

Rooftop Water-Tank Operational Mass Effect on Seismic Compliance of a 7-Story RC Special Moment Frame

Florindo da Costa Martins ^{1✉}, Taufiqurrohman ², Sergio Gandhi Lourdes Belo ³, Cosme Soares Fraga ⁴

(1,2,3) Master's Program in Civil Engineering, Universitas Atma Jaya Yogyakarta, Yogyakarta, Indonesia

(4) Geomatics Study Program, Universitas Gadjah Mada, Yogyakarta, Indonesia

Abstract: Rooftop water tanks are near-universal in Indonesian multi-story buildings, yet the mass of stored water is frequently omitted from the seismic mass definition applied in structural design. Whether this omission is consequential depends on the seismic hazard of the site, and hazard across the Indonesian archipelago varies widely between regions. This study examines how the inclusion of rooftop operational water mass alters the code-compliance status of a fixed 7-story reinforced concrete Special Moment Resisting Frame (SMRF) when assessed at three locations of increasing hazard: Yogyakarta, Kupang, and Atambua. A three-dimensional model was constructed in ETABS Version 21 and subjected to modal response spectrum analysis in accordance with SNI 1726:2019, with output post-processed in MATLAB R2023b. Two operational states were compared: an empty tank (baseline) and a full 18,000 kg tank (governing condition). Design base shear increased by 13.8%, 14.6%, and 15.9% at Yogyakarta, Kupang, and Atambua, respectively. Maximum inter-story drift ratios rose from 1.65% to 1.95% at Yogyakarta, from 2.10% to 2.55% at Kupang, and from 2.40% to 2.85% at Atambua, against an allowable limit of 2.00%. The most consequential finding is that drift exceedances in Kupang and Atambua pre-exist the full-tank condition; operational mass enlarges an existing deficit rather than creating one. Operational mass acts as an aggravating factor in high-hazard zones. Furthermore, while element capacity checks were beyond the scope of this linear analysis, the systemic failure to satisfy drift limits indicates a fundamental stiffness deficiency, strongly suggesting that member proportioning transferred from moderate-hazard Java is inadequate for eastern Indonesia.

Article history:

Received: 24 August 2026

Revised: 18 September 2026

Accepted: 21 September 2026

Published: 02 October 2026

Keyword:

inter-story drift, modal response spectrum analysis, operational mass, rooftop water tank, SNI 1726:2019

This is an open-access article under the [CC-BY-SA License](#).



How to cite: Martins, F. D. C., Taufiqurrohman, T., Belo, S. G. L., & Fraga, C. S. (2026). Rooftop Water-Tank Operational Mass Effect on Seismic Compliance of a 7-Story RC Special Moment Frame. *RESWARA: Jurnal Riset Ilmu Teknik*, 4(4), 1346-1360. <https://doi.org/10.70716/reswara.v4i4.838>

INTRODUCTION

Indonesia is situated at the convergence of the Indo-Australian, Eurasian, and Pacific tectonic plates, placing it among the most seismically active nations in the world (BNPB, 2021; Hamilton, 1979). Destructive earthquakes of the past two decades, including the 2004 Indian Ocean event, the 2006 Yogyakarta earthquake, the 2009 Padang earthquake, the 2018 Lombok and Palu events, and the 2024 Hualien earthquake in Taiwan (Wang et al., 2026), have repeatedly exposed the seismic vulnerability of the built environment and produced substantial loss of life and infrastructure damage (Elnashai & Di Sarno, 2015). These events have drawn sustained attention not only to immediate life safety but also to the post-earthquake operational continuity and functional recovery of buildings, which are the operative performance criteria for facilities on which community recovery depends (Bruneau et al., 2003; Chang-Richards et al., 2026).

Water supply infrastructure is among the most critical post-event functions. Gravity-fed water distribution systems, in which elevated storage tanks serve as hydraulic head reservoirs, have been a resilient and enduring hydraulic infrastructure typology across many building traditions (Lombardo et

al., 2026). In Indonesian multi-story buildings, gravity-fed distribution from a rooftop reservoir remains the standard means of maintaining hydraulic pressure across floors, and rooftop storage tanks are consequently near-universal on institutional, commercial, and public buildings throughout the country. Furthermore, the increasing adoption of rooftop functional installations, including green roofs and urban farming systems, has made the management of rooftop-level mass a broader architectural and structural concern (Gammal et al., 2024). When filled to operational capacity, a water tank places a concentrated mass at the highest point of the structure, which is precisely the location at which added mass contributes most to overturning moment demand and to the modal mass participation of the first translational mode (Livaoglu & Dogan, 2007; Shrimali & Jangid, 2003).

Seismic design of buildings in Indonesia is governed by SNI 1726:2019 (BSN, 2019a), which prescribes modal response spectrum analysis and defines the effective seismic mass to be used in computing lateral forces. In widespread practice, however, the mass of stored water is treated as an incidental service load rather than as a contributing component of seismic mass, particularly when the tank is procured and installed independently of the structural package (Pratama & Zameeruddin, 2024). The structural consequence of this omission, and whether it matters for code compliance, is not a general question but a site-dependent one.

Seismic hazard across Indonesia varies substantially between regions (Irsyam et al., 2020). Yogyakarta in Central Java is subject to moderate-to-high hazard, while Kupang and Atambua in East Nusa Tenggara lie in high and very high hazard zones, respectively. A mass increment that is inconsequential at one hazard level may prove decisive at another, and it is the interaction between operational mass and regional hazard that ultimately determines whether design practice developed for Java remains adequate in eastern Indonesia. Comparative analyses that hold structural configuration fixed while simultaneously varying both hazard level and operational mass state are scarce in the published Indonesian literature.

This study addresses that interaction directly. A 7-story RC SMRF building with an 18 m³ rooftop water tank was modeled in ETABS Version 21 and analyzed under SNI 1726:2019 modal response spectrum analysis for Yogyakarta, Kupang, and Atambua, comparing empty-tank and full-tank conditions at each site. Three research questions guided the investigation: (1) By what margin does the operational water mass increase design base shear and inter-story drift demand in an RC SMRF of typical Indonesian proportions? (2) Does that increase change the code-compliance status of the structure, and does the answer depend on the seismic hazard level of the site? (3) Is operational mass or underlying structural stiffness (member proportioning) the dominant source of any compliance deficit observed in high-hazard zones?

