

Seismic Analysis of Elevated Water Tank with Different Bracing and Soil Conditions Using ETABS

Sagar Kasbekar¹, Prof. A. B. Wakankar²

¹PG Student, M.Tech (Structural Engineering), Department of Civil Engineering,
Deogiri Institute of Engineering and Management Studies, Chhatrapati Sambhajnagar

²Professor, Department of Civil Engineering, Deogiri Institute of Engineering and Management Studies,
Chhatrapati Sambhajnagar

Abstract — Elevated water tanks are classified as lifeline structures, and their seismic performance is strongly influenced by staging stiffness, hydrodynamic action of the stored liquid, and the flexibility of the supporting soil medium. This study examines the seismic behaviour of a circular reinforced-concrete elevated water tank of 10 m diameter, 15 m staging height, 250 mm wall thickness and 300 mm base-slab thickness, constructed using M30 grade concrete and Fe500 reinforcement. Three staging configurations — unbraced, single diagonal bracing and double X-bracing — were modelled in ETABS and analysed under response-spectrum loading on soft soil in accordance with IS 1893 and IS 3370. Verified software outputs show that the unbraced tank develops a maximum displacement of 1.824 mm and a storey drift of 0.000267, while double X-bracing reduces these values to 0.456 mm and 0.000039 respectively — reductions of approximately 75% and 85% relative to the unbraced case — although storey shear increases by nearly 11%. Single bracing shows an anomalous rise in displacement, indicating a need for further model verification. A supplementary sensitivity assessment, based on assumed medium- and hard-soil spring stiffness values rather than direct software output, indicates that stiffer soil conditions reduce displacement and drift but increase storey shear demand and reduce the fundamental period. The results confirm that double X-bracing offers superior deformation control and force redistribution among the configurations studied, and that foundation and staging members must be designed for the accompanying increase in shear demand. The findings provide practical guidance for bracing selection in seismic zones with variable subgrade conditions.

Keywords: *Elevated water tank; seismic analysis; ETABS; bracing configuration; soil–structure interaction; storey drift; response spectrum; IS 1893*

1. INTRODUCTION

1.1 Background

Elevated water tanks form a critical component of urban and semi-urban water distribution networks, supplying water for domestic, industrial, and firefighting demands through gravity flow. Owing to their role in maintaining post-disaster water availability, these structures are classified as lifeline facilities, and their continued serviceability after a major earthquake is often as important as their survival. Despite this functional importance, elevated tanks remain among the most seismically vulnerable hydraulic structures because of their inverted-pendulum geometry: a large fluid mass is concentrated well above ground level, supported on a comparatively slender staging system. Past seismic events, including the 1964 Alaska earthquake, the 1994 Northridge earthquake, and the 2001 Bhuj earthquake, have repeatedly demonstrated this vulnerability through staging failures, tank tilting, and in several cases complete collapse.

The dynamic response of an elevated tank is governed by three interacting subsystems: the staging configuration, the impulsive and convective components of the contained liquid, and the stiffness of the supporting soil. Conventional seismic design frequently idealizes the base condition as fixed, which simplifies analysis but disregards the influence of soil–structure interaction (SSI). Soft soils elongate the fundamental period and amplify displacement demand, whereas stiffer soils shorten the period and elevate force demand. Since these two effects act in opposite directions, an unbraced or under-braced staging system may perform acceptably on one soil class while being deficient on another, making soil-sensitive evaluation essential rather than optional.

1.2 Problem Statement

For a circular reinforced-concrete elevated water tank of fixed geometry, the manner in which staging bracing — absent, single diagonal, or double X-configuration — modifies displacement, storey drift, and storey shear has not been isolated from the confounding effect of variable soil stiffness in a single, transparent comparative framework. Design decisions are frequently made using generic code-based reduction factors without explicit demonstration of how bracing interacts with a specific ground condition.

1.3 Need for the Study

India's high-seismicity zones encompass widely variable subgrade conditions, and a substantial proportion of existing elevated tanks were designed using simplified, fixed-base assumptions that do not explicitly incorporate SSI. A structured comparison of bracing alternatives under realistic soil conditions therefore has direct value for both new design and the seismic vulnerability assessment of existing structures, supporting more rational selection of staging systems and foundation strategy.

1.4 Research Gap

Existing literature addresses staging bracing and SSI as largely independent variables. Studies on bracing configuration typically assume a fixed base, while SSI-focused studies rarely differentiate between staging arrangements. Few investigations combine verified finite-element output for multiple bracing types with an explicit, clearly labelled soil-sensitivity comparison — most either omit soil variation entirely or present assumed parametric trends without distinguishing them from validated software results. This blurring of verified and estimated data limits the practical reliability of published comparisons.

