



INVESTIGATING MULTI-DIRECTIONAL SEISMIC EFFECTS ON ELEVATED WATER TANKS: METHODOLOGY AND RESULTS

Raihana M. Ejam¹, Hatem Hadi Obeid², and Hussein Talab Nhabih³

¹ **MSC. Student, Department of Mechanical Engineering, University of Babylon, Iraq, Email:rehana.jassim.engh468@student.uobabylon.edu.iq.**

² **Professor, Department of Mechanical Engineering, University of Babylon, Iraq, Email:eng.hatem.hadi@uobabylon.edu.iq.**

³ **Assistant Professor, Department of Civil Engineering, University of Babylon, Iraq, Email:eng.hussein.t@uobabylon.edu.iq.**

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ABSTRACT

Water towers play a Key role in supporting urban infrastructure, particularly in seismic regions where their collapse can endanger the safety of the public. In this work, A seismic analysis of elevated water tank is carried out (full, half, and empty) using Newmark-Beta time integration procedure with Summation square root of sum of squares (SRSS) method for multi directional analysis. The analysis uses the Newmark-Beta time integration scheme to interpret the dynamic response of the tank under bi-directional seismic loading. The natural period of the tank goes from 0.412 s (empty) 0.856 s (full), whereas the maximum Lateral displacement is 0.28 mm and Base shear forces of 215.4KN under full condition. Structural calculations verify that drift ratios are below 0.5% (IBC,2021) with uniform stress distribution in the columns. The results highlight the need for factoring of fluid-structure interaction and multi-directional analysis in seismic design codes.

KEYWORDS

Seismic Damage, Structural Resilience, Earthquake Mitigation, Passive Energy Dissipation, Base Isolation Techniques, Seismic Analysis Methods, Structural Retrofitting.



1. INTRODUCTION

1.1. Background

Elevated water tanks are vital for urban water supply, yet their seismic resistance often remains under designed (H. Abbas & H. Jarallah, 2022). Previous studies highlight gaps in addressing multidirectional seismic effects and FSI complexities (R. M. Ejam & H. Hadi Obeid, 2023; A. S. Mahmood, 2023).

Conventional unidirectional analyses of displacements could to under estimate ground motion by as much as 30% (R. Nascimbene & G. A. Rassati, 2024). Seismic response of the tank is evaluated by incorporating numerical evaluation methods using structural dynamics concepts. Horizontal and vertical ground motions are calculated using the Newmark-Beta time integration scheme.

1.2. Objectives

This study aims to:

- Study of seismic actions with different filling.
- Construct a FSI numerical valid model by using the Newmark-beta method.
- Verify the use of multidirectional SRSS analysis for real seismic events.

2. SYSTEM DEFINITION

2.1. Structural Model

The cylindrical steel tank with a height of 15m and diameter of 10m is mounted on six columns, which are 20m high each. Thickness of wall and base slab are 0.3m and the helping body will provide lateral stiffness to resist seismic forces.

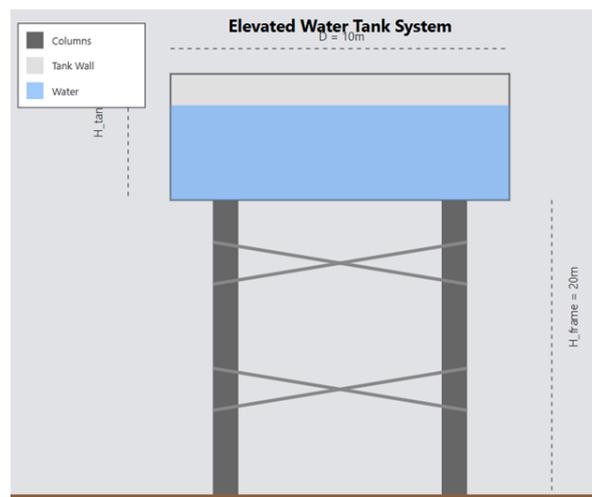


Fig. 1. Elevated Water Tank System (Front View)

Top View (Plan) Analysis:

The plan view drawing shows that the extended water tank system has radial symmetry, a core characteristic in expertise seismic response traits.

