

# A Multi-Modal Seismic Assessment of Elevated Reinforced Concrete Water Tanks with Frame, Braced, and Shear Wall Staging Using ETABS

Shweta Dwivedi<sup>1</sup>, Prof. Manorama Singh<sup>2</sup>, Prof. Anubhav Pandey<sup>3</sup>, Prof. Mihir Pandey<sup>4</sup>,  
Prof. Deepak Pandey<sup>5</sup>

<sup>1</sup>Scholar, Civil Engineering Department, JNCT Rewa M.P. 486001 India

<sup>2</sup>Guide Civil Engineering Department, JNCT Rewa M.P. 486001 India

<sup>3</sup>Co-Guide Civil Engineering Department, JNCT Rewa M.P. 486001 India

<sup>4,5</sup>Co-Guide Mechanical Engineering Department, JNCT Rewa M.P. 486001 India

**Abstract**—Elevated reinforced concrete (RC) water tanks occupy a critical position in civil infrastructure, serving simultaneously as everyday water supply utilities and as indispensable post-disaster resources when conventional distribution networks become inoperable. Unlike standard multi-storey frames, these structures concentrate a substantial proportion of their total mass at considerable height above the ground — a configuration that amplifies overturning demands, elongates the fundamental natural period when the support structure is compliant, and generates complex hydrodynamic forces within the liquid cargo during earthquake shaking.

The choice of staging — the structural assembly that transfers gravity, wind, and seismic loads from the container base to the foundation — is the most consequential design decision governing seismic performance. Three staging configurations currently dominate Indian practice: multi-column moment-resisting frames, diagonally braced frames, and hollow reinforced concrete shaft (shear wall) staging. Each confers a distinctly different lateral stiffness, natural period, and energy-absorption capacity on the overall system, yet no unified quantitative comparison of all three types within a single, consistent analytical framework has been published for the current generation of Indian seismic standards.

The present investigation addresses this gap by constructing geometrically equivalent three-dimensional finite element models of a 500 KL circular Intze-type elevated RC water tank on each of the three staging configurations within ETABS v20. Liquid-structure interaction is captured through the two-degree-of-freedom hydrodynamic mass analogue prescribed in IS 1893 (Part 2): 2014, which decomposes

the total liquid into an impulsive fraction rigidly coupled to the vessel walls and a convective fraction representing low-frequency surface sloshing. Seismic demand is evaluated via both the Equivalent Static Method and the Response Spectrum Method in accordance with IS 1893 (Part 1): 2016, spanning Zones III, IV, and V on medium soil, for empty and full fill conditions.

Six engineering demand parameters are extracted and cross-compared: fundamental impulsive natural period, design base shear, peak lateral displacement, inter-storey drift ratio in the staging bays, base overturning moment, and critical member axial force. Results confirm that shear wall staging provides the highest lateral rigidity with minimal deformations but attracts the greatest seismic force; braced frame staging occupies an intermediate position in both stiffness and force demand; and moment frame staging admits the largest lateral excursions while mobilising the lowest inertial forces. These findings provide a quantitative basis for staging selection aligned with site-specific seismic hazard levels and structural performance objectives.

**Index Terms**—Elevated RC water tank; seismic staging comparison; two-mass hydrodynamic model; ETABS analysis; equivalent static method; response spectrum method; base shear; lateral displacement; shear wall staging; braced frame staging.

## I. INTRODUCTION

### 1.1 Background and Motivation

Continuity of potable water supply is among the highest operational priorities in the aftermath of a

major earthquake. Gravity-fed elevated storage tanks retain the ability to distribute water even when electrical power and pumping infrastructure are disrupted — but only if the tank structure itself survives strong shaking. This conditional resilience assigns elevated water tanks a strategic public-safety role that far exceeds their routine utility function, and it demands that their seismic design be treated with commensurate rigor.

The structural geometry of elevated tanks is inherently unfavorable under seismic loading. A disproportionately large share of the system mass — comprising the stored liquid and the container shell — is concentrated at an elevation several times the breadth of the support structure. The resulting high center of gravity produces large overturning moments at the foundation interface and, when the staging is flexible, extends the fundamental period well into the seismic-hazard-sensitive range. Compounding these geometric disadvantages, the liquid content is dynamically active: it imposes inertial pressures on the container walls and oscillates in prolonged sloshing modes that can persist long after strong ground motion has ceased.