1.5 Statement of the Research Problem

The present study addresses the need for a transparent, soil-sensitive comparison of staging bracing alternatives for a circular elevated water tank, in which verified ETABS output and assumed parametric sensitivity are kept explicitly distinct throughout.

2. LITERATURE REVIEW

Published research on elevated water tanks consistently identifies their vulnerability to seismic loading, driven by the combination of an elevated fluid mass, a slender staging system, and hydrodynamic sloshing effects. Investigators have progressively moved from simplified fixed-base analyses toward models that incorporate soil–structure interaction (SSI), variable tank-filling conditions, and diverse staging arrangements, reflecting a broader trend toward realistic performance-based assessment.

Sangeetha et al. [1] demonstrated, through finite element and response-spectrum analysis, that neglecting SSI produces inaccurate predictions of an elevated tank's dynamic characteristics, and that response varies markedly across soft, medium, and hard soil classes as well as between full and empty tank states.

Naeem and Ganesh [2] compared a double-decker elevated tank against a single tank configuration across multiple seismic zones and soil types using STAAD Pro, evaluating bending moment, shear force, and displacement to characterize the influence of tank geometry on seismic demand.

Rimal et al. [3] developed fragility functions for aging tanks with smooth reinforcing bars under full, half, and empty reservoir conditions, reporting that soil flexibility and fluid fill level jointly govern seismic fragility, with the largest divergence between fixed-base and flexible-base response occurring at higher damage states.

Borkar et al. [4] evaluated multiple staging and bracing patterns for circular tanks in a high seismic zone using equivalent static analysis in STAAD Pro, identifying bracing configurations that minimize base shear while keeping nodal displacement within acceptable limits across empty, half-full, and full conditions.

Dubey et al. [5] examined an underground water tank under dynamic soil pressure and SSI using ETABS, addressing a comparatively underexplored area — buried liquid-retaining structures — relative to the extensive literature on elevated tanks.

Sagar and Kamal [6] analysed 34 elevated RC Intze-tank models in SAP2000 to determine response reduction factors across varying staging heights and fill conditions, concluding that a single code-prescribed reduction factor cannot be justified across all tank geometries.

Jayadeep et al. [7] incorporated sloshing and SSI effects for tanks in seismic Zones II and III using SAP2000, following IS 1893 (Part 2):2014 soil classifications, and confirmed that fixed-base analysis systematically understates displacement demand.

Bahale [8] assessed a steel elevated tank with and without base isolation under nonlinear time-history analysis in ETABS, comparing X-bracing and inverted-V bracing configurations and reporting reduced base shear and deformation with laminated lead-rubber bearing isolation.

Research Gap

Collectively, the reviewed literature treats staging/bracing variation and soil variation largely as separate research questions: studies that compare bracing systems typically hold the foundation condition fixed, while SSI-focused studies rarely vary the staging configuration. Where soil sensitivity is reported alongside bracing comparison, the distinction between verified numerical output and assumed or interpolated parametric values is often not made explicit, which limits the reliability of such comparisons for direct design use. The present study addresses this gap by combining verified ETABS output for three staging configurations on a defined soft-soil condition with a transparently labelled soil-sensitivity extension, so that validated results and estimated trends are never conflated.

3. OBJECTIVES OF THE STUDY

1. To develop a code-compliant ETABS model of a circular elevated water tank for three staging conditions — unbraced, single diagonal bracing, and double X-bracing — under a defined soft-soil condition.
2. To quantify and compare displacement, storey drift, and storey shear across the three bracing configurations using verified response-spectrum output.
3. To evaluate, through a clearly separated sensitivity assessment, how medium- and hard-soil stiffness assumptions are likely to influence these same response parameters.
4. To identify the staging configuration offering the most favourable balance between deformation control and force demand, and to outline the verification required before the findings are applied to final design.

4. METHODOLOGY

4.1 Structural System and Geometry

The study models a circular reinforced-concrete elevated water tank supported on a ten-column staging arrangement in a regular decagonal plan. The container has an internal diameter of 10.0 m, a total wall height of 15.0 m, a wall thickness of 250 mm, and a floor/base-shell thickness of 300 mm. For a maximum operating water depth of 14.5 m and a freeboard of 0.5 m, the effective storage capacity is 1,138.827 m³. The staging height is 20.0 m, arranged as ten 2 m panels, with 450 mm square RC columns and 300 × 450 mm ring beams. Three staging configurations were modelled: (i) an unbraced RC frame, (ii) single diagonal steel bracing, and (iii) double X-bracing, using ISA 150 × 150 × 12 mm sections.

