hossein; Christopoulos, Constantin (2019). Development of low-cost Seismic Isolation Platform (SIP) for mass implementation in developing countries 12th Canadian Conference on Earthquake Engineering,
- Skandalos, K., Afshari, H., Hare, W., & Tesfamariam, S (2020). Multi-objective optimization of inter-story isolated buildings using metaheuristic and derivative-free algorithms. *Soil*

Dynamics and Earthquake Engineering, 132, 106058.
<https://doi.org/https://doi.org/10.1016/j.soildyn.2020.106058>

United Nations Department of Economic and Social Affairs
(2014). World Urbanization Prospects.

Wang, L., Nagarajaiah, S., Shi, W., & Zhou, Y (2022). Seismic performance improvement of base-isolated structures using a semi-active tuned mass damper. Engineering Structures, 271, 114963.
<https://doi.org/https://doi.org/10.1016/j.engstruct.2022.114963>

World Bank (2023). Global Rapid Post-Disaster Damage Estimation (GRADE) Report- Mw 7.8 Türkiye-Syria Earthquake – Assessment of the Impact on Syria.

Ziyaeifar, M., Gidfar, S., & Nekooei, M (2012). A model for Mass Isolation study in seismic design of structures. Structural Control and Health Monitoring, 19(6), 627-645.
<https://doi.org/10.1002/stc.459>