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NONLINEAR SEISMIC ANALYSIS: VISCOUS DAMPERS VS CONVENTIONAL DUAL SYSTEMS IN DATA CENTER

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Abstract

The seismic resistance of data center is crucial due to its contribution to the ability to maintain business continuity when faced with a high seismic force. In this subject, the current paper aims at performing a comparative analysis of the structural behavior of conventional dual system and modified system equipped with fluid viscous dampers to reveal different approaches towards the development of seismic resistant design. Nonlinear time history analysis was applied using 11 sets of ground motion records for different earthquakes. Three damper schemes were compared to the conventional dual system design, the performance indicators of which were evaluated as base shear, story drift, and structural mass. The obtained results have shown that the use of fluid viscous dampers affects the dynamic behavior of structures resulting in up to 60% decrease in base shear values while improving the control of deformations, decreasing the values of average story drift in X by 5% and in Y direction by 39%. Moreover, the damp models showed a reduction in the values of structural mass of approximately 18.8%.

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Introduction

Data centers infrastructure stands as critical infrastructure which supports essential digital services, which require performances objectives extending beyond life safety to include immediate post-earthquake functionality and operational continuity, unlike conventional building criteria. Studies and guidelines indicate that excessive inter – story drift may result in malfunction or failure of server racks and cable trays and cooling systems and interruptible power supply units, which support operation (Shang et al., 2022). The process of ensuring control of structural response, including lateral displacement and vibration mitigation, constitutes a required seismic design of data center buildings

The divergence in seismic resilience requirements stands as the primarily distinction which arises between the international standard TIA – 942 – B and the Indonesian national standard SNI 8799 -1:2023, which incorporates the provisions of SNI 1726:2019 (Badan Standardisasi Nasional, 2023; Telecommunications Industry Association, 2017). The foundation of the Indonesian code framework constitutes a life safety and collapse prevention philosophy, which governs structural designs to preclude failure under strong ground motions while encompassing limited emphasis on post-earthquake functionality. The consequence of this philosophical orientation lies in the absence of an explicit requirement for supplemental energy dissipation systems, providing that the structural system satisfied the prescribed seismic resistance criteria. In direct contrast, the performance-oriented paradigm adopted by TIA – 942 – B established operational continuity and immediate occupancy and functional resilience as primary objectives, particularly for tier III and tier IV data center. The parameter of these objective mandates the implementation of supplemental damping system for tier III and Tier IV facilities and the designation of minimum Seismic Design Category D (Telecommunications Industry Association, 2017). The accumulation of these procedural and philosophical distinctions signal that two standards vary not merely in their technical prescriptions which shape design parameters, but in their foundational performance objectives which informs resilience strategies, with SNI privileging life safety and collapse prevention, while TIA – 942 – B indicates functional resilience and service continuity. The process of direct comparison between these difference approaches stands as essential for the evaluation of their effectiveness in the seismic design of data center (Su, Li, Chen, & Dai, 2018).

Previous studies have shown that supplemental damping systems significantly improve seismic performance by reducing structural damage and controlling lateral displacement.(Bao et al., 2025; Kaur, Matsagar, & Nagpal, 2012; Tedha, Rommel, & Kumalasari, 2025; Wasey, Masihuddin Siddiqui, & Azeem, 2022). In addition, the incorporation of dampers in conventional buildings can effectively control inter-story drift demands under seismic loading (Bagheri, Barghian, Saieri, & Farzinfar, 2015; Lan et al., 2024; Nguyen-Thai, Ly, Nguyen, & Nguyen-Thoi, 2024). Experimental and analytical studies have shown that damping systems can reduce lateral displacements induced by earthquakes by approximately 25–40% (Bagheri et al., 2015; Bashir Pour, 2022; Kimeze & Kyakula, 2023). In critical facilities, the use of passive energy dissipation has been shown to significantly enhance operational continuity by reducing structural response and limiting damage to non-structural components and sensitive equipment (Bagheri et al., 2015; Ding, Song, Zhai, & Wen, 2025; Lan et al., 2024). Previous studies indicate that the effectiveness of damping systems is strongly governed by the type and quantity of dampers (Nguyen-Thai et al., 2024; Singh & Kumar Tiwary, 2022; Soong & Jr, 2002). In contrast, for a given damper type and number, variations in their placement generally produce comparable global structural response (Abdel Raheem, Ahmed, Ahmed, & Abdel-shafy, 2018; Faruk, Singh, & Mondal, 2023; Sharma, Parmar, Gautam, Choudhary, & Gohil, 2023). In high-tier data center facilities, conventional structural systems are generally insufficient to achieve the required levels of seismic performance, as they are not capable of meeting the stringent demands for operational continuity and system resilience under strong ground motions (Cimellaro, Noori, Kammouh, Terzic, & Mahin, 2022; Erkus, Polat, & Darama, 2018)

Despite these advancements, no prior study has directly compared the seismic design implications of adopting different seismic design philosophies under SNI 8799-1:2023 and TIA-942-B for data center buildings. In addition, the influence of damper configuration on the seismic performance of data center structures has not been systematically evaluated, especially under Indonesian seismic conditions. Moreover, studies employing nonlinear time history analysis (NLTHA) using hazard-consistent BSE-2N ground motions for data center applications are still limited.