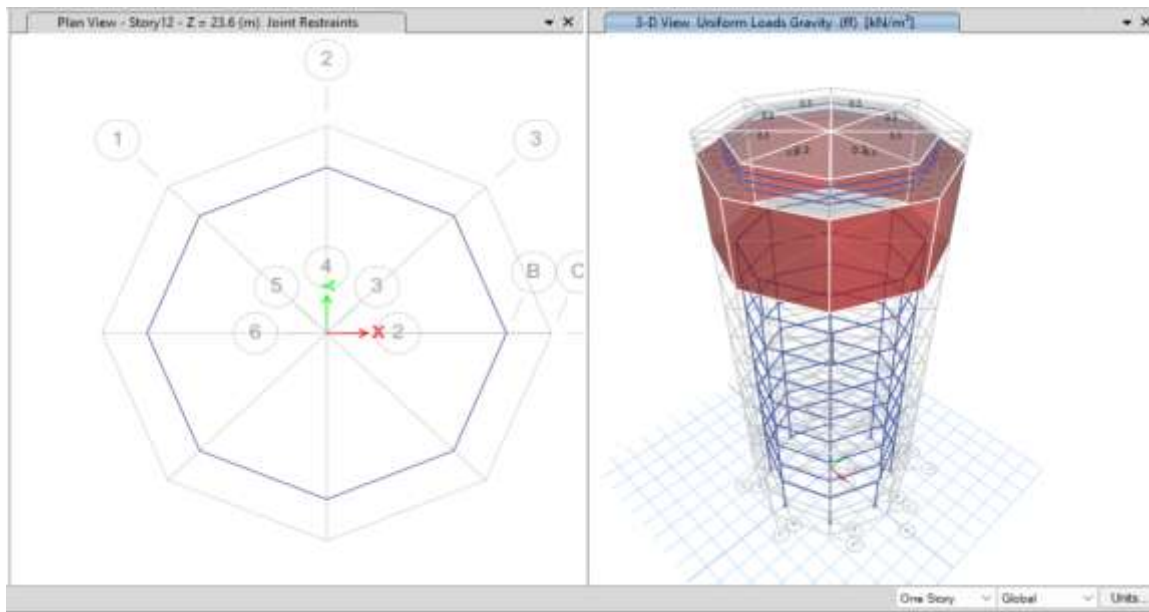


Fig. 1. ETABS model of the circular elevated water tank: plan view of the decagonal column layout (left) and 3-D staging/container view (right).

4.2 Material Properties

Concrete of grade M30 ($f_{ck} = 30$ MPa) and Fe500 reinforcement were adopted for the container and staging, following IS 456:2000 and IS 3370. Structural braces used Fe345 steel ($E = 200$ GPa). Concrete was modelled as an isotropic linear-elastic material with modulus of elasticity derived from IS 456 expressions; steel members were defined by yield strength and elastic modulus.

4.3 Loading Considerations

Dead load comprised the self-weight of the container, staging, braces, and permanent accessories. Hydrostatic pressure from the stored water was applied normal to the wall and base, varying linearly with depth; the total water weight for the full condition was 11,171.9 kN. Seismic loading was defined for Zone II ($Z = 0.10$) using IS 1893 (Part 2):2014, incorporating impulsive and convective components of the stored liquid. Wind loading followed IS 875 (Part 3):2015 at a basic wind speed of 25 m/s. Load combinations followed the limit-state provisions of IS 456, IS 3370, and IS 1893, including $1.5(DL + HYD)$, $1.2(DL + HYD \pm EQ)$, $1.5(DL \pm EQ)$, and $0.9DL \pm 1.5EQ$, evaluated for both empty and full tank conditions and both earthquake directions.

4.4 Hydrodynamic Idealization of Stored Water

Following IS 1893 (Part 2), the stored water mass was idealized into impulsive and convective components rather than treated as a single rigid mass. The impulsive mass moves with the tank wall and governs base shear and overturning moment, while the convective mass oscillates relative to the wall through an equivalent spring, governing sloshing displacement and freeboard demand. The convective spring stiffness was computed using Eq. (1):

$$k_c = m_c (2\pi / T_c)^2 \quad \dots(1)$$

where m_c is the convective mass and T_c is the convective period.