Historical earthquake reconnaissance underscores these concerns with empirical evidence. Post-event surveys following the 2001 Bhuj earthquake in Gujarat — which caused approximately 20,000 fatalities and devastated regional water infrastructure — documented extensive distress and outright collapse of elevated tank staging systems, particularly those designed to pre-revision codal editions. Comparable observations were recorded after the 1999 Chamoli event in Uttarakhand and international earthquakes including the 1990 Manjil-Rudbar earthquake in Iran. A recurring observation across these incidents was that tanks of similar capacity exhibited markedly different survival outcomes attributable to differences in staging configuration, a pattern that directly motivates the systematic comparative investigation reported here.

### 1.2 Overview of Staging Systems

The staging of an elevated water tank encompasses all structural elements that transmit container loads to the foundation. Three configurations are widely adopted in Indian and global practice:

**Moment-Resisting Frame Staging:** A set of reinforced concrete columns, typically four to eight,

arranged in a circular or rectangular plan and connected by horizontal ring beams at one or more intermediate levels. Lateral resistance develops entirely through flexural rigidity at the column-beam joints, producing a ductile yet relatively compliant system with long natural periods and modest base shear at the cost of large lateral deformations.

**Diagonally Braced Frame Staging:** Diagonal members — reinforced concrete struts or steel sections — are introduced between the columns to enhance stiffness. This arrangement shortens the natural period, increases seismic force demand, and simultaneously reduces lateral displacement compared to pure frame staging. Braced staging offers a practical compromise between the flexibility of frames and the rigidity of shear walls, and is increasingly specified for moderate-to-high seismic regions.

**Shear Wall (RC Shaft) Staging:** A continuous hollow reinforced concrete shaft, circular or polygonal in cross-section, replaces the discrete column arrangement. The monolithic shell confers exceptional in-plane stiffness and torsional resistance, resulting in very small lateral deformations. However, the high stiffness shortens the natural period substantially, driving the structure into the peak-acceleration region of the design spectrum and generating elevated inertial force demands.

### 1.3 Research Gap and Objectives

Although the seismic response of elevated water tanks has attracted sustained research attention, studies that directly and simultaneously compare all three major staging typologies within a single consistent analytical framework — governed by the current Indian seismic codes IS 1893 (Part 1): 2016 and IS 1893 (Part 2): 2014 — across multiple seismic zones and fill conditions remain scarce. Many existing comparative works examine only two staging variants, employ simplified two-dimensional models that cannot capture torsional and three-dimensional interaction effects, or rely on superseded code editions.

The present study addresses this gap through the following specific objectives: (i) to construct geometrically equivalent three-dimensional ETABS models of elevated RC water tanks on frame, braced frame, and shear wall staging, incorporating the two-

mass hydrodynamic idealization of IS 1893 (Part 2): 2014; (ii) to apply both the Equivalent Static Method and the Response Spectrum Method across Zones III, IV, and V for empty and full fill states; (iii) to extract, tabulate, and comparatively interpret six engineering demand parameters; (iv) to identify the sensitivity of each staging type to seismic zone and fill level variation; and (v) to translate the findings into practical design guidance for structural engineers.

## II. LITERATURE REVIEW

A representative selection of peer-reviewed studies that inform the analytical approach and contextualise the findings of this investigation is summarised below.

### 2.1 Parametric Investigations

Rao and Reddy (2021) conducted a parametric study using ETABS to examine how variations in staging height and tank capacity affect the seismic response of elevated RC water tanks. Their work demonstrated that taller staging configurations lead to a marked increase in lateral displacement and inter-storey drift, attributable to the reduction in overall lateral stiffness with increasing height. Tanks with larger storage volumes were found to attract greater base shear owing to the higher seismic weight, and the authors concluded that geometric scalability must be explicitly accounted for when extending design recommendations across different tank sizes and height categories.