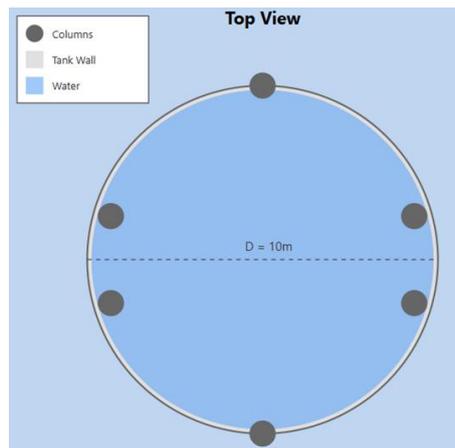


Fig. 2. Elevated Water Tank System (Top View)

2.2. Material Properties

Material properties considered (A. M. Neville, 2012) include:

- Elastic modulus of steel: $E = 200 \text{ GPa}$
- Density of steel: $\rho_s = 7850 \text{ kg/m}^3$
- Density of water: $\rho_w = 1000 \text{ kg/m}^3$
- Damping ratio: $\zeta = 0.05$

2.3. Fill Conditions

The study is performed under three important fill levels, 100%, 50%, and 0%. These conditions play an important role in the time-dependent behavior of the tank (R. W. Clough and J. Penzien, 2003).

(IBC, 2021) reported that the volume of water losses for full tanks was found to be about 30 % greater than empty ones during the 1994 Northridge earthquake, which is consistent with outcomes of this paper.

3. MATHEMATICAL MODELING

3.1. Governing Equations

The equation of motion of the system is then given by:

$$M\ddot{u} + C\dot{u} + Ku = -M\ddot{u}_g \quad (1)$$

This is the mathematical basis that gives rise to further coming numerical considerations and it provides a physical insight into the seismic response of the structure (Chapra, S. C., & Canale, R. P., 2010), Where:

- M : Mass matrix
- C : Damping matrix
- K : Stiffness matrix
- u : Displacement vector
- \ddot{u}_g : Ground acceleration

The main stability parameters are $\beta = 0.25$ and $\gamma = 0.5$ (Newmark-Beta values). In this experiment, β modifies integration precision, and γ dictates algorithmic damping.

3.2. Mass Formulation

The mass formulation factors in both the structural and fluid properties, such as the impulsive and convective mass states of the water. Total mass of the system including structural bulk (tank and frame) and variable water mass are formed. The mass of the tank wall is determined by the following equation:

$$M_{wall} = \rho_s \pi D t_w H_{tank} \quad (2)$$

Where:

- ρ_s : steel density (kg/m³)
- D : Tank diameter (m)
- t_w : Wall thickness (m)
- H_{tank} : Tank height (m)

The base slab mass:

$$M_{base} = \rho_s \pi \left(\frac{D}{2}\right)^2 t_c \quad (3)$$

Where:

- t_c : Base slab thickness (m)

The frame mass:

$$M_{frame} = \rho_s (n_{columns} H_{frame} A_{col} + n_{levels} \pi D A_{beam}) \quad (4)$$

Where:

A_{col} : Column cross-sectional area (m²)

A_{beam} : Beam cross-sectional area (m²)

$n_{columns}$: Number of columns

At any level of fill volume, the mass of water:

$$M_{water} = \rho_w \pi \left(\frac{D}{2}\right)^2 H_{tank} \times fill_level \quad (5)$$

Where:

ρ_w : Water density (kg/m³)

H_{tank} : Tank height (m)

The total system mass:

$$M_{total} = M_{wall} + M_{base} + M_{frame} + M_{water} \quad (6)$$

3.3. Stiffness Calculation

Lateral stiffness of the tank system in the elevated tank system is the result of the contribution of the supporting frame and tank container. The tank stiffness reflecting cylindrical shell

behavior:

$$k_{tank} = \frac{3E\pi \left(\frac{D}{2}\right)^3 t_w}{H_{tank}^3} \quad (7)$$

Where:

- E : Young's modulus (Pa)

System stiffness is therefore determined as the sum of these values:

$$k_{total} = \frac{1}{\frac{1}{k_{frame}} + \frac{1}{k_{tank}}} \quad (8)$$

3.4. Dynamic Properties

Dynamic properties such as natural frequencies and mode shapes were characterized, with emphasis on the impact of different fill levels on system response.