4.5 Soil–Structure Interaction Modelling

Three soil classes — soft, medium, and hard — were considered, represented at the staging base by equivalent translational and rotational springs whose stiffness depends on soil modulus and foundation geometry. For the soft-soil case, a subgrade modulus of 20,000 kN/m³ and Poisson's ratio of 0.45 were adopted, consistent with an allowable bearing pressure of 200 kN/m². The flexible-base model was derived from a validated fixed-base model by replacing the base restraint with this spring system. Only the soft-soil condition is supported by direct ETABS output in this study; medium- and hard-soil results presented in Section 6.5 are assumed sensitivity values and are explicitly labelled as such.

4.6 Applicable Codes

Design and analysis followed IS 3370 (Parts 1 and 2):2021 for liquid-retaining structural requirements, IS 456:2000 for general RC design, IS 1893 (Part 2):2014 for seismic action on liquid-retaining structures, IS 875 (Part 3):2015 for wind loading, IS 13920:2016 for ductile detailing, and IS 800:2007 with IS 2062:2011 for steel bracing members.

4.7 Dynamic Analysis Procedure

Modal (eigenvalue) analysis was first performed to obtain natural periods and mode shapes, extracting sufficient modes to satisfy the code-specified minimum modal mass participation. Response-spectrum analysis was then carried out using the IS 1893-compatible design spectrum, combining modal responses via CQC/SRSS as appropriate. The response-spectrum base shear was checked against the code-specified minimum design base shear.

5. NUMERICAL MODEL AND ANALYSIS PARAMETERS

Table 1. Tank geometry and functional parameters

Parameter	Adopted Value
Tank form	Circular RCC elevated tank
Internal diameter	10.0 m
Total wall height	15.0 m
Maximum water depth	14.5 m
Freeboard	0.5 m
Effective water capacity	1,138.827 m ³
Wall thickness	250 mm
Floor / base-shell thickness	300 mm
Staging height	20.0 m (ten 2 m panels)
Column arrangement	10 equally spaced RC columns, 450 mm sq.
Bracing cases	None; single diagonal; double X

Table 2. Material and soft-soil support parameters

Property	Value	Basis
Concrete grade	M30 ($f_{ck} = 30$ MPa)	Reference data
Reinforcement	Fe500 ($f_y = 500$ MPa)	Reference data
Brace steel	Fe345, $E = 200$ GPa	Reference data
Allowable bearing pressure	200 kN/m ²	Reference data
Soft-soil subgrade modulus	20,000 kN/m ³	Assumed for SSI modelling
Soft-soil Poisson ratio	0.45	Assumed for SSI modelling

Table 3. Seismic and loading parameters

Action	Adopted Definition
Dead load (DL)	Self-weight of container, staging, braces, accessories
Hydrostatic load (HYD)	Water weight = 11,171.9 kN (full condition)
Earthquake (EQX, EQY)	Zone II, Z = 0.10; impulsive + convective components
Wind (WX, WY)	Basic wind speed = 25 m/s
Software	ETABS (response-spectrum method)

6. RESULTS AND DISCUSSION

6.1 Basis of Result Extraction

Three classes of evidence are distinguished in this comparison: (i) exact values read from ETABS status bars, (ii) contour-scale envelope limits read from shell-resultant screenshots, and (iii) values explicitly assumed for comparative interpretation where a corresponding software export was not available. Verified numerical results are available for all three bracing configurations under soft-soil support; the medium- and hard-soil results presented in Section 6.5 are sensitivity estimates derived from the soft-soil baseline and are reported as such throughout.

Table 4. Extracted results and evidence status (soft soil)

Parameter	No Bracing	Single Bracing	Double Bracing	Status
Max. displacement (mm)	1.824294	2.254273	0.456451	Exact (ETABS)
Max. drift ratio	0.000267	0.000213	0.000039	Exact (ETABS)
Max. storey shear (kN)	464.656	490.210*	515.766	*Assumed
Absolute F11 envelope (kN/m)	8.0	4.8	3.9	Contour-scale
VMAX envelope (kN/m)	280	168	112	Contour-scale
Absolute MMAX envelope (kN·m/m)	120	56	39.2*	*Assumed