Patel et al. (2020) compared the Equivalent Static Method and the Response Spectrum Method for elevated tanks under multiple seismic zones, demonstrating that for regular, symmetric configurations the two procedures yield closely comparable base shear values — typically within acceptable engineering tolerance — with first-mode participation dominating the dynamic response. While the equivalent static approach was validated as adequate for routine design, the authors noted that irregular geometries and higher-mode contributions necessitate the full response spectrum treatment.

### 2.2 Comparative Staging Studies

Singh and Singh (2018) compared frame and braced staging systems and found that the introduction of

diagonal bracing substantially increases lateral stiffness, reduces peak displacement and drift, and redistributes lateral force demand away from the primary columns. They also identified that bracing members themselves attract significant axial forces, making attention to slenderness control and connection detailing critical for reliable performance. The study characterized braced staging as well-suited to moderate seismic zones where the full rigidity of shear wall staging is economically unnecessary.

Jain and Goel (2015) examined the dynamic characteristics of elevated tanks with flexible staging systems using SAP2000, confirming the well-established inverse relationship between staging flexibility and seismic force demand while highlighting that excessive compliance leads to serviceability problems through large inter-storey drift. They advocated performance-based design approaches that explicitly consider the competing requirements of force limitation and deformation control.

Dutta and Jain (2000) provided an early but foundational comparison of frame and shear wall staging, establishing the fundamental trade-off between the low force demand of flexible frames and the low displacement demand of stiff shaft systems. Their work also discussed implications of the response reduction factor in code-based design and remains a standard reference in the field.

### 2.3 Hydrodynamic Effects

Malhotra et al. (2012) investigated hydrodynamic pressure distribution in liquid-retaining structures, demonstrating that separating the liquid response into impulsive and convective components is essential for accurate seismic force estimation. The study showed that neglecting sloshing effects leads to significant errors in force prediction, and that tank geometry — particularly the liquid depth-to-diameter ratio — controls the dominant sloshing frequency. These findings underpin the two-mass idealization adopted in IS 1893 (Part 2): 2014 and applied directly in the present work.

Shrimali and Jangid (2003) examined fluid-structure interaction effects analytically, demonstrating that increased damping reduces sloshing amplitudes and overall response, and that support conditions at the base significantly influence hydrodynamic pressure distribution. Their work reinforced the need for

accurate modeling of the liquid-structure interface in seismic assessment of tank systems.

### III. THEORETICAL FRAMEWORK

#### 3.1 Two-Mass Hydrodynamic Idealization

When horizontal ground acceleration is imparted to an elevated tank, the contained liquid does not behave as a single rigid body. A portion of the liquid — located in the lower zone of the vessel and constrained by wall rigidity — accelerates in phase with the container structure; this is designated the impulsive component. The remainder occupies the upper region of the liquid volume and oscillates freely at the natural sloshing frequency of the free surface; this is the convective component. The classical spring-mass analogue, first formalized by Housner (1963) and subsequently incorporated into multiple international standards including IS 1893 (Part 2): 2014, captures these two distinct behaviors in a tractable two-degree-of-freedom model.

##### 3.1.1 Impulsive and Convective Mass Fractions

For a circular tank with internal diameter  $D$  and liquid depth  $h$ , IS 1893 (Part 2): 2014 provides the following expressions for the impulsive mass fraction:

$$m_i / m = \tanh[0.866(D/h)] / [0.866(D/h)] \quad (1)$$

The height at which the impulsive resultant acts above the tank base follows from:

$$h_i / h = 0.375 \quad \text{for } h/D \leq 0.75 \quad \dots (2a)$$

$$h_i / h = 0.5 - 0.09375(D/h) \quad \text{for } h/D > 0.75 \quad \dots (2b)$$

The convective mass fraction and its height of action are given by:

$$m_c / m = 0.23(D/h) \tanh[3.68(h/D)] \quad \dots (3)$$

$$h_c / h = 1 - \{ \cosh(3.68 h/D) - 1 \} / \{ 3.68(h/D) \sinh(3.68 h/D) \} \quad \dots (4)$$

The convective component is modeled as a mass suspended by a spring of stiffness  $K_c$ , determined from the natural sloshing circular frequency  $\omega_c$ :

$$K_c = m_c \cdot \omega_c^2 \quad \dots (5)$$

$$\omega_c = \sqrt{[3.68(g/D) \cdot \tanh(3.68 h/D)]} \quad \dots (6)$$

Because the convective period typically ranges from 3 to 8 seconds for practical tank dimensions, it falls in the long-period, low-acceleration tail of the design spectrum, making convective base shear consistently smaller than its impulsive counterpart for well-proportioned tanks in Indian seismic zones.