While this study is grounded in Indonesian seismic provisions and site conditions, the findings carry broader international relevance. Data center is globally distributed critical infrastructure, and the problem of the life safety requirements of building codes against the requirement of TIA – 942 – B not only specific in Indonesia. Countries with similar seismic behavior within Southeast Asia are facing similar problems. Moreover, the behavior of fluid viscous dampers under nonlinear seismic force and its influence are universally applicable findings. The methodology and conclusion presented herein, particularly regarding the nonlinear behavior of fluid viscous damper under seismic excitation and their effectiveness, are transferable to any area where supplemental damping system, such as fluid viscous dampers, are considered critical infrastructure under high seismic hazard.

Research Methods

Building description and structural system

The building being observed is tier IV reinforced concrete structure data center, 12 floors high, located in Depok, West Java, Indonesia. According to SNI 1726:2019, the site is subjected to high seismic risk. This condition requires the highest level of fault tolerance and redundancy to function continuously even during earthquakes. As a critical infrastructure building, maintaining structural performance during seismic conditions is a main consideration for design. The building has a floor plan of 40 m × 24 m and a total structural height of 52 m. The symmetric plan geometry ensures a balanced distribution of mass and lateral stiffness in both principal directions. The typical floor plan is shown in Figure. 1.



Figure 1. Floor Plan of The Data Center Building Showing the Moment Frame Layout and Shear Wall Locations

The three-dimensional structural configurations of the building, including the moment resisting frame system, shear wall locations, and floor-to-floor arrangements, is shown in Figure 2.

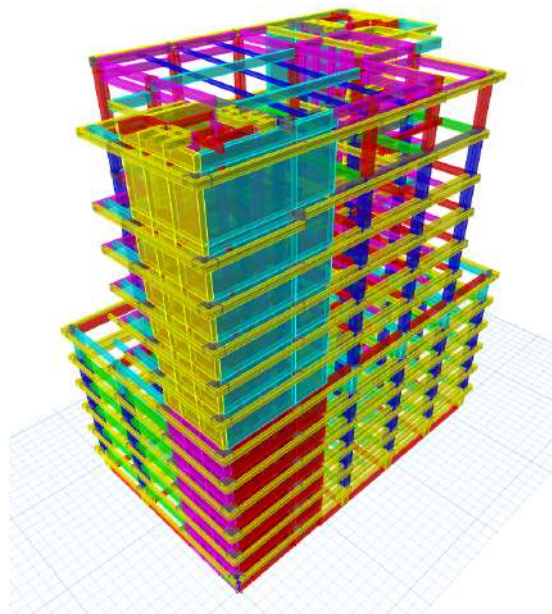


Figure 2. Three-dimensional view of the data center building structural model

Each floor serves a distinct functional purpose, as summarized in Table 1. The ground floor (Floor 1) functions as a plaza with a 4 m story height. Floors 2–6 house the primary data center operations (4 m each), Floor 7 serves as a mechanical transition podium (4.5 m), Floors 8–11 are designated as classrooms (4 m each), Floor 12 is an auditorium (6 m), and Floor 13 accommodates building utilities and MEP equipment. The prescribed loading criteria for area other than data center were determined in accordance with the applicable building loading standards and occupancy based design (American Society of Civil Engineers, 2022; Badan Standardisasi Nasional, 2020).

Table 1. Floor Functions and Floor-to-Floor Heights

Floor	Function / Usage	Floor-to-Floor Height (m)	Description
1	Plaza	4	Main Reception and Circulation Area
2 – 6	Data Center	4	Primary Server Rooms
7	Podium	4.5	Outdoor Area
8 - 11	Classrooms	4	Teaching And Training Facilities
12	Auditorium	6	Large-Capacity Assembly and Hall
13	Utilities	-	Equipment Area

The lateral load resisting system stands as a dual scheme which integrates Special Moment Resisting Frames (SMRF) and reinforced concrete shear walls, providing ductility and stiffness for drift control. Symmetrical shear wall placement in orthogonal directions and primary member dimensions in Table 2 constitute design specifications.

Table 2. Primary Structural Dimension for Dual System

Area	Beam (mm)		Column (mm)	Shear Wall (mm)		
	X	Y		X ₁	X ₂	Y
1	550 × 850	450 × 800	1000 × 1000	650	500	700
2 - 6	550 × 850	450 × 800	950 × 950	650	500	700
7	500 × 800	400 × 700	850 × 850	450	300	400

Area	Beam (mm)		Column (mm)	Shear Wall (mm)		
	X	Y		X ₁	X ₂	Y
8 - 11	450 × 750	350 × 750	800 × 800	450	300	400
12	400 × 800	400 × 750	750 × 750	450	300	400

The structural concrete used in this study has compressive strength of 30 MPa, an elastic modulus of $4700\sqrt{f_c}$ MPa. The reinforcing steel column is BJTS 420B, with yield strength of 420 MPa, a tensile strength of 525 MPa, and elastic modulus 200,000 MPa.