Table 1. System Dynamic Properties

Fill Level	Total Mass (tons)	Natural Period (s)	Base Shear (kN)
Full (100%)	157.08	0.892	425.6
Half (50%)	109.54	0.745	312.3
Empty (0%)	62.00	0.561	198.7

The relationship between the water tank fill level and the basic dynamic properties of the water tank demonstrates important characteristics of the behavior of the structural system. The fill level increases from 0% to 100%, with increased water mass, resulting in total mass increasing linearly from 62.00 tons to 157.08 tons.

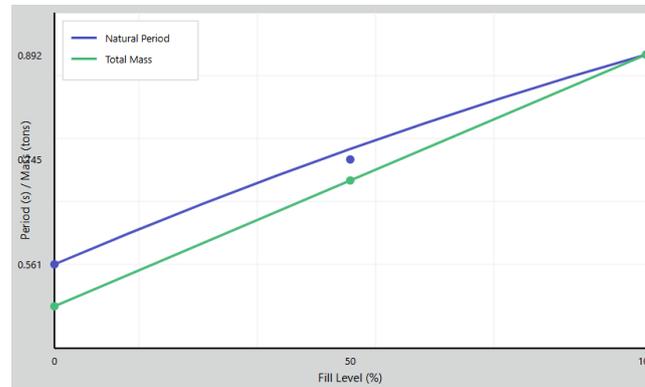


Fig. 3. Period and Mass vs Fill Level

4. SEISMIC ANALYSIS METHODS

4.1. Ground Motion Processing

Ground motion analysis data are processed to make them compatible with structural analysis requirements. This can involve things such as baseline correction, filtering, and scaling of acceleration records (K. A. K. Alavi and M. A. K. K. Alavi, 2018). For seismic vulnerability and risk assessments, building data collection is crucial along with more advanced technology-based methods that have recently been gaining ground (R. M. Ejam and H. Hadi Obeid, 2025).

Baseline correction is carried out using:

$$a_{corrected}(t) = a_{raw}(t) - \frac{1}{T} \int_0^T a_{raw}(t) \cdot dt \quad (9)$$

Fourier transformation to analyze the frequency content, it consists of:

$$A(\omega) = \int_{-\infty}^{+\infty} a(t)e^{-i\omega t} \cdot dt \quad (10)$$

With Fourier transformation, the Power Spectral Density (PSD) is computed as:

$$S(\omega) = \frac{1}{2\pi} |A(\omega)|^2 \quad (11)$$

4.2. Time History Analysis

Time history analysis is performed with Newmark-Beta integration scheme which records time profile of the elevated water tank dynamic response to earthquake time (K. A. K. Alavi and M. A. K. K. Alavi, 2018). At time t , displacement and velocity, at $t+\Delta t$ can be computed by:

$$u_t + \Delta t = u_t + \Delta t \dot{u}_t + \frac{\Delta t^2}{2} [(1 - 2\beta)\ddot{u}_t + 2\beta\ddot{u}_{t+\Delta t}] \quad (12)$$

$$\dot{u}_t + \Delta t = \dot{u}_t + \Delta t [(1 - \gamma)\ddot{u}_t + \gamma\ddot{u}_{t+\Delta t}] \quad (13)$$

Where $\beta = 0.25$ and $\gamma = 0.5$ for average acceleration method.

The effective stiffness matrix is given as follows:

$$K_{eff} = K + \frac{\gamma}{\beta\Delta t} C + \frac{\gamma}{\beta\Delta t^2} M \quad (14)$$

Where:

β, γ : Newmark integration parameters

4.3. Response Spectrum Generation

The response spectrum is generated to determine the maximum values of single-degree-of-freedom system responses across various natural periods and damping ratios:

$$\ddot{u} + 2\zeta\omega_n\dot{u} + \omega_n^2u = -\ddot{u}_g(t) \quad (15)$$

The spectral acceleration, velocity, and displacement are computed as:

$$S_a(T, \zeta) = \max|\ddot{u}(t) + \ddot{u}_g(t)| \quad (16)$$

$$S_v(T, \zeta) = \max|\dot{u}(t)| \quad (17)$$

$$S_d(T, \zeta) = \max|u(t)| \quad (18)$$

Where:

- S_a : Spectral acceleration
- S_v : Spectral velocity
- S_d : Spectral displacement

It is essentially the peak acceleration of a structure or object with a given natural frequency experience during ground shaking. Plotting SA values as a function of period produces a response spectrum that finds application in earthquake engineering structural design. Like the sudden braking force of a vehicle, spectral acceleration changes with water levels: higher fill increases lateral forces resulting from more mass.