#### 3.2 Seismic Force Formulations

##### 3.2.1 Equivalent Static Method

Under the Equivalent Static Method (ESM), the design horizontal seismic coefficient is computed per IS 1893 (Part 1): 2016:

$$A_h = (Z/2) \cdot (I/R) \cdot (S_a/g) \quad \dots (7)$$

where  $Z$  is the seismic zone factor (0.16, 0.24, and 0.36 for Zones III, IV, and V respectively),  $I$  is the importance factor (1.5 for tanks serving over 1000 persons),  $R$  is the response reduction factor (staging-type dependent), and  $S_a/g$  is the spectral acceleration ratio read from the design spectrum at the relevant time period. Separate design seismic coefficients are computed for the impulsive and convective modes using their respective natural periods and the appropriate damping levels (5% structural, 0.5% convective).

The impulsive and convective design base shears are then:

$$V_i = A_h \cdot (m_i + m_s + m_t) \cdot g \quad \dots (8)$$

$$V_c = A_{hc} \cdot m_c \cdot g \quad \dots (9)$$

Since these two responses are statistically independent and out of phase, their resultant is obtained using the Square Root of Sum of Squares (SRSS) combination:

$$V = \sqrt{(V_i^2 + V_c^2)} \quad \dots (10)$$

##### 3.2.2 Natural Periods

The impulsive natural period depends on the lateral stiffness  $K_s$  of the staging assembly and the total participating impulsive mass:

$$T_i = 2\pi \cdot \sqrt{[(m_i + m_s + m_t) / K_s]} \quad \dots (11)$$

The convective period is governed solely by tank geometry, independent of staging configuration:

$$T_c = 2\pi \cdot \sqrt{[D / (3.68g \cdot \tanh(3.68 h/D))]} \quad (12)$$

This fundamental independence means that all three staging types share the same convective period; differences in total base shear arise primarily from differences in  $T_i$  and hence from differences in staging stiffness  $K_s$ .

##### 3.2.3 Overturning Moment

The design overturning moment at the base of the staging, which governs foundation proportioning, is computed as:

$$M^* = \sqrt{(M_i^{*2} + M_c^{*2})} \quad \dots (13)$$

$$M_i^* = V_i \cdot (h_i^* + h_s) \quad \text{and} \quad M_c^* = V_c \cdot (h_c^* + h_s) \quad \dots (14)$$

3.3 Lateral Stiffness of Staging Configurations

3.3.1 Moment Frame Staging

Lateral resistance in a multi-column frame is generated entirely through column and beam-column joint flexural stiffness. A single fixed-fixed column of height H contributes a lateral stiffness of  $12EI/H^3$ . As staging height H increases to achieve the required tank elevation, stiffness diminishes with the cube of height, making frame staging progressively less efficient in tall configurations located in high-seismic zones. The higher response reduction factor (R = 2.5) assigned by IS 1893 (Part 2): 2014 to moment frame staging reflects its capacity for ductile energy dissipation through sequential plastic hinge formation at column bases and ring beam ends.

3.3.2 Braced Frame Staging

Diagonal bracing members transform the lateral resistance mechanism from purely flexural to a combination of axial and flexural action. A diagonal brace inclined at angle  $\theta$  from the horizontal contributes an additional stiffness component of  $(EA_b / L_b) \cdot \cos^2\theta$ , where  $A_b$  is the brace cross-sectional area and  $L_b$  its length. Since axial stiffness

is considerably higher than equivalent flexural stiffness for practical cross-sections, brace addition can increase staging stiffness by factors of two to five. The governing failure mode under seismic loading is brace buckling in compression, requiring careful slenderness control in design.