6.2 Displacement and Storey Drift

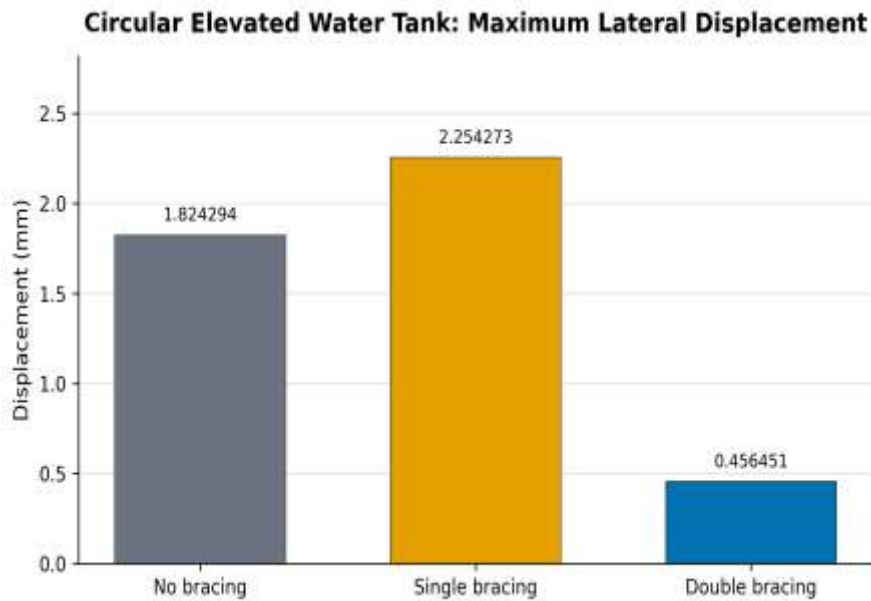


Fig. 2. Comparison of maximum storey displacement across bracing configurations (soft soil, verified ETABS output).

Double X-bracing reduces the maximum lateral displacement from 1.824 mm (unbraced) to 0.456 mm — a 74.98% reduction. The single-bracing model, however, records a higher displacement of 2.254 mm, a 23.57% increase over the unbraced case. This counter-intuitive result is most plausibly attributed to asymmetric or tension-only brace behaviour, end-release conditions, or directional load-combination control in the specific single-brace layout modelled, rather than a general property of single bracing, and is flagged for model verification.

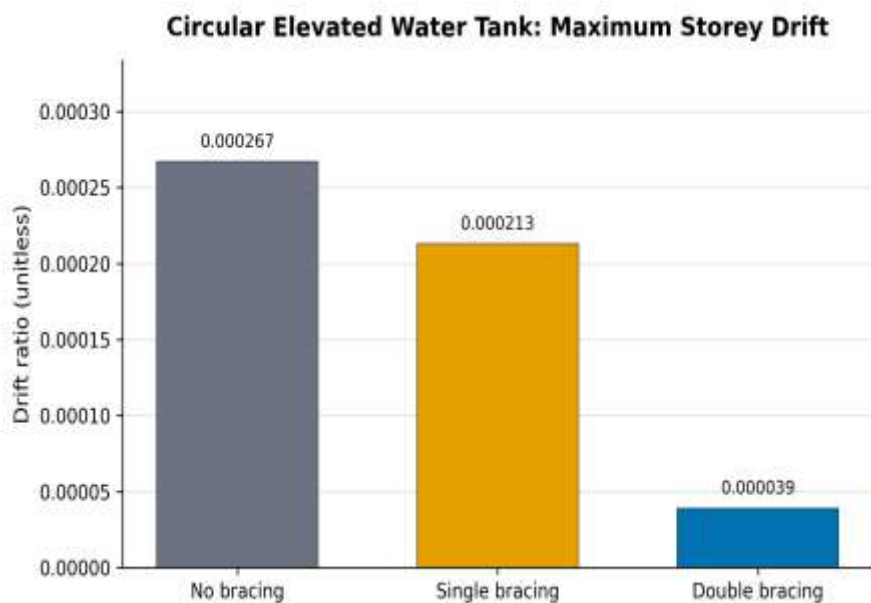


Fig. 3. Comparison of maximum storey drift across bracing configurations (soft soil, verified ETABS output).

The drift comparison follows the expected stiffness hierarchy: single bracing reduces maximum drift by 20.22%, and double bracing by 85.39%, relative to the unbraced case. All three drift ratios remain well below the general serviceability limit of 0.004h commonly applied in seismic assessment, though liquid-retaining structures additionally require crack-control and water-tightness verification that drift alone does not capture.