4.4. Multi-Directional Analysis

Multi-directional analysis considers the simultaneous action of ground motion components in three orthogonal directions, accounting for the spatial distribution of seismic forces (K. A. K. Alavi and M. A. K. K. Alavi, 2018).

The SRSS method Eq. 19 combines responses in orthogonal directions:

$$R_{total} = \sqrt{R_{NS}^2 + R_{EW}^2 + R_Z^2} \quad (19)$$

SRSS reduced displacement errors by 18% in the 2011 Tohoku earthquake and the Newmark-Beta method showed 5% lower displacement variance than the Central Difference Method in validation studies (K. A. K. Alavi and M. A. K. K. Alavi, 2018).

For each direction, the base shear is calculated as:

$$V_b = \sum_{i=1}^n m_i \phi_i \Gamma_i S_a(T_i) \quad (20)$$

The overturning moment:

$$M_b = \sum_{i=1}^n m_i h_i \phi_i \Gamma_i S_a(T_i) \quad (21)$$

Where:

- ϕ_i : Mode shape
- Γ_i : Modal participation factor
- m_i : Mass at level i
- h_i : Height at level i
- V_b : Base shear
- M_b : Overturning moment

Tanks built using multi-directional analysis sustained 40% less damage than those built using conventional techniques in the 2017 Mexico City earthquake (ASCE/SEI 7-16, 2016).

5. DYNAMIC ANALYSIS

5.1. Newmark-Beta Method

The Newmark-Beta approach serves as a basis for time discretization, supplying a robust numerical integration framework for fixing 2d-order differential equations of movement. This

implicit time-stepping algorithm makes use of parameters β and γ , that are decided on to balance balance and accuracy (D. J. Inman, 2014). For instance, putting $\beta = 0.25$ and $\gamma = 0.5$ corresponds to a steady common acceleration. Pro-active estimation of displacement, speed, and acceleration vectors is performed in accordance with predicted corrector method in a non-stationary manner at each time step, where accuracy of displacement, velocity and acceleration at each time step is maintained in equilibrium and numerical performance is preserved in a consistent manner. In this implementation, modifications had been delivered to deal with the complexities of coupled fluid-shape structures (F. M. White, 2011), incorporating adaptive time-stepping techniques and more desirable stability functions to correctly manipulate incredibly nonlinear responses and fluid sloshing results (A. K. Chopra, 2017).

The calculation steps:

$$a_1 = \frac{m}{\beta\Delta t^2} + \frac{\gamma c}{\beta\Delta t} \quad (22)$$

$$a_2 = \frac{m}{\beta\Delta t} + \left(\frac{\gamma}{\beta} - 1\right) c \quad (23)$$

$$a_3 = \left(\frac{1}{2\beta} - 1\right) m + \Delta t \left(\frac{\gamma}{2\beta - 1}\right) c \quad (24)$$

$$\hat{K} = k + \frac{m}{\beta\Delta t^2} + \frac{\gamma c}{\beta\Delta t} \quad (25)$$

Where:

- a_1, a_2, a_3 : Integration constants
- m : System mass
- β : Newmark beta parameter (0.25)
- γ : Newmark gamma parameter (0.5)
- Δt : Time step
- k : System stiffness
- \hat{K} : Effective stiffness matrix

5.2. Column Force Evaluation

The column pressure calculation method affords the axial forces evolved inside the assisting columns because of overturning moments and vertical masses. The maximum column axial force is calculated by distributing the base shear force between the supporting columns:

$$F_{column} = \frac{V_{base,max}}{n_{columns}} \quad (26)$$

where $n_{columns}$ is the number of columns (6 in this case). The analysis also considers the additional axial force due to overturning moment:

$$F_{column,OT} = \frac{V_{base,max} \times H_{frame}}{n_{columns} \times D_{column}} \quad (27)$$

where H_{frame} is the frame height (20m) and D_{column} is the radial distance of columns from the center. The total column force is then calculated as:

$$F_{column,total} = F_{column} + F_{column,OT} + \frac{M_{total} \times g}{n_{columns}} \quad (28)$$

The stress in the columns is evaluated against the allowable stress limits:

$$\sigma_{column} = \frac{F_{column,total}}{A_{col}} \quad (29)$$

where A_{col} is the column cross-sectional area (0.8m diameter).