Fluid Viscous Damper Modelling and Configuration

Viscous dampers are modelled as nonlinear link elements in using the *Damper Exponential* property type facility in ETABS (Kaur et al., 2012). Damper are installed as diagonal bracing to participate lateral force subjected to the structure during earthquake (Liu, Wu, & Donà, 2018; Wang, 2017). For this work, an exponent value of α equal to 0.2. Lower sub-linear exponent is used since it greatly reduces damper force when velocities reach high condition during earthquake excitation but still manages the effectiveness of energy dissipation when amplitudes are considered small (Walsh, Marin-Artieda, & McElroy, 2024). The main purpose is to protect valuable equipment installed inside the building. The complete damper specifications are provided in Table 3.

Table 3. Damper Specification

Parameter	Direction	
	X	Y
Velocity Exponent (α)	0.2	0.2
Numbers of Damper	24	24
Effective stiffness, K_{eff}	262589.4 kN/m	233043.5 kN/m
Linear damping	10063.83 kN.s/m	8931.478329 kN.s/m
Non-Linear damping	1822.125 kN.s/m	1617.103949 kN.s/m

Choice of location of the dampers in each of configurations is mainly limited by architectural and operational considerations. In actual conditions, placement of dampers is only permitted in those-structural bays where there are no critical equipment paths or operational areas. It clarifies the rationale behind the three configurations variant for the analysis; these conditions represent a progression from an ideal, symmetric damper configuration to progressively more asymmetric configuration, as dictated by architectural constraints that limit the available space for damper installation in real building condition, shown in Figures 3, 4, and 5.



Figure 3. Configuration 1: Damper Location
Floor Plan

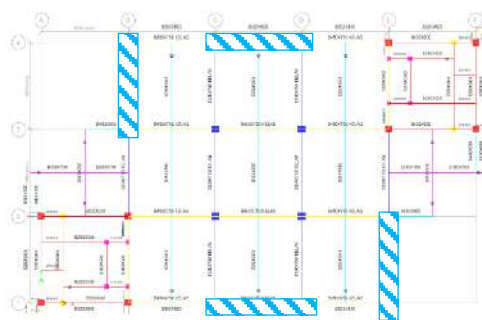


Figure 4. Configuration 2: Damper Location Floor Plan



Figure 5. Configuration 3: Damper Location Floor Plan

The earthquake resistance system consists of moment frames. The structural performance is achieved by the formation of plastic hinges at predetermined beam and column regions in accordance with design philosophy requirements (Choi, Kim, Lee, Hong, & Park, 2013; Tian & Dong, 2020). The concentrated hinge approach was conducted to present nonlinear behavior efficiently within the model, allowing the deformation and energy dissipation capacity of the structural members to be captured with reasonable computational efficiency (PEER/ATC-72-1, 2010; Powell, 2010)

Ground Motion Selection and Scaling

Eleven pairs of ground motion records were selected in accordance with the *Indonesian Seismic Hazard Deaggregation Map for Earthquake-Resistant Infrastructure Planning and Evaluation* (2024). With 11 pairs (≥ 7), Indonesian seismic provisions permit the use of the mean structural response across all records as the design demand, yielding a statistically stable seismic demand estimate. Records represent the three dominant source mechanisms at the Depok, West Java site: shallow crustal, deep subduction (Benioff), and shallow subduction (Megathrust). The selected records are listed in Table 4.

Table 4. 11 Ground Motions Data

Type	Name	Years	Magnitude
Shallow Thrust	Northern California	1954	6.50
	Friuli Italy	1976	6.50
	Coalinga California	1983	6.36
	L'Aquila Italy	2009	6.30
Benioff	Iwate Japan (Hachinohe)	2011	7.40

	Tokachi Oki Japan (Toyokoro)	2003	7.37
	Tokachi Oki Japan (Chokubetsu)	2003	7.37
	Tokachi Oki Japan (Urahoro)	2003	7.37
	Chile South America (PEL)	2010	8.81
Megathrust	Chile South America (SNJM)	2010	8.81
	Chile South America (OLMU)	2010	8.81

The target spectrum is the BSE-2N (Basic Safety Earthquake 2 — New) hazard level, corresponding to a 2% probability of exceedance in 50 years (return period of 2,500 years), in accordance with FEMA P-58 and ASCE 41. This upper-bound hazard level is appropriate for a critical data center facility and was derived from the *Indonesian Seismic Hazard Deaggregation Map (2024)* for the building site. Ground motion records were then matched to the BSE-2N target spectrum using the spectral matching feature in ETABS. The BSE-2N target spectrum is presented in Figure 6.