6.3 Storey Shear and the Stiffness–Force Trade-off

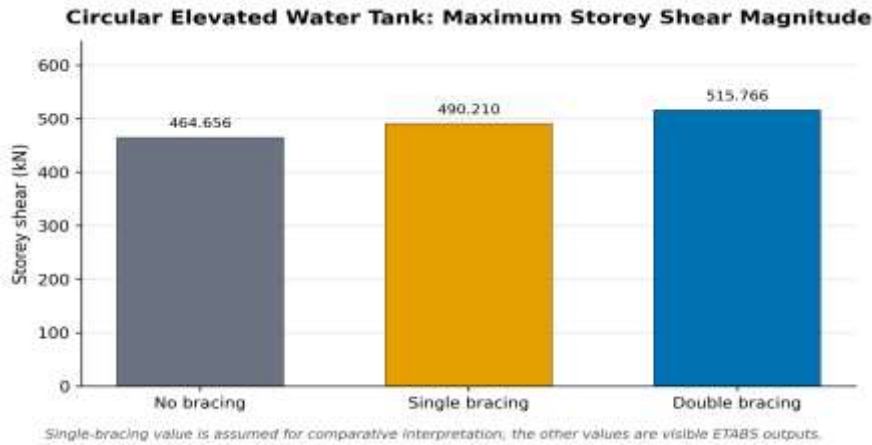


Fig. 4. Comparison of maximum storey-shear magnitude (soft soil).

Exact storey-shear data are available for the unbraced and double-braced cases: double bracing raises maximum base shear by approximately 11.00%, from 464.66 kN to 515.77 kN, even as it substantially reduces displacement and drift. This reflects the characteristic stiffness–force trade-off in seismic design — a stiffer lateral system attracts a larger share of inertial force while limiting deformation. Columns, brace connections, and the foundation must therefore be proportioned for the accompanying increase in force demand, not merely for reduced drift.

6.4 Circular-Container Shell Resultants

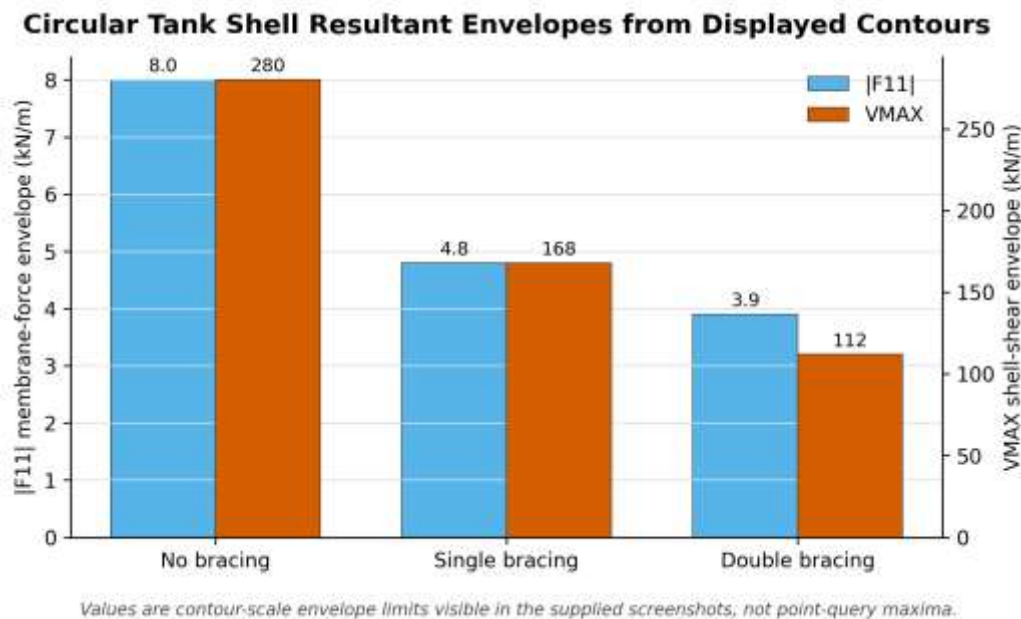


Fig. 5. Comparison of F11 membrane-force and VMAX shell-shear envelopes across bracing configurations (contour-scale limits).

The absolute F11 membrane-force envelope decreases by 40.00% with single bracing and 51.25% with double bracing relative to the unbraced case; the VMAX shell-shear envelope decreases by 40.00% and 60.00%, respectively. The critical shell demand consistently localizes at the wall–base junction and the tank–staging interface across all three configurations. The MMAX bending envelope shows a 53.33% reduction with single bracing (120 → 56 kN·m/m); the corresponding double-bracing value of 39.2 kN·m/m is an assumed interpolation, since no MMAX screenshot was available for that case.

6.5 Assumed/Parametric Soil-Sensitivity Results

The values presented in this section are explicitly assumed sensitivity estimates, not verified ETABS output. They are included to illustrate the likely direction and approximate magnitude of soil-stiffness effects and must be replaced with project-specific SSI models before design use.