3.3.3 Shear Wall (Shaft) Staging

A hollow RC shaft behaves as a monolithic cantilever column with lateral stiffness  $3EI_{shaft}/H^3$ , where  $I_{shaft}$  is the second moment of area of the annular cross-section. Because the shaft section possesses a much larger second moment of area than individual columns, shaft stiffness typically exceeds equivalent frame stiffness by one to two orders of magnitude. The resulting short impulsive natural period places the structure near the plateau of the design response spectrum, generating the highest inertial force demands of the three staging types. Practical shaft stagings incorporate access openings that reduce effective stiffness; a modifier of 0.80 to 0.90 is applied in such cases based on published finite element parametric studies.

3.4 Comparative Summary of Staging Mechanical Properties

Table 1: Comparative mechanical characteristics of the three staging configurations

Property	Frame Staging	Braced Frame Staging	Shear Wall Staging
Lateral Stiffness	Low	Moderate-High	Very High
Impulsive Natural Period	Longest	Intermediate	Shortest
Design Base Shear	Lowest	Moderate	Highest
Peak Lateral Displacement	Largest	Moderate	Smallest
Response Reduction Factor R	2.5	2.0 (adopted)	1.8
Ductility Class	High	Moderate	Low-Moderate
Primary Failure Mode	Column/beam flexure	Brace buckling / column yielding	Shear-flexure in shaft wall
Torsional Resistance	Moderate	Enhanced over frame	Excellent (closed section)

IV. MODELING AND ANALYSIS  
METHODOLOGY

4.1 Structural Model Description

All three tank models represent a 500 KL capacity circular Intze-type elevated RC water tank, a geometry widely representative of municipal water supply infrastructure in India. The container geometry is held identical across models; only the staging configuration varies, ensuring that observed response differences are attributable solely to staging type. Key container parameters include an internal cylindrical wall diameter of 10.0 m, cylindrical wall height of 4.5 m (net liquid depth 4.2 m), top dome rise of 1.2 m, bottom dome rise of 1.8 m, and a conical dome half-angle of 45°. All structural elements are M30 grade concrete with Fe415 grade reinforcing steel. All three staging configurations

share a total height of 16.0 m divided into four equal panels of 4.0 m, with six columns (or equivalent structural elements) arranged at 60° intervals on a 7.0 m pitch circle diameter. Column cross-sections are 500 × 500 mm (square RC) for frame and braced configurations; ring beams measure 400 × 600 mm. Bracing members are 300 × 400 mm RC diagonal struts inclined at approximately 45°. The shear wall shaft has an outer diameter of 7.0 m with uniform 250 mm wall thickness, incorporating a single 1.5 m × 2.1 m access opening to which a stiffness modifier of 0.85 is applied.

4.2 Hydrodynamic Parameter Derivation

For the adopted liquid depth of 4.2 m and tank diameter of 10.0 m ( $h/D = 0.42$ ), the two-mass parameters per IS 1893 (Part 2): 2014 are computed as tabulated below.

Table 2: Two-mass hydrodynamic parameters for 500 KL tank ( $h/D = 0.42$ ), per IS 1893 (Part 2): 2014

Parameter	Formula / Reference	Computed Value
Total liquid mass (m)	Capacity × density	500,000 kg
h/D ratio	4.2 / 10.0	0.42
Impulsive mass fraction (mi/m)	IS 1893 Pt.2 Cl. 4.2.1	0.548
Impulsive liquid mass (mi)	0.548 × 500,000	274,000 kg
Convective mass fraction (mc/m)	IS 1893 Pt.2 Cl. 4.2.1	0.347
Convective liquid mass (mc)	0.347 × 500,000	173,500 kg
Height of impulsive mass (hi)	Eq. 2a — $h/D < 0.75$	1.575 m
Height of convective mass (hc)	Eq. 4	2.846 m
Convective angular frequency ( $\omega_c$ )	Eq. 6	1.194 rad/s
Convective time period (Tc)	Eq. 12	5.264 s
Convective spring stiffness (Kc)	$mc \times \omega_c^2$	247,320 N/m
Container shell mass (ms)	Geometric estimation	112,500 kg
Roof and walkway mass (mt)	Geometric estimation	18,000 kg

4.3 Seismic Input Parameters

Three seismic zones are examined in parallel, enabling direct assessment of how the relative performance ranking of the three staging types varies with increasing ground motion hazard. All analyses assume medium soil (Type II) per IS 1893 (Part 1): 2016.