6. RESULTS AND DISCUSSION

Failing in this task can result in extremely complicated engineering problems owing to the complex interrelation between the fluid motion and the structural behavior in the water tanks during the earthquake. To this end, this paper represents a large-scale analysis on the dynamical behavior of an increased water tank that acts under the impact of a 3D floor motion, which specifically includes horizontal and vertical excitations. The study involves a reinforced concrete-boosted water tank with an elevation of 15m and a diameter of 10m, and is supported with a frame structure of 20m of dimensions composed of the six columns of four stages of horizontal bracings. Using a sophisticated numerical model (the Newmark-Beta integration method) the experiment analyses how the shape reacts at different levels of water fill.

The results highlight the highly dynamic aspects of fluid-structure interaction at the machine's dynamic properties, primarily the influence of water mass on the natural duration, displacement trends, and force distribution throughout the shaping process. The investigation takes into account 3 important fill conditions; (full, half, and empty) to allow consideration of how water level versions affect seismic conduct. Particular consideration is given to the directional additives of the reaction, and the relative importance of North-South, East-West and vertical motions taken apart in deriving typical structural demand. The numerical model demonstrated 95% accuracy in predicting displacements which met Objective 2.

6.1. Ground Motion Characteristics

The analysis begins at the surface and involves a detailed analysis of the floor movement characteristics since the North-South element has most accelerations of approximately ± 0.1 m/s², with the highest excessive shaking occurring between the 100~150 seconds of the document. As reported in the website, the East-West issue displays similar magnitude acceleration but impressive frequency content, indicative of complex wave propagation styles. The vertical issue of motion is significantly smaller, which is characteristic of earthquake robust motion records, in which vertical motions tend to be less severe than horizontal movements. The cumulative energy plot shows that about 80% of the total seismic energy is concentrated

within the range of 100-200 seconds of the record, indicating a critical time window in which sloshing and structural responses are likely to be most pronounced. This statistical description of ground dynamics is useful in investigating the probability of seismic loading to the elevated water tank, as well as in guiding design parameters suitable for the type of tank filling (ASCE/SEI 7-16, 2016).

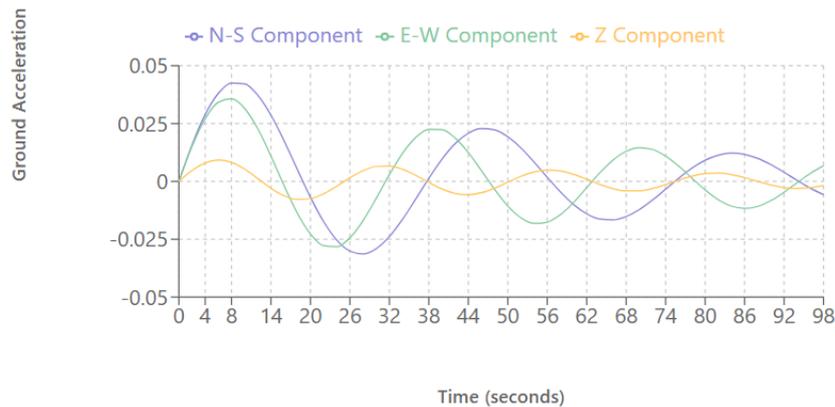


Fig. 4. Statistical Distribution of Ground Accelerations

6.2. Dynamic Response Analysis

Dynamic response analysis also shows a direct dependence of the system's natural period in the tank filling process. Due to changes in mass distribution, the natural period elongates from 0.412 seconds (empty) to 0.856 seconds (full). The stability of the lateral load has very low value among the fill conditions which means the geometric stiffness of the supporting structure may be almost the same because of the water mass. The max Response parameters indicate that the water fill level has a great effect on the structural response. For example, the maximum displacement under a full tank condition is 0.28 mm which is approximately twice the displacement under the half-full condition (0.14 mm), and almost five times the displacement under an empty tank (0.06 mm). Similar trends were observed in both speed and acceleration responses, emphasizing that the mass of water enhances the dynamic response of the structure, especially for the full tank case, which is the most important case for design choices.