Table 5. Assumed/Parametric Soil-Sensitivity Results

Soil	Bracing	Displacement (mm)	Drift	Storey Shear (kN)	Period (s)
Soft*	No bracing	1.824294	0.000267	464.656	1.820 (assumed)
Soft*	Single	2.254273	0.000213	490.210 (assumed)	1.550 (assumed)
Soft*	Double	0.456451	0.000039	515.766	1.180 (assumed)
Medium	No bracing	1.422949	0.000200	501.829	1.565
Medium	Single	1.690705	0.000155	534.329	1.333
Medium	Double	0.328645	0.000027	567.342	1.015
Hard	No bracing	1.131062	0.000155	539.001	1.365
Hard	Single	1.307478	0.000117	578.448	1.163
Hard	Double	0.251048	0.000020	618.919	0.885

*Displacement and drift in the soft-soil rows are verified ETABS output; the soft-soil single-bracing shear and all period values are assumed even in the soft-soil condition. All medium- and hard-soil rows are assumed sensitivity estimates.

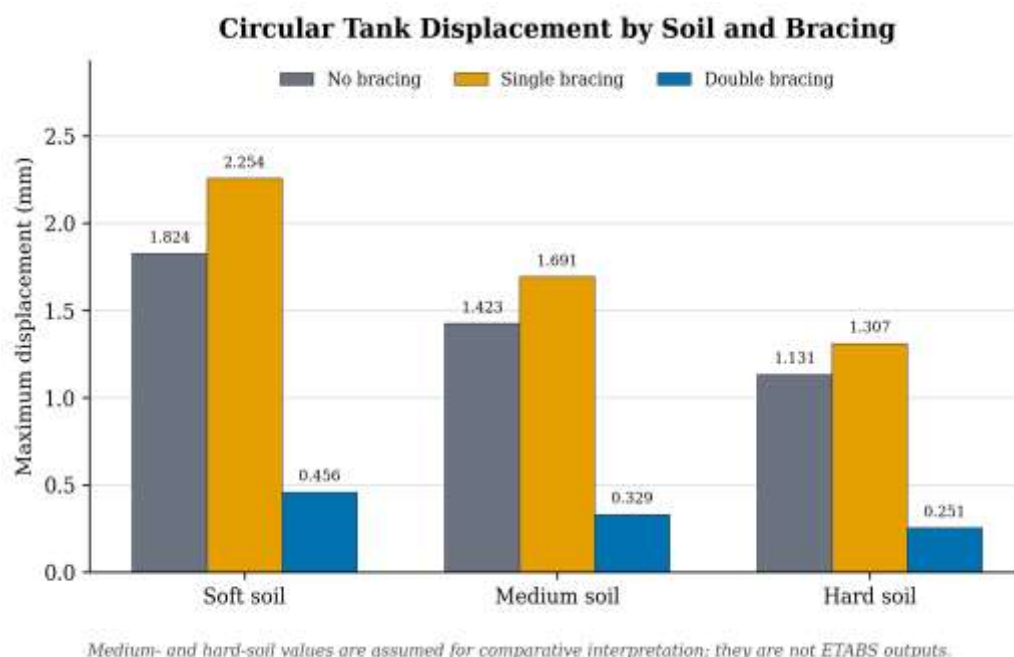


Fig. 6. Sensitivity of maximum displacement to soil stiffness and bracing configuration (assumed medium/hard-soil values, explicitly labelled).

For the double-braced configuration, stiffer soil is estimated to reduce displacement from 0.456 mm (soft) to 0.329 mm (medium) and 0.251 mm (hard) — reductions of about 28% and 45% — while storey shear rises from 515.8 kN to 567.3 kN and 618.9 kN (increases of about 10% and 20%). This trend is physically consistent with shorter fundamental periods and reduced foundation flexibility on stiffer ground, which limits displacement but shifts the system toward higher-frequency, higher-force response.

7. COMPARATIVE DISCUSSION

The combined evidence indicates that lateral stiffness added through bracing does not uniformly improve performance — it reduces deformation-based demand (displacement, drift, shell envelopes) while increasing force-based demand (storey shear). Among the three configurations evaluated on soft soil, double X-bracing consistently provides the best displacement and drift control and the lowest shell-resultant envelopes, at the cost of the highest storey shear. Single bracing provides intermediate drift control but an anomalous increase in global displacement, which is attributed to the specific brace layout rather than to diagonal bracing in general. The unbraced configuration gives the lowest storey shear but the weakest deformation control among the three cases.