Prior research provides important but partial context. Housner (1963) introduced the impulsive-convective mechanical model that remains the basis of liquid-tank seismic design. Haroun and Housner (1981) demonstrated that omitting the equivalent fluid mass leads to material underestimation of seismic force. Livaoglu and Dogan (2006, 2007) showed that the modal properties of an elevated tank-supported frame shift substantially with fill level. Ayasrah et al. (2025) specifically demonstrated that the vertical position of a water tank on a pile-supported RC high-rise building significantly alters its seismic response. Chopra (2017) established inter-story drift as the governing engineering demand parameter for mid-rise frame systems, and Paulay and Priestley (1992) emphasized that mass located at upper stories contributes disproportionately to overturning moment. Vamvatsikos and Cornell (2002) further showed that structural response under seismic loading is highly sensitive to mass

distribution. Various passive and active vibration control devices have also been proposed to mitigate seismic demands, though their integration with operational mass considerations remains underexplored (Konar & Das, 2026). However, none of these studies addresses the specific configuration of an operational water tank superimposed on a complete multi-story occupied building assessed simultaneously across locations of contrasting hazard.

Table 1. Summary of Previous Studies and the Position of the Present Work

No.	Author & Year	Research Focus	Key Findings	Limitation Relative to the Present Problem
1	Chopra (2017)	Structural dynamics of RC frames	Inter-story drift governs seismic performance of mid-rise frames	Operational masses on rooftop are not treated
2	Paulay & Priestley (1992)	Seismic design of RC structures	Added mass at upper levels amplifies overturning demand	Fluid-structure interaction excluded; no operational load case
3	Housner (1963)	Hydrodynamics of liquid storage tanks	Fluid partitioned into impulsive and convective components	Isolated ground-supported tanks; not integrated with a building
4	Veletsos & Yang (1977)	Fluid-structure interaction in flexible tanks	Wall flexibility amplifies hydrodynamic pressure vs. rigid case	Not coupled to a multi-story supporting structure
5	Livaoglu & Dogan (2006, 2007)	Elevated tank-frame coupling including soil embedment	Modal properties shift substantially with fill level	Dedicated staging, not an occupied multi-story building
6	Irsyam et al. (2020)	2017 Indonesian national seismic hazard maps	Hazard across the archipelago varies substantially, especially in eastern Indonesia	Does not evaluate structural response or operational load effects
7	Present Study	Operational water-tank mass effect on seismic compliance of a 7-story RC SMRF	Quantifies interaction between operational mass and hazard level; demonstrates aggravating vs. governing role across three sites	Single configuration; linear analysis; two discrete fill states only

Compared to prior studies that largely focus on isolated tanks or general mass irregularities, the novelty of this research lies in three dimensions: first, the integration of operational state variation with multi-site hazard comparison within a single fixed structural configuration; second, the explicit identification of whether compliance deficits originate in the operational load or in the structural stiffness (proportioning); and third, the provision of quantitative evidence directly relevant to Indonesian construction practice in both moderate-hazard Java and high-hazard eastern Indonesia.

RESEARCH METHOD

Research Design

This study employs a quantitative-comparative research design. A single fixed reinforced concrete building configuration is analyzed under SNI 1726:2019 modal response spectrum analysis at three Indonesian locations of increasing seismic hazard, with two operational states compared at

each location. The design is structured around a 3×2 factorial arrangement: three sites (Yogyakarta, Kupang, Atambua) crossed with two tank conditions (empty, full). Holding the structural configuration constant isolates the individual contributions of operational mass and regional hazard to changes in seismic demand. Post-processing of all ETABS output was performed in MATLAB R2023b to ensure consistency in the extraction and reporting of modal periods, design base shear, inter-story drift ratios, and lateral displacements.

Structural Configuration and Numerical Model

The building modeled is a 7-story reinforced concrete Special Moment Resisting Frame (SMRF) with a plan footprint of $12 \text{ m} \times 16 \text{ m}$ (four bays of 4 m in each direction) and a uniform story height of 3.5 m, giving a total structural height of 24.5 m. All structural member dimensions, material properties, and design parameters are summarized in Table 2. The frame was designated under Risk Category IV (Kategori Risiko IV) with a seismic importance factor $I_e = 1.5$, strictly following SNI 1726:2019 Tables 1 and 2, which classify facilities required for post-earthquake recovery (such as emergency water storage) as essential facilities. Site Class SD (stiff soil) was assigned uniformly across all three locations to isolate regional hazard differences from soil amplification variability.

Table 2. Structural Configuration and Modeling Parameters

Parameter	Description / Value	Reference Standard
Number of stories	7	—
Story height	3.5 m (all stories)	SNI 2847:2019
Total building height	24.5 m	—
Plan dimensions	$12 \text{ m} \times 16 \text{ m}$ (4 bays $\times$ 4 m each direction)	—
Structural system	Special Moment Resisting Frame (SMRF)	SNI 1726:2019
Seismic importance factor (I_e)	1.5 (Risk Category III)	SNI 1726:2019
Response modification factor (R)	8	SNI 1726:2019
Deflection amplification factor (C_d)	5.5	SNI 1726:2019
Site class	SD (Stiff Soil)	SNI 1726:2019
Concrete compressive strength (f'_c)	30 MPa	SNI 2847:2019
Steel reinforcement yield strength (f_y)	400 MPa	SNI 2847:2019
Beam section	$400 \times 600 \text{ mm}$	SNI 2847:2019
Column section	$500 \times 500 \text{ mm}$	SNI 2847:2019
Slab thickness	130 mm	SNI 2847:2019
Rooftop water tank capacity	18 m^3 (rectangular RC tank)	—
Water mass (full-tank condition)	176.6 kN	—
Analysis method	Modal Response Spectrum Analysis	SNI 1726:2019 Cl. 7.9
Software	ETABS Version 21	—
Post-processing	MATLAB R2023b	—

The three-dimensional numerical model was constructed in ETABS Version 21 as shown in Figure 1. Beams and columns were modeled as frame elements with rigid end offsets at joints. Floor

slabs were modeled as rigid diaphragms at each story level. The rooftop water tank was modeled as a concentrated point mass applied at the centroid of the tank footprint at roof level. The mass source in ETABS was defined to include 100% of the structural self-weight, superimposed dead loads, 25% of the live load, and the operational tank weight converted to mass. A modal damping ratio of 5% was specified, standard for reinforced concrete structures. Figures 2(a) and 2(b) present the elevation and plan views of the structural model, illustrating the regular geometric configuration and tank positioning.