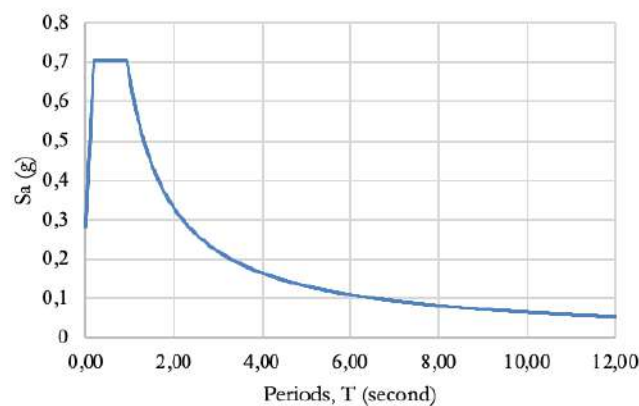


Figure 6. Targeted response spectra: BSE-2N

Figure 7 presents the scaled response spectra of eleven ground motion pairs relative to the BSE-2N target spectrum. Each record was scaled within the period range of interest to ensure the mean spectrum of the record set does not fall below the target spectrum, and scaled ground motions adequately represent the design-level seismic demand of subsequent nonlinear response history analysis.

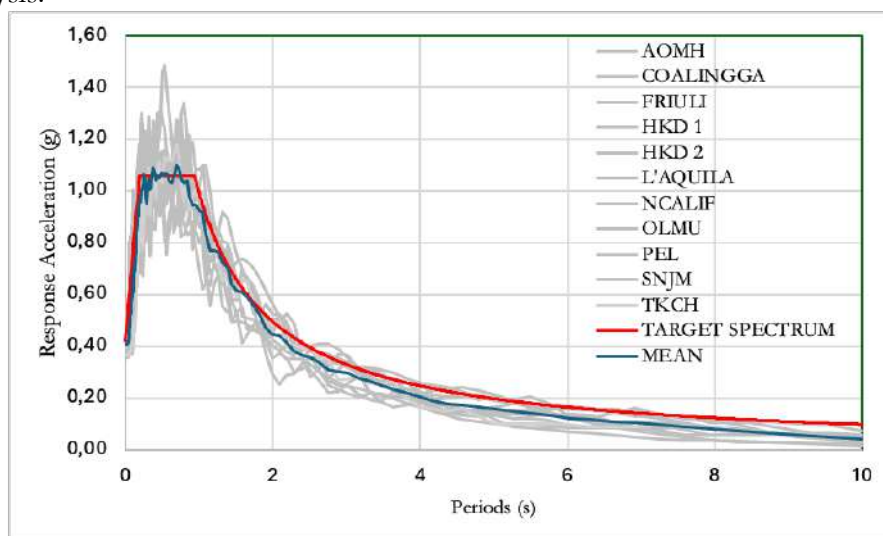


Figure 7. Matched Ground Motions

Research Results and Discussion

Dynamic Characteristics and Modal Properties

The seismic behavior of the dual system building was analyzed to determine period, mode shape, and mass participation ratios along two directions. Table 5 shows the modal participation mass ratio along in X and Y axis for the dual system building.

Table 5. Modal Properties of the Dual System Structure

Mode	Period sec	UX	UY	RZ	Σ UX	Σ UY	Σ RZ
1	1.653	0.0437	0.4998	9.83E-07	0.0437	0.4998	9.83E-07
2	1.056	0.5034	0.0448	0.0001	0.5471	0.5447	0.0001
3	0.817	0.0001	0.0001	0.56	0.5472	0.5447	0.5601
4	0.552	0.0082	0.2488	0.0004	0.5553	0.7935	0.5605
5	0.358	0.2698	0.0102	1.76E-05	0.8251	0.8037	0.5605
6	0.326	3.37E-05	0.0441	0.0248	0.8252	0.8478	0.5853
7	0.287	0.0002	0.0145	0.1817	0.8253	0.8624	0.7671
8	0.249	0.0007	0.0282	0.0575	0.826	0.8906	0.8245
9	0.225	0.0003	0.0229	0.0214	0.8263	0.9135	0.8459
10	0.203	0.0059	0.0042	0.0071	0.8321	0.9177	0.8531

The addition of fluid viscous dampers has been observed to have an impact regarding the dynamics behavior, displayed by change of the periods and modal mass distribution in the system (Mansoori & Moghadam, 2009). This enhanced the ability of the structure to dissipate energy will be directly related to its response under earthquake loadings, this can be clearly demonstrated from the effects of the dampers on the system in table 6.

Table 6. Structural Response Comparison

Parameter	Dual System	Damper
T - X Direction (s)	1.056	2.657
T - Y Direction (s)	1.653	3.144
Mass Participation X — Mode 1	54.71%	29.04%
Mass Participation Y — Mode 1	49.98%	65.22%