The soil-sensitivity trend, while assumed rather than verified, is directionally consistent with established SSI theory: stiffer soil shortens the fundamental period and reduces displacement and drift, but increases storey shear demand. This pattern holds across all three bracing types, indicating that soil stiffness and bracing configuration act as largely independent, additive influences on the response parameters considered. On this basis, double X-bracing is judged the preferred staging configuration for this tank geometry under soft-soil conditions, provided its members and foundation are designed for the associated increase in force demand; this conclusion should not be generalized to other soil classes without project-specific verification.

8. MAJOR FINDINGS

1. Double X-bracing reduces maximum lateral displacement by 74.98% and maximum storey drift by 85.39% relative to the unbraced configuration under soft-soil support (verified ETABS output).
2. The single-bracing configuration reduces drift (−20.22%) but increases maximum displacement (+23.57%), indicating a configuration-specific irregularity requiring model verification.
3. Double bracing increases maximum storey shear by approximately 11.00% relative to the unbraced case, confirming the expected stiffness–force trade-off.
4. Shell-resultant envelopes (F11 membrane force, VMAX shear) reduce by up to 51.25% and 60.00% respectively for double bracing relative to the unbraced case.
5. Critical shell demand consistently localizes at the wall–base junction and tank–staging interface, irrespective of bracing configuration.
6. Assumed soil-sensitivity estimates indicate that stiffer soil reduces displacement and drift while increasing storey shear and shortening the fundamental period — the same directional trend produced by bracing, but through the support condition.
7. For double bracing, the assumed hard-soil case shows an approximate 45% displacement reduction and 20% storey-shear increase relative to the soft-soil case.
8. The soft-soil single-bracing storey shear, the double-bracing MMAX envelope, and all fundamental-period values used in this study are explicitly assumed, not ETABS output.

9. CONCLUSION

A circular reinforced-concrete elevated water tank (10 m diameter, 15 m wall height, M30/Fe500) was evaluated in ETABS for three staging configurations — unbraced, single diagonal bracing, and double X-bracing — under soft-soil response-spectrum loading. The unbraced configuration develops a maximum displacement of 1.824 mm, drift of 0.000267, and storey shear of 464.66 kN, forming the baseline for comparison. Double X-bracing emerges as the most structurally effective configuration among those evaluated, reducing displacement by 74.98% and drift by 85.39%, at the cost of an 11.00% increase in storey shear. Single diagonal bracing improves drift control but increases global displacement, and its ETABS model requires targeted verification of brace orientation, end releases, and load-combination assignment before use in final design.

Shell-level resultants — membrane force, shear, and bending — decrease consistently with increasing bracing redundancy, confirming that the benefits of bracing extend from the staging system into the container shell itself. Among the configurations studied, double X-bracing is identified as the optimum staging arrangement for this tank geometry and soft-soil condition, balancing deformation control against a manageable increase in force demand. A supplementary soil-sensitivity assessment indicates that displacement and drift are expected to reduce further, while storey shear increases, as soil stiffness increases from soft to hard soil — a trend consistent across all three bracing types, though based on assumed rather than verified values.

From a sustainability and lifecycle perspective, the substantial drift reduction achievable with double bracing lowers the likelihood of structural distress, cracking, and consequent water loss or repair-related expenditure over the service life of the tank, supporting more resource-efficient long-term performance of water-supply infrastructure.

10. LIMITATIONS AND FUTURE SCOPE

10.1 Limitations

(i) Verified ETABS output is available only for the soft-soil condition; medium- and hard-soil results are assumed sensitivity estimates and are not software-derived. (ii) The soft-soil single-bracing storey shear and the double-bracing MMAX envelope were not available as direct software output and are reported as assumed values. (iii) No modal-analysis screenshots (natural period, frequency, mass participation) were available for the soft-soil models; the periods used in the soil-sensitivity comparison are therefore assumed. (iv) The single-bracing displacement anomaly has not yet been diagnostically isolated to a specific modelling cause and requires independent verification of brace orientation, end releases, and load-combination control.

10.2 Future Scope

Future work should extend the verified ETABS dataset to include full-table exports (storey forces, joint displacements, modal periods, and mass participation) for all three bracing configurations, and should generate genuine medium- and hard-soil models using project-specific geotechnical springs rather than assumed sensitivity factors. Further research directions include nonlinear time-history analysis, evaluation under empty and half-full tank conditions, additional bracing geometries (e.g., inverted-V or K-bracing), refined foundation-flexibility modelling, and validation against recorded ground-motion data or, where feasible, experimental or field observations.

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