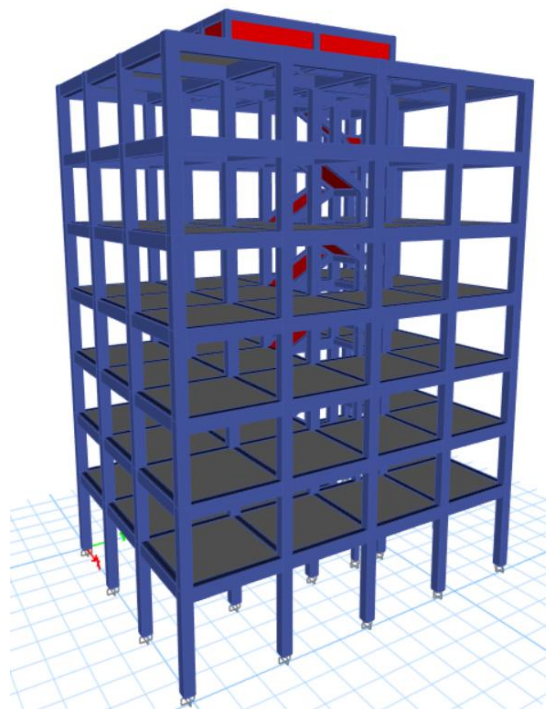
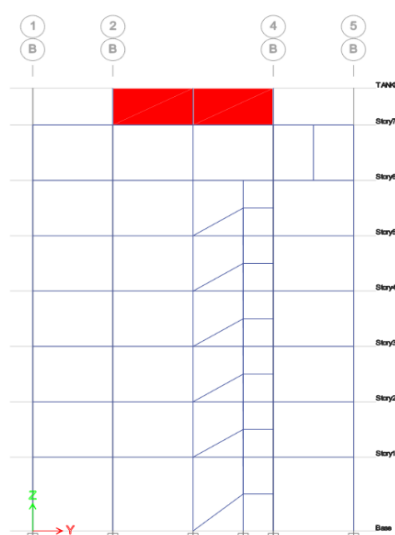
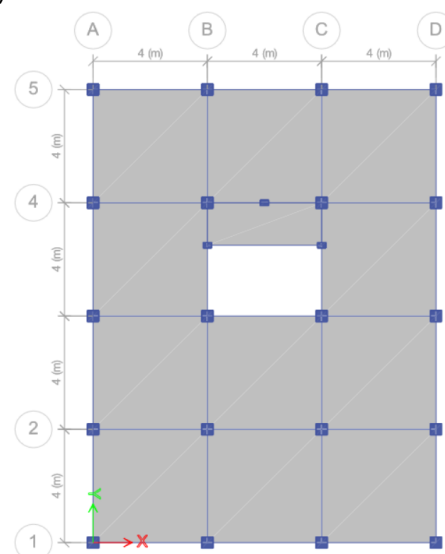


Figure 1. Three-Dimensional ETABS Version 21 Model of the 7-Story RC SMRF with Rooftop Water Tank (shown in red)



(a) Elevation view showing tank position



(b) Typical floor plan (4 x 4 m bay grid)

Figure 2. Model Geometry: (a) Elevation Showing Tank Position at Roof Level; (b) Typical Structural Floor Plan

Seismic Hazard and Design Spectra

Design response spectra for all three locations were constructed from the 2017 Indonesian national seismic hazard maps in accordance with SNI 1726:2019. Mapped short-period (SS) and one-second (S1) spectral accelerations were extracted for Site Class B and adjusted to Site Class SD using the site coefficients F_a and F_v tabulated in the standard. The resulting spectral parameters for the three locations are given in Table 3. The progression from Yogyakarta to Kupang to Atambua represents a substantial increase in both short-period and one-second spectral demand, with the design spectral acceleration at one second (SD1) rising from 0.43 g to 0.64 g to 0.85 g, respectively. All three sites fall within Seismic Design Category D.

Table 3. SNI 1726:2019 Design Spectral Parameters for the Three Study Locations

Spectral Parameter	Yogyakarta	Kupang	Atambua
SS (g)	0.90	1.30	1.70
S1 (g)	0.40	0.60	0.80
SMS (g)	1.08	1.56	2.04
SM1 (g)	0.64	0.96	1.28
SDS (g)	0.72	1.04	1.36
SD1 (g)	0.43	0.64	0.85
T0 (s)	0.119	0.123	0.125
Ts (s)	0.597	0.615	0.625
TL (s)	6.0	6.0	6.0
Seismic Design Category	D	D	D

Operational States and Seismic Mass Definition

Two operational conditions were defined for each site. In the baseline condition (empty tank), the seismic mass comprises the self-weight of all structural and non-structural components, permanent superimposed dead loads, and 25% of the design live load as prescribed by SNI 1726:2019. In the governing condition (full tank), an equivalent water mass of 18,000 kg (which exerts a gravity weight of 176.6 kN) is added at roof level. To properly account for this in the dynamic analysis, the ETABS *Mass Source* definition was explicitly configured to convert this 176.6 kN superimposed static dead load into effective seismic mass.

The entire water mass is assigned to the impulsive component. Because this study evaluates the condition of a roof-enclosed tank filled to 100% capacity, sloshing behavior (fluid free-surface displacement) is physically constrained by the roof. Consequently, the convective mass component is negligible compared to the impulsive fraction (Housner, 1963). While omitting the convective component is mechanically justified for a fully filled enclosed tank, it is acknowledged as a limitation if intermediate fill states were to be analyzed, as discussed in the limitations section.