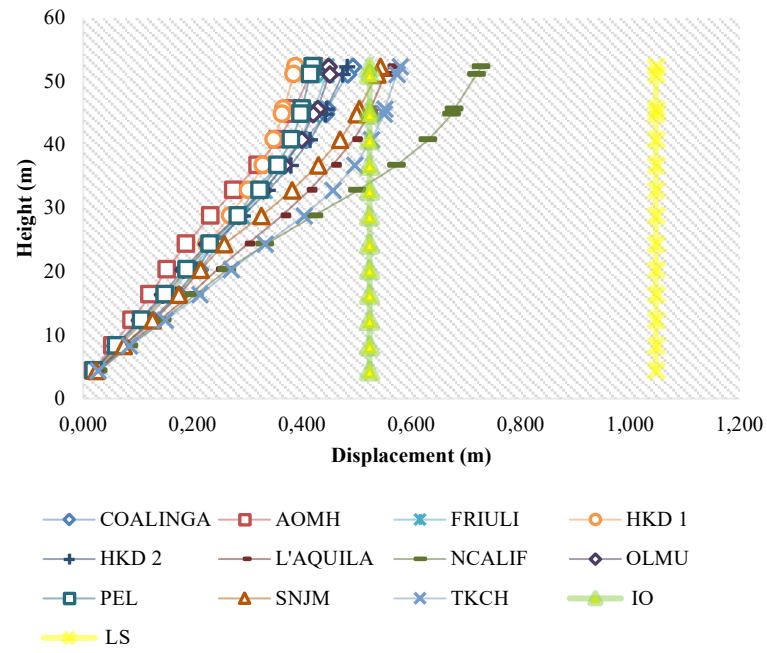
However, it should be noted that the period shift resulting from the damping effect is insignificant, considering the structure type, which is moment resisting frame. In such frames, lateral load is resisted through the stiffness of the flexural element. Hence, the application of fluid viscous dampers results in better energy dissipation than conventional systems. Furthermore, the effects of fluid viscous damper are shown by the reduction of base shear averaging approximately 60% relative to standard system, shown in table 7. The base shear values obtained from the viscous damper system within 3 configurations were relatively similar, which is consistent with the previous finding that shear wall greatly increase the building stiffness parameter (Alam, Banerjee, Mahadeven, Gupta, & Parashar, 2024; Cheng, He, Xu, & Yang, 2025; Ozkul, Kurtbeyoglu, Borekci, Zengin, & Kocak, 2019; Pizarro, Massone, & Rojas, 2023).

Table 7. Base Shear Comparison

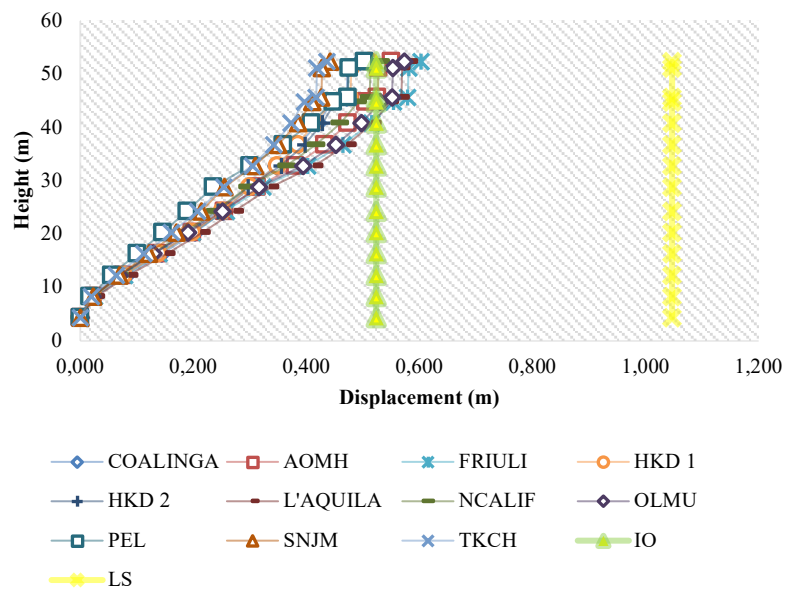
Time History	Shear Force (kN)		Percentage Reduction
	Dual System	Viscous Damper	
OLMU	75609.3751	27453.9379	64%
AOMH	90826.0291	26618.9039	71%
TKCH	82387.9794	23437.20603	72%
HKD 1	93313.6044	29689.52947	68%
HKD 2	84366.7125	24463.77157	71%
PEL	95000.9989	21955.60067	77%
SNJM	102119.982	27456.2615	73%
NCALIF	94218.5698	24907.7583	74%
FRIULI	81202.702	27287.9562	66%
COALINGA	103340.2727	30343.1511	71%
L'AQUILA	81203.3677	32585.54037	60%

Story Displacement Analysis

The story displacement presents as one of the most demanding criteria for evaluate the seismic behavior of building structure (Haque, Ashravi, & Hasan, 2025; Yuan, Tuken, & Sezen, 2019). This criterion assigns the lateral displacement of each level in relation to the base level due to seismic excitation, high values of story displacement could point to low levels of lateral support in buildings, which might result in their failure. Hence, it becomes essential to examine the story displacement response to ensure the proper stability and usability of buildings during earthquake. The story displacement data are presented in the figure 8, 9, 10, and 11 below, based on the IO criterion at 1% an LS criterion of 2% of total story displacement (Applied Technology Council, 1996; Badan Standardisasi Nasional (BSN), 2019; Federal Emergency Management Agency, 2000).