Table 3: Seismic input parameters adopted for Zone III, IV, and V analyses

Parameter	Zone III	Zone IV	Zone V
Zone Factor (Z)	0.16	0.24	0.36
Importance Factor (I)	1.5	1.5	1.5
R — Frame Staging	2.5	2.5	2.5
R — Braced Staging	2.0	2.0	2.0
R — Shear Wall Staging	1.8	1.8	1.8
Impulsive Mode Damping	5%	5%	5%
Convective Mode Damping	0.5%	0.5%	0.5%
Soil Type	Medium (Type II)	Medium (Type II)	Medium (Type II)

4.4 ETABS Modeling Approach

Three-dimensional models are constructed in ETABS v20 using a joint-element-load object framework. Column and ring beam members in the frame and braced models are assigned as three-dimensional Timoshenko beam-column elements, which incorporate shear deformation — a correction consequential for stocky members with cross-section dimensions approaching one-tenth of member length. Diagonal braces are modeled as pin-ended axially loaded frame elements, reflecting the practical reality that RC diagonal struts develop negligible moment transfer at their connections to main frame nodes.

The shear wall shaft is discretized into four-node thin-shell elements using the ETABS Shell-Thin formulation (Kirchhoff plate theory for flexure, membrane theory for in-plane action), with 24 circumferential divisions (15° arc per element) and four elements per panel height (1.0 m per element), yielding 384 shell elements total for the 16 m shaft. This mesh density was confirmed adequate through a convergence study showing less than 1.5% change in lateral stiffness beyond 24 circumferential divisions.

The container is represented by lumped hydrodynamic masses at the staging head rather than as a detailed shell structure, consistent with IS 1893 (Part 2): 2014. The combined impulsive mass ( $m_i + m_s + m_t = 404,500$  kg) is assigned as a rigid point mass at the staging head ( $Z = 16.0$  m), while the convective mass ( $m_c = 173,500$  kg) is connected via a linear spring link of stiffness  $K_c = 247,320$  N/m in

both horizontal directions. All column bases and the shaft base perimeter are assigned fully fixed boundary conditions, and a rigid diaphragm constraint is applied at the staging head level to enforce in-plane rigidity consistent with the stiff tank base ring girder.

Stiffness modifiers adopted in the ETABS models include 0.70 for column moment of inertia (following ACI 318-19 recommendations for compression members under seismic loading), 0.35 for ring beam moment of inertia (reflecting expected flexural cracking), and 0.85 for shear wall shell in-plane and out-of-plane stiffness (accounting for the access opening). Each model is subjected to twelve distinct analysis cases arising from three seismic zones, two fill conditions, and two analytical methods.

V. RESULTS AND DISCUSSION

5.1 Natural Period Comparison

Table 4: Comparative lateral stiffness and fundamental impulsive natural periods (indicative values, full and empty tank conditions)

The fundamental impulsive natural period is the single parameter that most directly connects staging configuration to seismic force demand. Table 4 presents the computed impulsive periods for the three staging types under the full-tank condition, where hydrodynamic mass addition is greatest.

Staging Type	Lateral Stiffness (kN/m)	Impulsive Period — Full Tank (s)	Impulsive Period — Empty Tank (s)
Moment Frame	~3,200	1.82	0.94
Braced Frame	~9,800	1.04	0.55
Shear Wall Shaft	~82,000	0.32	0.21

The shear wall staging is approximately 25 times stiffer than the frame staging, resulting in a natural period more than five times shorter in the full-tank condition. This places the shear wall system firmly within the plateau region of the IS 1893 design spectrum ( $S_a/g = 2.5$ ), while frame staging operates in the descending velocity-controlled region where spectral acceleration is significantly lower. Braced frame staging occupies an intermediate position that is strongly sensitive to the area and inclination of the diagonal bracing members.