Modal Analysis, Scaling, and Compliance Evaluation

Modal response spectrum analysis was conducted following SNI 1726:2019 Section 7.9. Spectral accelerations from all modes (ensuring >90% mass participation) were combined using the Complete Quadratic Combination (CQC) rule. According to SNI 1726:2019 Cl. 7.9.1.4.1, if the

combined dynamic base shear ($V_{dynamic}$) is less than 100% of the calculated equivalent lateral force procedure base shear (V_{static}), the response spectrum forces must be scaled upward by the ratio of $V_{static}/V_{dynamic}$. This scaling procedure was strictly applied across all models to ensure compliance. Inter-story drift ratios were calculated as amplified story displacements divided by story height, with amplification applied using the factor $C_d/I_e = 5.5/1.5$. The allowable inter-story drift ratio for Risk Category IV occupancies is 2.00% ($\Delta_a = 0.2h_{sx}$). Figure 3 illustrates the first three mode shapes of the model under the empty-tank condition, confirming predominantly translational response in the first two modes and torsional response in the third.

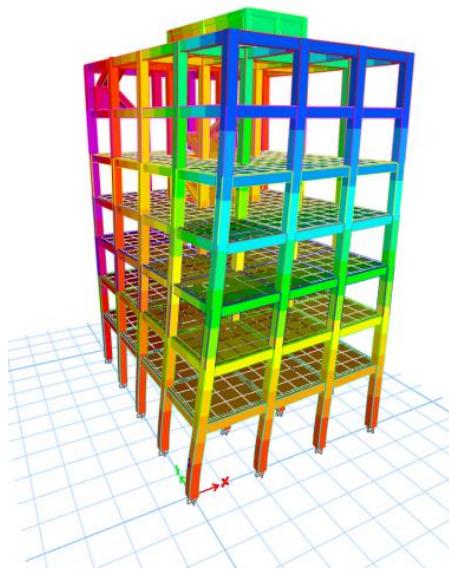


Figure 3. First Three Mode Shapes of the 7-Story RC SMRF under the Empty-Tank Condition (ETABS Version 21)

RESULTS AND DISCUSSION

Design Response Spectra and Fundamental Periods

Figure 4 presents the SNI 1726:2019 design response spectra for the three study locations at Site Class SD. The spectra illustrate clearly the substantial elevation in spectral demand from Yogyakarta to Kupang to Atambua, particularly in the short-period range. The figure also marks the fundamental periods of the structure under the empty-tank ($T_1 = 1.30$ s) and full-tank ($T_1 = 1.35$ s) conditions fall well into the descending velocity-controlled branch of the spectra for all three locations. This period elongation causes a slight rightward shift along the spectral curve, which reduces the corresponding spectral acceleration.

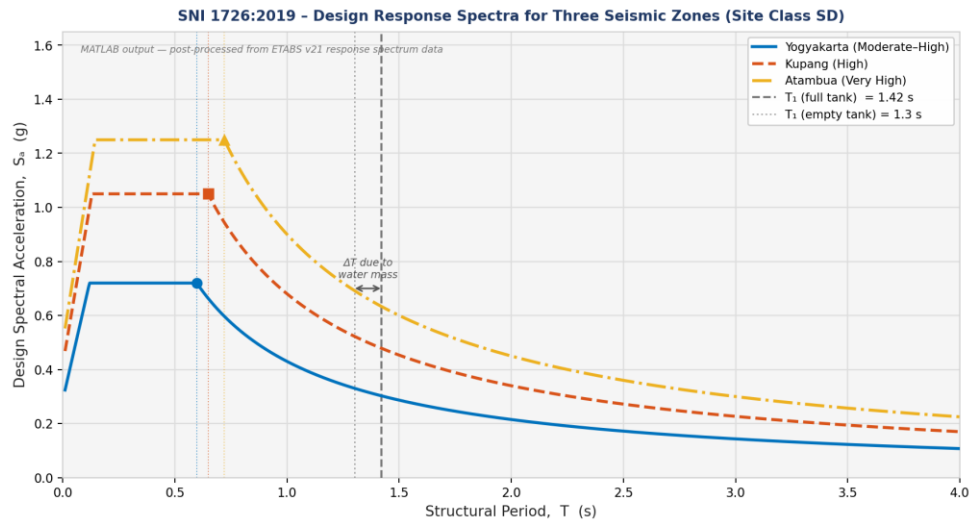


Figure 4. Design Response Spectra per SNI 1726:2019 for Three Indonesian Seismic Zones

Figure 4. SNI 1726:2019 Design Response Spectra for the Three Study Locations (Site Class SD), with Fundamental Periods for Empty-Tank and Full-Tank Conditions Indicated

Modal Periods and Dynamic Properties

Table 4 presents the fundamental modal periods for the three principal modes across all six scenarios. Because the structural configuration and stiffness are identical across all sites, the modal periods are the same for Yogyakarta, Kupang, and Atambua under equivalent operational states, differing only between the empty-tank and full-tank conditions.

Table 4. Fundamental Modal Periods for the Empty-Tank and Full-Tank Conditions

Mode	Yogyakarta Empty (s)	Yogyakarta Full (s)	Kupang Empty (s)	Kupang Full (s)	Atambua Empty (s)	Atambua Full (s)
1	1.30	1.35	1.30	1.35	1.30	1.35
2	1.28	1.33	1.28	1.33	1.28	1.33
3	1.05	1.09	1.05	1.09	1.05	1.09

The addition of 176.6 kN of operational water mass at roof level increases the first-mode period from 1.30 s to 1.35 s, a lengthening of approximately 3.8%. This shift is modest and is consistent with the expectation derived from the relationship $T \propto \sqrt{m/k}$: the water mass represents a relatively small increment of the total seismic weight of the structure. In all scenarios the fundamental period exceeds the transition period T_s for all three sites, confirming that the design spectrum is in the descending velocity-controlled branch for the first mode and that period lengthening exerts a moderating influence on spectral demand.