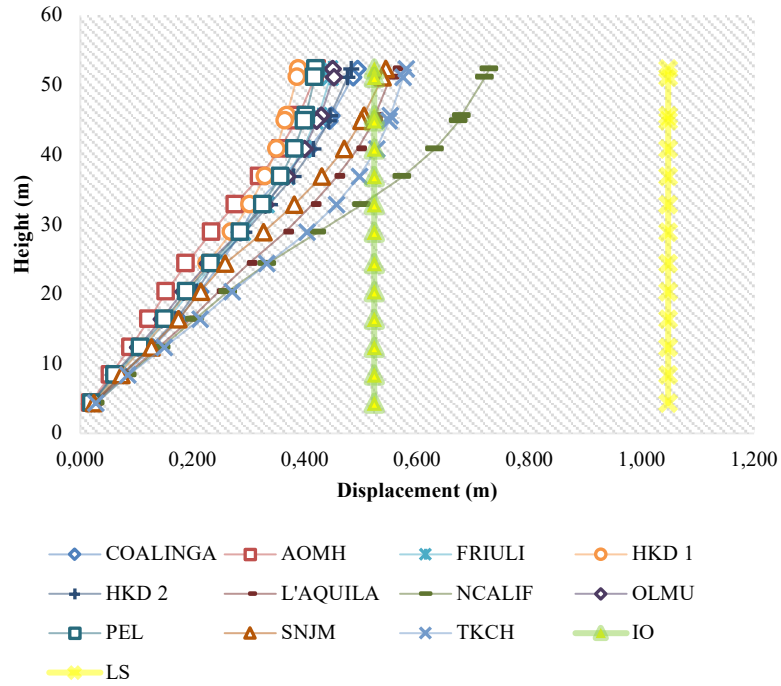


a) Story Displacement X-Direction

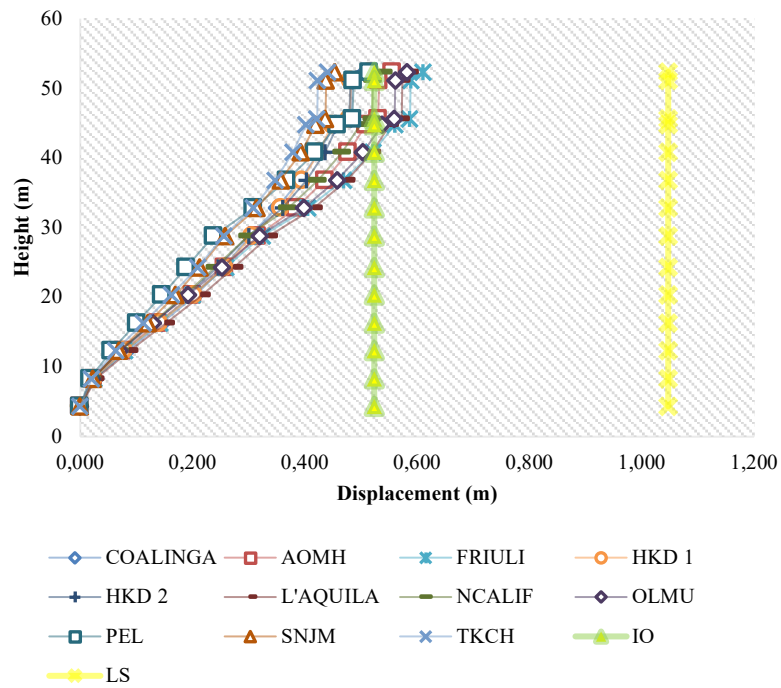


b) Story Displacement Y-Direction

Figure 8. Story Displacement for Configuration 1

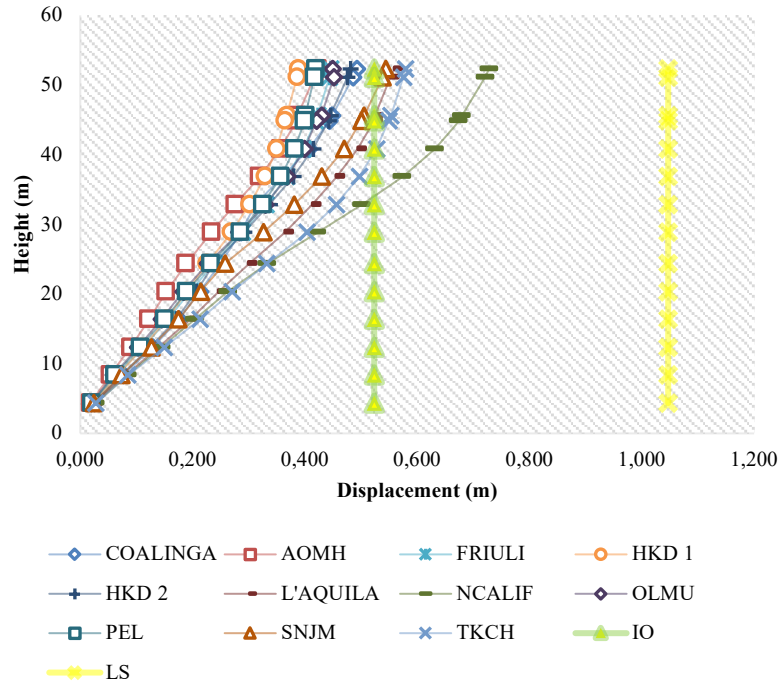


a) Story Displacement X-Direction

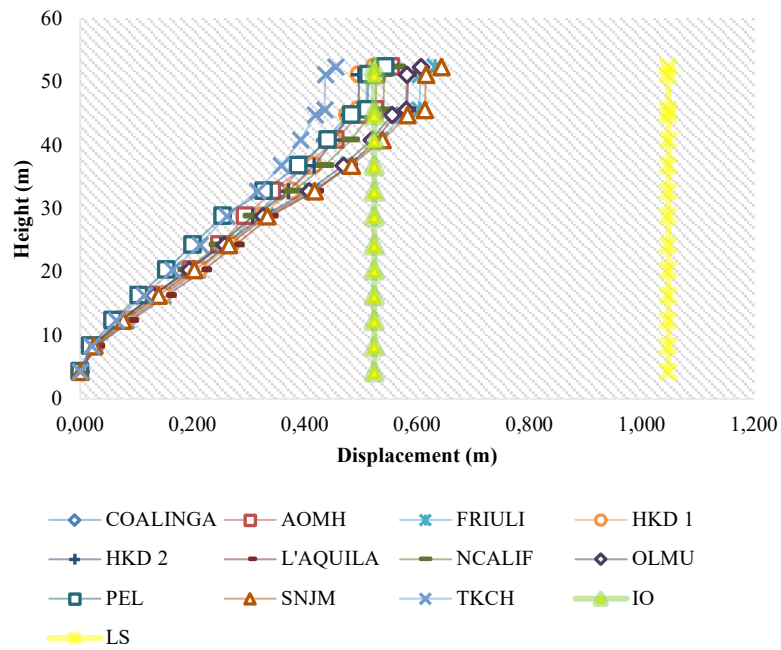


b) Story Displacement Y-Direction

Figure 9. Story Displacement for Configuration 2

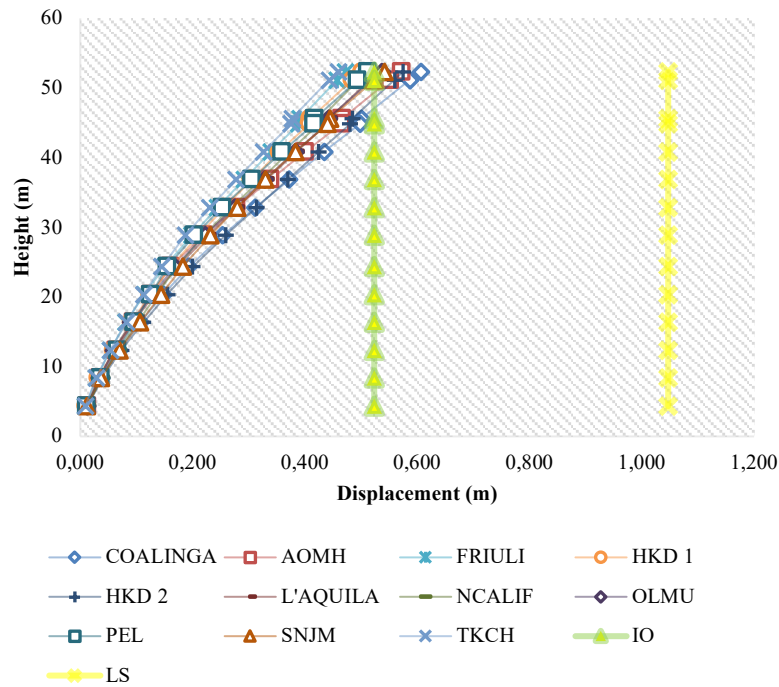


a) Story Displacement X-Direction

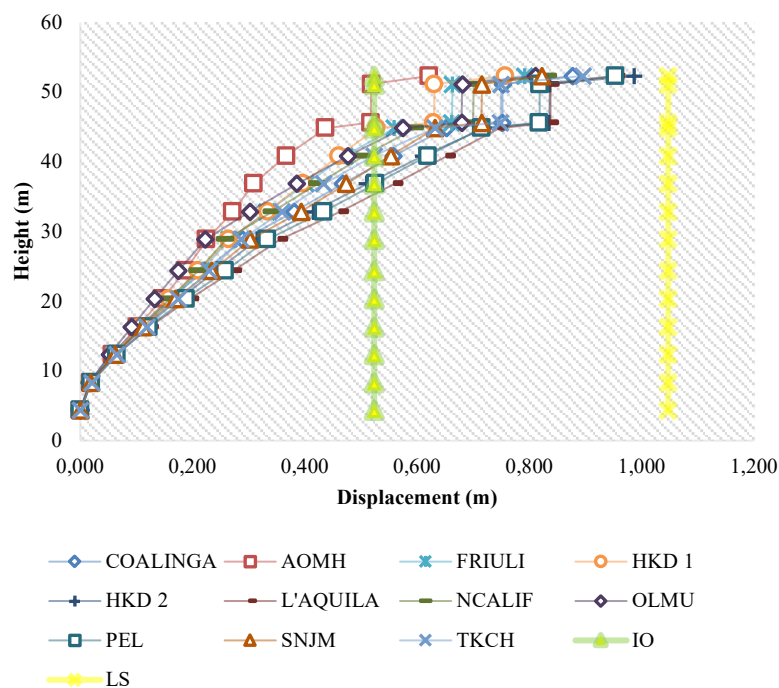


b) Story Displacement Y-Direction

Figure 10. Story Displacement for Configuration 3



a) Story Displacement X-Direction



b) Story Displacement Y-Direction

Figure 11. Story Displacement for Dual System

In relation to the base shear response, a noticeable reduction in story displacement is shown in structures with viscous dampers compared to the conventional dual system. The reduction becomes significant in the Y-direction ground motion, which corresponds to the weaker axis of the building where the lateral stiffness of the structural system is relatively lower. For comparison