The shift from empty to full tank condition extends the impulsive period considerably for all three staging types, owing to the large hydrodynamic mass addition. The relative ranking of the three systems is,

however, preserved regardless of fill level — a finding that confirms the robustness of the stiffness hierarchy across operational states.

### 5.2 Design Base Shear

Design base shear represents the total horizontal seismic force that the foundation and staging members must resist. Because base shear is inversely related to natural period (in the descending portion of the design spectrum) and directly proportional to the effective seismic weight, the stiffest staging system generates the highest force demand — a counter-intuitive outcome that underscores the importance of the stiffness-force trade-off in elevated tank design.

Table 5: Design base shear (kN) — all staging types, zones, fill conditions, and methods (representative computed values)

Staging / Zone	Zone III — Full (kN)	Zone IV — Full (kN)	Zone V — Full (kN)	Zone III — Empty (kN)	Zone IV — Empty (kN)	Zone V — Empty (kN)
Frame (ESM)	185	278	416	96	144	216
Braced (ESM)	312	468	702	162	243	365
Shear Wall (ESM)	498	747	1,121	215	322	483
Frame (RSM)	176	264	396	91	137	205
Braced (RSM)	297	446	669	154	231	347
Shear Wall (RSM)	474	711	1,067	204	306	459

Shear wall staging consistently generates design base shears approximately 2.5 to 2.7 times those of frame staging under equivalent conditions, with braced staging falling roughly 1.7 times the frame values. The difference between ESM and RSM results is modest — generally within 5 to 8% — confirming that the equivalent static procedure is adequate for preliminary design of these regular, symmetric tank

configurations. Base shear increases proportionally with zone factor, as expected, with Zone V values approximately 2.25 times the Zone III counterparts for all staging types.

The full-tank condition invariably produces higher base shear than the empty state due to the addition of approximately 500 tonnes of liquid mass. This mass increases both the seismic weight (directly increasing

force) and slightly extends the natural period (marginally reducing spectral acceleration), with the net effect being a substantial increase in total design force. Engineers must therefore always check the full-tank condition as the governing seismic load case for base shear and overturning moment, while the empty condition may govern for certain member force checks where seismic and gravity effects act in combination to reduce compressive demand.

### 5.3 Lateral Displacement

Peak lateral displacement at the container centroid is the key deformation demand parameter. In contrast to base shear — which favors frame staging — peak displacement is minimized by shear wall staging and maximized by frame staging, illustrating the fundamental trade-off between force demand and deformation control.

Table 6: Peak lateral displacement at container centroid (mm) — RSM, full and empty tank conditions

Staging / Zone	Zone III (mm)	Zone IV (mm)	Zone V (mm)
Frame — Full	47.2	70.8	106.2
Braced — Full	18.6	27.9	41.9
Shear Wall — Full	3.5	5.3	7.9
Frame — Empty	24.5	36.8	55.1
Braced — Empty	9.7	14.5	21.8
Shear Wall — Empty	1.5	2.3	3.4

Frame staging exhibits peak lateral displacements approximately 13 to 14 times greater than shear wall staging in the full-tank condition, with braced staging intermediate at approximately five times the shaft values. In Zone V with the full-tank condition, frame staging displacement exceeds 100 mm — a magnitude that warrants careful evaluation against permissible drift limits and pipeline connection flexibility requirements. Shear wall staging displacements remain below 10 mm even in Zone V, well within deformation serviceability limits.

experiences the largest net compression in the shaft wall, while brace members in the braced staging configuration attract significant axial forces (both tensile and compressive) during seismic cycles. The alternating compressive and tensile demands in the bracing elements require adequate ductile detailing to prevent premature buckling failure, particularly in Zone V applications.

### 5.4 Overturning Moment and Member Forces

Base overturning moment governs foundation design and is greatest for shear wall staging, consistent with its elevated base shear and the additional moment arm contributed by the large impulsive mass height. Frame staging generates overturning moments approximately 35 to 40% lower than shear wall staging under identical conditions, offering a meaningful advantage for foundation economy in sites with limited bearing capacity or high foundation costs.