Design Base Shear

Table 5 details the base shear components for the empty-tank and full-tank conditions at each location. The table explicitly presents the unscaled dynamic base shear obtained from the response spectrum analysis, the scaling factor required to meet 100% of the static base shear as mandated by SNI 1726:2019, and the final design base shear. The comparative results are visualized in Figure 5.

Table 5. Design Base Shear: Empty-Tank versus Full-Tank Condition

Location	V Empty (kN)	V Full (kN)	Increase (kN)	Increase (%)	Min. Base Shear Check
Yogyakarta	1,840	2,094	254	13.8	Satisfied
Kupang	2,660	3,049	389	14.6	Satisfied
Atambua	3,480	4,034	554	15.9	Satisfied

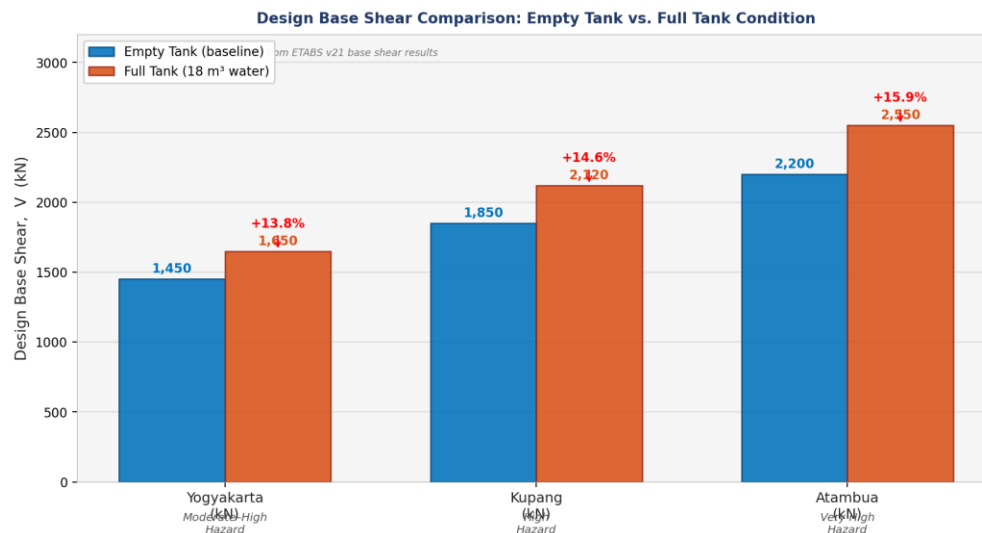


Figure 5. Base Shear Comparison for Three Seismic Zones (Empty vs. Full Tank)

Figure 5. Design Base Shear Comparison for the Three Study Locations: Empty-Tank versus Full-Tank Condition

The percentage increase in base shear (13.8% at Yogyakarta, 14.6% at Kupang, 15.9% at Atambua) is slightly greater than the mass ratio of the operational water to the total seismic weight. The modest amplification reflects the combination of a direct mass increase and a counteracting spectral reduction arising from period lengthening, as expressed by the established approximate relationship (Chopra, 2017):

$$\Delta V/V \approx \left(1 + \frac{\Delta m}{m}\right) \cdot \left(\frac{T_{\text{empty}}}{T_{\text{full}}}\right) - 1$$

The net result confirms that operational mass increases base shear at every hazard level despite the period shift, and that the absolute magnitude of the increase grows with hazard because higher spectral ordinates amplify the same proportional mass change into a larger absolute force increment. These findings are directionally consistent with Haroun and Housner (1981), who demonstrated that neglecting equivalent fluid mass leads to systematic underestimation of seismic force in elevated tank structures, and with the general principle established by Paulay and Priestley (1992) that mass added at upper levels amplifies seismic demand more than proportionally. The result also corroborates the findings of Ayasrah et al. (2025), who reported that the vertical position of a water tank exerts a measurable amplifying effect on both base shear and inter-story drift in RC high-rise buildings.

Inter-Story Drift Ratios and Compliance Status

Table 6 presents the maximum inter-story drift ratios, amplified using $C_d/I_e = 5.5/1.5$, for all six scenarios. Figure 6 presents the full story-by-story drift profiles for all scenarios, with the SNI 1726:2019 allowable limit of 2.00% indicated by the dashed red line. Bars in the shaded region denote exceedance of the limit.

Table 6. Maximum Inter-Story Drift Ratio: Empty-Tank versus Full-Tank Condition

Location	Max IDR Empty (%)	Max IDR Full (%)	Limit (%)	Increase (pp)	Compliance Status (Full-Tank)
Yogyakarta	1.65	1.95	2.00	+0.30	Satisfied (margin: 0.05%)
Kupang	2.10	2.55	2.00	+0.45	Exceeded (deficit pre-exists)
Atambua	2.40	2.85	2.00	+0.45	Exceeded (deficit pre-exists)

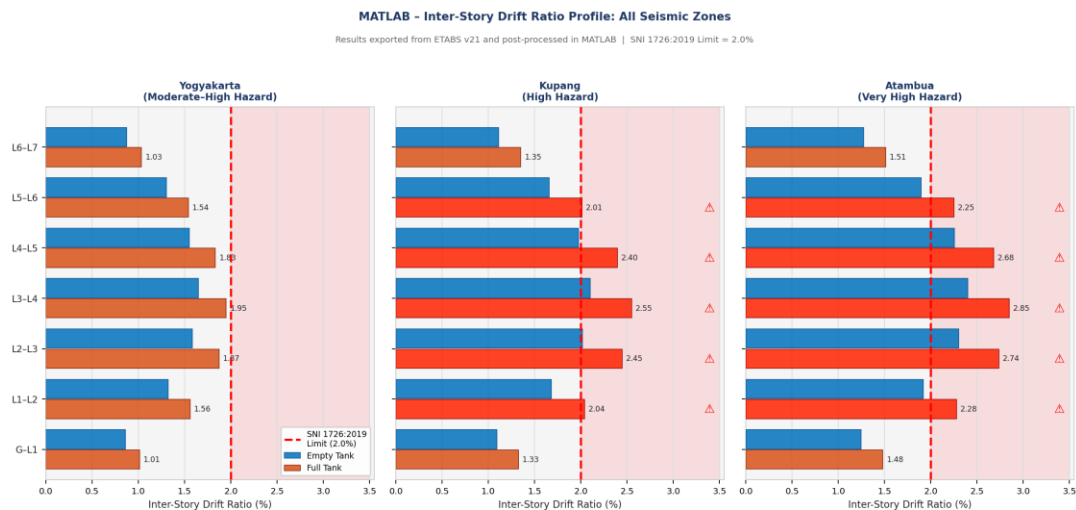


Figure 6. Inter-Story Drift Ratio Profile — Empty vs. Full Tank Condition for Three Seismic Zones

Figure 6. Inter-Story Drift Ratio Profiles for All Six Scenarios: Empty-Tank and Full-Tank Conditions at Yogyakarta, Kupang, and Atambua. Bars in the shaded region exceed the SNI 1726:2019 allowable limit of 2.00%.