purposes, the average story displacement values obtained from the analyzed ground motion records are presented in the following tables 8 and 9.

Table 8. Average Inter-Story Displacement X-Direction (mm)

	COAL	AOMH	FRI	HD 1	HD 2	L'AQUI	NCAL	OLMU	PEL	SNJM	TKCH
Damper	35.20	30.21	31.82	27.79	34.42	39.99	52.03	32.37	29.98	38.85	41.41
Dual System	43.31	40.88	33.72	35.85	41.06	38.02	36.63	38.37	36.60	38.66	32.79

Table 9. Average Inter-Story Displacement Y-Direction (mm)

	COAL	AOMH	FRI	HD 1	HD 2	L'AQUI	NCAL	OLMU	PEL	SNJM	TKCH
Damper	37.02	39.95	44.10	37.32	36.50	42.50	39.38	42.20	37.45	36.87	31.91
Dual System	65.61	47.02	59.30	57.46	73.72	69.52	62.65	60.62	70.28	60.63	67.50

The incorporation of shear walls, in agreement with previous studies, has given a considerable contribution to the reduction of lateral displacement by enhancing structural stiffness, which limits the extent of deformation (Cheng et al., 2025; Kusuma & Machmoed, 2019). Based on data shown in table 8 and 9, showing the addition of fluid viscous dampers demonstrate the improvement in displacement control, there is a considerable reduction in displacement when fluid viscous dampers are applied to the model as compared to the standard dual system. On average across the three damper configurations, given the relatively small difference between them, displacement is reduced by about 5% of the dual system response in the X-direction, and about 39% of the response in the Y-direction. Table 10 shows a comparative analysis of displacement for different damper configurations, emphasizing the effects of such damper on lateral performance of the structure.

Table 10. Average Inter-Story Displacement for Damper Configurations

	X – Direction (mm)	Y – Direction (mm)
Configuration 1	35.8072	37.4823
Configuration 2	35.8329	38.0211
Configuration 3	35.8332	40.4586

Of the three setups, displacement in the X-direction shows almost the same performance, implying that the damping configuration does not have any compelling effect on the displacement in this direction. On the other hand, in the Y-direction, the displacement is minimal for setup 1. Generally, configuration 1 exhibits the best performance, while the slight distinction in the X-direction, consistent with previous findings, indicate that displacement in this direction depends largely on the structural manner (Bruschi, Calvi, & Quaglini, 2021; Shang et al., 2022; Yang, Han, Xu, & Zhang, 2025).

Mass Analysis

A comparison of the total structural mass is performed to evaluate the efficiency of material usage in each structural system. The total structural mass of the analyzed models, used to assess the efficiency of material utilization, is presented in Table 11. It should be noted that the reported structural mass does not include the mass contribution of the viscous dampers.

Table 11. Mass Comparison

Structural System	Total Mass (kg)	Reduction (%)
Dual System	24,279,071.28	—
Viscous Damper	19,724,140.44	18.8%

As presented in Table 10, the structural configuration incorporating viscous dampers results in an approximately 18.8% reduction in total structural mass compared to the conventional dual system. This reduction reflects a more efficient utilization of structural material, indicating that the incorporation of supplemental damping devices allows the structure to achieve the required performance with a significantly lower structural volume.

Conclusion

The results of the Nonlinear Time History Analysis (NLTHA) indicate that the incorporation of viscous dampers significantly improves the seismic performance of the structural system compared to the conventional dual system. The use of viscous damping consistently outperformed the conventional dual system in all performance indicator: The average base shear demand for all configurations were reduced by 60%, average story displacement for all configurations decreased by 5% in X – direction and 39% in Y – direction, and total structural mass was reduced by 18.8%, showing the mass efficiency of viscous damper.

The best lateral deformation control is accomplished using configuration 1, especially in Y-axis. Almost similar responses in the X-axis among the three configurations reveal that the deformation response on the X-axis depends on the frame stiffness instead of the location of the damper. However, the deformation response in the Y-axis relies on the configuration of the dampers. The conclusion has a bearing of infrastructure development in which case the use of viscous damper can benefit a building to satisfy the objective of TIA-942-B without neglecting the standard requirement of local standard.

The present study is subject to several limitations. Results are based on a single building geometry with a fixed damper property set ($\alpha = 0.2$); Soil-structure interaction is outside the scope of this work. Future studies should examine parametric variation of damper properties, and soil-structure interaction under the soft soil conditions.

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