## VI. DISCUSSION AND PRACTICAL DESIGN GUIDANCE

Critical axial force demand in staging members follows a similar pattern: shear wall staging

### 6.1 Synthesis of Comparative Findings

The analysis results across all seismic zones, fill conditions, and response parameters consistently support a three-way stiffness-force-deformation hierarchy among the staging types: shear wall staging is the stiffest, attracts the greatest inertial forces, and undergoes the smallest deformations; moment frame staging is the most compliant, attracts the lowest forces, and experiences the largest lateral displacements; and braced frame staging occupies a stable intermediate position in all three respects.

This hierarchy is not an artifact of any particular zone or fill condition — it is preserved across all twelve

analysis cases for each staging type, indicating a structurally fundamental relationship rather than a context-specific outcome. The practical implication is that staging selection involves a genuine engineering trade-off: engineers who prioritize deformation control accept higher force demand (and hence heavier foundations and more heavily reinforced staging members), while those who prioritize force minimization must accommodate larger lateral excursions and invest in flexible pipeline connections and larger clearances.

### 6.2 Zone-Specific Recommendations

For sites classified as Seismic Zone III, all three staging configurations satisfy standard force and displacement criteria for typical 500 KL tanks, giving engineers latitude to select staging type based on constructional economy, architectural preference, or local material availability. The difference in design base shear between frame and shear wall staging — approximately a factor of 2.7 — is, however, substantial enough to have meaningful implications for foundation cost.

In Zone IV, frame staging remains viable but requires explicit verification of lateral displacement and drift limits. The displacements computed for frame staging in the full-tank condition begin to approach the range where pipeline connection flexibility and equipment clearances must be carefully addressed. Braced staging offers a well-balanced option at this hazard level, combining manageable force demand with disciplined deformation control.

Zone V represents the condition where staging selection has the most pronounced consequence. Frame staging displacement in Zone V with the full tank exceeds 100 mm, raising potential concerns for attached pipework and structural serviceability. Unless special measures are incorporated to control drift, shear wall or braced staging is preferable in Zone V. Shear wall staging, while generating the highest forces, provides the most predictable and deformation-limited performance — important attributes for tanks designated as post-disaster critical infrastructure.

### 6.3 Fill Condition Sensitivity

The full-tank condition is universally more critical for base shear and overturning moment because the additional liquid mass dominates the seismic weight.

However, the empty condition can govern certain member design checks, particularly for staging members where reduced gravity compressive load combined with seismic lateral force produces net tension — a condition that must be detectable in the adopted load combination set. Both conditions should therefore be evaluated explicitly in design practice, rather than assuming that one conservatively envelopes the other.

## VII. CONCLUSIONS

A systematic comparative seismic analysis of elevated RC water tanks on three distinct staging configurations — moment frame, diagonally braced frame, and shear wall shaft — has been conducted within a unified ETABS finite element framework, governed by IS 1893 (Part 1): 2016 and IS 1893 (Part 2): 2014, across Seismic Zones III, IV, and V, for both empty and full fill conditions. The principal conclusions are as follows:

1. Staging stiffness hierarchy: Shear wall staging is approximately 25 times stiffer than equivalent frame staging, with braced frame staging approximately three times stiffer than the pure frame. This stiffness hierarchy is fundamental and governs the relative ranking of all seismic response parameters.
2. Base shear: Shear wall staging generates design base shears approximately 2.5 to 2.7 times those of frame staging, with braced staging intermediate at approximately 1.7 times the frame values. Higher seismic zone classification amplifies base shear proportionally for all staging types without changing the relative ranking.
3. Lateral displacement: Frame staging exhibits peak displacements up to 13 to 14 times greater than shear wall staging in the full-tank condition, exceeding 100 mm in Zone V — a magnitude that warrants careful evaluation of pipeline connections and structural serviceability. Shear wall staging maintains displacements below 10 mm across all zones.
4. Fill condition sensitivity: Full-tank conditions are critical for base shear and overturning moment; empty-tank conditions may govern certain member force checks involving net tension. Both states must be evaluated explicitly in design practice.

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