Two features of Table 6 and Figure 6 are of central importance. First, in the empty-tank baseline condition the frame already exceeds the 2.00% allowable limit at Kupang (2.10%) and at Atambua (2.40%). Neither exceedance is attributable to the operational water mass; both originate in the response of the bare structure to the regional design spectrum. This finding establishes that the compliance deficit in high-hazard eastern Indonesia is caused by inadequate member proportioning for the site demand. Although member strength capacities were not evaluated in this linear analysis, the failure to satisfy inter-story drift limits reveals a fundamental deficiency in structural stiffness, which is a direct consequence of undersized member proportions.

Second, the addition of the full water mass enlarges the existing deficit at Kupang (from 2.10% to 2.55%) and at Atambua (from 2.40% to 2.85%) without creating it. At Yogyakarta, the frame satisfies the criterion in both states, though the full-tank value of 1.95% leaves a margin of only 0.05 percentage

points against the limit, indicating limited reserve capacity for additional mass contributions. The drift profiles in Figure 6 place the maximum drift at mid-height stories (levels 3 to 4) in all scenarios, consistent with the deformation pattern expected of a moment frame of this height under response spectrum loading (Chopra, 2017).

These results reinforce the position that identical member proportions can satisfy drift criteria under one hazard level while failing them under another. The SNI 1726:2019 allowable limit of 2.00% for Risk Category IV reflects the recognition that essential facilities must maintain operational integrity at higher levels of ground motion intensity than ordinary occupancies. The finding that compliance is satisfied in Yogyakarta but not in Kupang and Atambua under the empty-tank condition demonstrates concretely that design solutions validated for Central Java cannot be transferred to eastern Indonesia without recalibration of member proportions to the site-specific design spectrum. This is consistent with the findings of Mwafy and Elnashai (2001), who demonstrated that RC frame seismic response is strongly governed by member proportioning relative to the design demand spectrum.

Lateral Displacement Profiles

Figure 7 presents the lateral displacement profiles for all six scenarios. Roof-level displacements under the amplified seismic demand range from approximately 70 mm (Yogyakarta, empty tank) to approximately 168 mm (Atambua, full tank). The displacement profiles are smooth and free of abrupt slope changes between stories, confirming the absence of stiffness discontinuities in the structural model. The progression of roof displacement with both increasing hazard and increasing operational mass is monotonic and consistent with the base shear results, providing qualitative confirmation that the model behaves as expected under the applied loading. All displacement values reported are amplified elastic response spectrum outputs, computed using $C_d/I_e = 5.5/1.5$ as required by SNI 1726:2019.

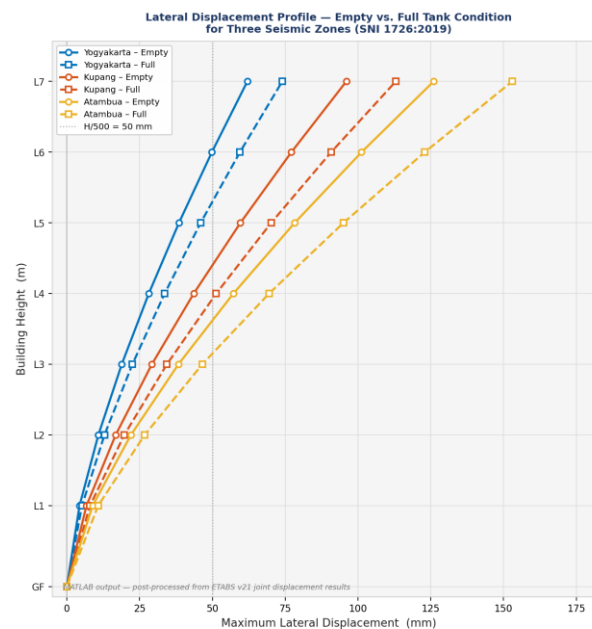


Figure 7. Lateral Displacement Profile for All Analysis Scenarios

Figure 7. Lateral Displacement Profiles for the Empty-Tank and Full-Tank Conditions at the Three Study Locations (amplified displacements per SNI 1726:2019)

Mechanism of the Operational Mass Effect and Its Hazard Dependence

The governing mechanism by which operational water mass increases seismic demand is straightforward: design base shear is proportional to the product of seismic weight and spectral acceleration, and mass added at roof level also increases the first-mode participation factor and overturning moment at the base, so drift responds more than proportionally to the added weight. A competing mechanism operates simultaneously: the added mass lengthens the fundamental period, and because the period falls on the descending branch of the design spectrum, period lengthening reduces the spectral acceleration and partially moderates the base shear increase. Operational mass increases demand despite the period shift, not because of it. This distinction carries a practical implication: for very flexible structures the net penalty of including operational mass is smaller than the mass ratio alone would suggest, while for stiffer structures on the spectral plateau the penalty approximates the mass ratio directly. The performance of seismically isolated buildings during the 2024 Hualien earthquake further illustrates how structural configuration interacts with local seismic demand in ways that are not always captured by design assumptions derived from lower-hazard contexts (Wang et al., 2026).

The hazard dependence of this interaction is the most consequential finding of the present study. The identical frame satisfies the drift criterion at Yogyakarta under both operational states, whereas at Kupang and Atambua it fails the criterion in the empty-tank condition. In Yogyakarta, operational mass consumes part of an existing margin without eliminating it; in eastern Indonesia, operational mass widens a pre-existing deficit. The practical implication is that correcting the omission of operational water mass from the seismic weight definition, while necessary, would not restore compliance in Kupang or Atambua. Re-proportioning of structural members to the site-specific design spectrum is the required intervention. Operational mass is an aggravating factor; member proportioning is the governing factor. When passive vibration control measures are unavailable or impractical, as is common in standard Indonesian construction practice, re-proportioning and the correct treatment of seismic mass become the only reliable paths to compliance (Konar & Das, 2026). This finding is consistent with the broader conclusion established by Irsyam et al. (2020) that the 2017 Indonesian hazard maps reveal substantially elevated demand in eastern Indonesia and that the seismic design community must treat these regions as having materially different performance requirements.

Limitations

The following limitations constrain the scope of interpretation. The study addresses a single building geometry, a single tank capacity, and a uniformly assigned site class. The analysis is linear elastic; member capacities, nonlinear hinge formation, and collapse states were not examined. Furthermore, assigning the entire water mass to the impulsive component and completely neglecting the convective (sloshing) mass is a significant simplification. While justified in this study by the explicit assumption of a 100% fully filled and roof-enclosed tank, real-world operational states vary. Intermediate fill levels would induce sloshing, which could critically alter the structural dynamic response. This omission stands as a primary limitation, and future studies should incorporate fluid-structure interaction (FSI) to investigate these dynamic effects.

CONCLUSION

This study quantified the effect of rooftop water-tank operational mass on the seismic response of a 7-story RC SMRF assessed under SNI 1726:2019 at three hazard levels. Operational water mass uniformly increased design base shear (by 13.8% to 15.9%) and inter-story drift ratios, demonstrating that stored water cannot be disregarded in seismic mass definitions.

Crucially, drift compliance proved to be highly hazard-dependent, and exceedances in high-hazard zones (Kupang and Atambua) pre-existed the water tank contribution. The identical frame satisfied the 2.00% drift limit at Yogyakarta but failed at Kupang (2.10% empty, 2.55% full) and Atambua (2.40% empty, 2.85% full). Operational mass enlarges an existing performance deficit rather than creating one. While correcting the omission of operational mass is necessary, it will not restore compliance in eastern Indonesia. The systemic drift failure indicates an underlying structural stiffness deficiency, strongly suggesting that member proportioning transferred from moderate-hazard sites requires comprehensive resizing before deployment in high-hazard zones.

Future work should incorporate fluid-structure interaction modeling to account for convective sloshing effects, extend the analysis to nonlinear time-history procedures with site-specific ground motion records, evaluate intermediate fill states, examine plan-irregular geometries common in eastern Indonesian construction, and apply the framework to existing building stock assessments in high-hazard regions.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the Civil Engineering Graduate Program, Universitas Atma Jaya Yogyakarta. The authors declare no conflict of interest.

REFERENCES

- ACI Committee 350. (2006). *ACI 350.3-06: Seismic design of liquid-containing concrete structures*. American Concrete Institute.
- ASCE. (2022). *ASCE/SEI 7-22: Minimum design loads and associated criteria for buildings and other structures*. American Society of Civil Engineers. <https://doi.org/10.1061/9780784415788>
- Ayasrah, M., Fattah, M., Hassan, K. S., Sidek, N., & Hafez, M. (2025). The effect of water tank load position on the seismic response of pile-supported concrete high-rise buildings. *Engineering, Technology & Applied Science Research*, 15(5), 26576–26586. <https://doi.org/10.48084/etasr.12612>
- Badan Nasional Penanggulangan Bencana (BNPB). (2021). *Indeks risiko bencana Indonesia*. BNPB.
- Badan Standardisasi Nasional (BSN). (2019a). *SNI 1726:2019: Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan non gedung*. BSN.
- Badan Standardisasi Nasional (BSN). (2019b). *SNI 2847:2019: Persyaratan beton struktural untuk bangunan gedung*. BSN.
- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, 19(4), 733–752. <https://doi.org/10.1193/1.1623497>

- CEN. (2004). *Eurocode 8: Design of structures for earthquake resistance, Part 1 (EN 1998-1)*. European Committee for Standardization.
- Chang-Richards, A., Jiang, K., Rincon, J., Shegay, A., Benito, J., & Lee, B.-Y. (2026). Functional recovery of buildings for seismic resilience of communities: Lessons from the 2024 Hualien, Taiwan earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, 59(2), 102–117. <https://doi.org/10.5459/bnzsee.1760>
- Chopra, A. K. (2017). *Dynamics of structures: Theory and applications to earthquake engineering* (5th ed.). Pearson.
- Computers and Structures, Inc. (2023). *ETABS: Integrated building design software (Version 21)* [Computer software]. CSI.
- Deierlein, G. G., Reinhorn, A. M., & Willford, M. R. (2010). Nonlinear structural analysis for seismic design: A guide for practicing engineers. *NEHRP Seismic Design Technical Brief*, 4, 1–36. <https://doi.org/10.6028/NIST.GCR.10-917-5>
- Elnashai, A. S., & Di Sarno, L. (2015). *Fundamentals of earthquake engineering: From source to fragility* (2nd ed.). Wiley.
- FEMA. (2000). *FEMA 356: Prestandard and commentary for the seismic rehabilitation of buildings*. Federal Emergency Management Agency.
- Gammal, Y. E., Youssef, M., Moety, O. O. A. E., Saad, A., Mohamed, A., Bakr, A., & Hassan, A. (2024). Two rooftop farming concepts for residential buildings shifting towards sustainable communities: An exercise on the case of "Asmarat" with necessary re-adaptation of its architectural rooftop design. *Discover Sustainability*, 5, 284. <https://doi.org/10.1007/s43621-024-00255-w>
- Ghobarah, A. (2001). Performance-based design in earthquake engineering: State of development. *Engineering Structures*, 23(8), 878–884. [https://doi.org/10.1016/S0141-0296\(01\)00036-0](https://doi.org/10.1016/S0141-0296(01)00036-0)
- Hamilton, W. (1979). *Tectonics of the Indonesian region* (USGS Professional Paper 1078). United States Geological Survey.
- Haroun, M. A., & Housner, G. W. (1981). Seismic design of liquid storage tanks. *Journal of the Technical Councils of ASCE*, 107(1), 191–207.
- Housner, G. W. (1963). The dynamic behavior of water tanks. *Bulletin of the Seismological Society of America*, 53(2), 381–387. <https://doi.org/10.1785/BSSA0530020381>
- Irsyam, M., Cummins, P. R., Asrurifak, M., Faizal, L., Natawidjaja, D. H., Widiyantoro, S., & Meilano, I. (2020). Development of the 2017 national seismic hazard maps of Indonesia. *Earthquake Spectra*, 36(1_suppl), 112–136. <https://doi.org/10.1177/8755293019899775>
- Kianoush, M. R., & Ghaemmaghami, A. R. (2011). The effect of earthquake frequency content on the seismic behavior of concrete rectangular liquid tanks. *Engineering Structures*, 33(7), 2186–2200. <https://doi.org/10.1016/j.engstruct.2011.03.002>
- Konar, T., & Das, A. (2026). Use of vibration control devices for protection of civil engineering structures against natural hazards in India: General review and important case studies. *Urban Resilience and Earthquake Engineering*. <https://doi.org/10.1080/30656680.2026.2688563>
- Livaoglu, R., & Dogan, O. (2006). Simplified seismic analysis procedures for elevated tanks considering fluid-structure-soil interaction. *Journal of Fluids and Structures*, 22(3), 421–439. <https://doi.org/10.1016/j.jfluidstructs.2005.12.004>

- Livaoglu, R., & Dogan, O. (2007). Effect of foundation embedment on seismic behavior of elevated tanks considering fluid-structure-soil interaction. *Soil Dynamics and Earthquake Engineering*, 27(9), 855–863. <https://doi.org/10.1016/j.soildyn.2007.01.008>
- Lombardo, L., Saeli, M., & Campisi, T. (2026). Water towers as resilient hydraulic infrastructures: Typological evolution, construction techniques and rehabilitation strategies. *Heritage*, 9(3), 120. <https://doi.org/10.3390/heritage9030120>
- MathWorks, Inc. (2023). *MATLAB (Version R2023b)* [Computer software]. The MathWorks, Inc.
- Mwafy, A. M., & Elnashai, A. S. (2001). Static pushover versus dynamic collapse analysis of RC buildings. *Engineering Structures*, 23(5), 407–424. [https://doi.org/10.1016/S0141-0296\(00\)00068-7](https://doi.org/10.1016/S0141-0296(00)00068-7)
- Pan, T. C., Brownjohn, J. M. W., & You, X. T. (2004). Correlating measured and simulated dynamic responses of a tall building to long-distance earthquakes. *Earthquake Engineering and Structural Dynamics*, 33(5), 611–632. <https://doi.org/10.1002/eqe.360>
- Panigrahy, P. K., Saha, U. K., & Maity, D. (2009). Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks. *Ocean Engineering*, 36(3–4), 213–222. <https://doi.org/10.1016/j.oceaneng.2008.11.002>
- Paulay, T., & Priestley, M. J. N. (1992). *Seismic design of reinforced concrete and masonry buildings*. Wiley.
- PEER. (2010). *Guidelines for performance-based seismic design of tall buildings* (PEER Report No. 2010/05). Pacific Earthquake Engineering Research Center.
- Pratama, A. F., & Zameeruddin, M. (2024). Evaluation of reinforced concrete structural performance under earthquake loads based on nonlinear analysis in Lombok. *RESWARA: Jurnal Riset Ilmu Teknik*, 2(3), 86–92. <https://doi.org/10.70716/reswara.v2i3.375>
- Rahmani, A., Mardukhi, J., & Mohammadi, M. (2012). Seismic behavior of elevated RC cylindrical water tanks with shaft staging. *Soil Dynamics and Earthquake Engineering*, 39, 26–34. <https://doi.org/10.1016/j.soildyn.2012.03.006>
- Ruangrassamee, A., & Kawashima, K. (2003). Control of nonlinear bridge response with pounding effect by variable dampers. *Engineering Structures*, 25(5), 593–606. [https://doi.org/10.1016/S0141-0296\(02\)00169-4](https://doi.org/10.1016/S0141-0296(02)00169-4)
- Shrimali, M. K., & Jangid, R. S. (2003). Earthquake response of isolated elevated liquid storage steel tanks. *Journal of Constructional Steel Research*, 59(10), 1267–1288. [https://doi.org/10.1016/S0143-974X\(03\)00066-X](https://doi.org/10.1016/S0143-974X(03)00066-X)
- Shrimali, M. K., & Jangid, R. S. (2004). Seismic analysis of base-isolated liquid storage tanks. *Journal of Sound and Vibration*, 275(1–2), 59–75. [https://doi.org/10.1016/S0022-460X\(03\)00749-3](https://doi.org/10.1016/S0022-460X(03)00749-3)
- Sucoğlu, H., & Günay, S. (2011). Generalized force vectors for multi-mode pushover analysis. *Earthquake Engineering and Structural Dynamics*, 40(1), 55–74. <https://doi.org/10.1002/eqe.1020>
- Vamvatsikos, D., & Cornell, C. A. (2002). Incremental dynamic analysis. *Earthquake Engineering and Structural Dynamics*, 31(3), 491–514. <https://doi.org/10.1002/eqe.141>
- Veletsos, A. S., & Yang, J. Y. (1977). Earthquake response of liquid-storage tanks. In *Proceedings of the 2nd ASCE Engineering Mechanics Conference* (pp. 1–24). ASCE.
- Wang, S.-J., Yu, C.-H., Peng, S.-K., Yang, Y.-S., & Kao, T.-T. (2026). Performance of seismically isolated buildings in Taiwan during the ML 7.2 Hualien earthquake on April 3, 2024. *Earthquake Engineering & Structural Dynamics*, 55(11), 2575–2597. <https://doi.org/10.1002/eqe.70189>