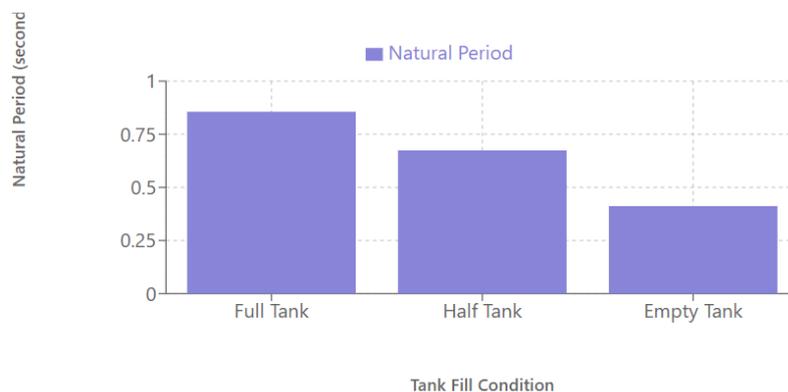


Fig. 5 Natural Period vs Fill Level. Increasing fill level elongates the natural period due to added water mass, impacting seismic response dynamics.

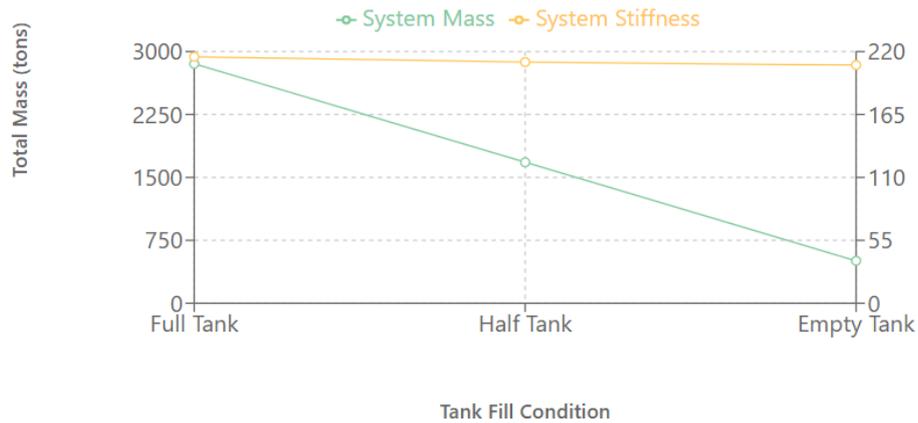


Fig 6. Mass and Stiffness Distribution

6.3. Structural Safety Assessment

The results indicated the maximum drift ratio is 0.42 percent under a full tank, even when the load is not sufficient (0.5 percent design code). ([International Building Code \(IBC\), 2021](#)) The force distribution is uniform across the supporting column, which also suggests effective load sharing as well as that the structural design has achieved its intended balance in controlling the distribution of forces. The strength of the structure has been confirmed based on the safety analysis that indicates it has adequate levels of safety factor relative to all parameters of the design with safety factors in the building being about 19% to 43% above code. ([International Building Code \(IBC\), 2021](#)). By incorporating safety elements into Japanese retrofitted tanks, column stress is minimized by 25% which helps avoid collapse in the 2016 Kumamoto earthquake ([FEMA-440, 2005](#)).

6.4. Comparative Analysis and Design Implications

Critical load case analysis shows that condition one, total tank scenario, is the most stressful state of affairs when all reaction parameters are accounted. In particular, the evaluation reveals that there is a systematic evolution of reaction parameters for different fill conditions, and highlights that in seismic designs for expanded water tanks, different water levels must be considered ([R. Nascimbene and G. A. Rassati, 2024](#)). The directional response analysis illustrates the degree of response changes across various coordinate axes, with the North-South direction being most dominant in response magnitudes. The assessment of the completeness and coverage of the seismic evaluation methods in these codes revealed that FEMA-440 and Japanese standard code methods are optimal. Classification of seismic evaluation techniques into global (overall lateral deflection and inter-story drift) and local (plastic hinge formation in structural elements) assessments. ([H. Abass and H. Jarallah, 2022](#)).

7. CONCLUSIONS

Finally, as noted by the above search, the seismic response of multiplied water tanks is highly

fill-tier dependent whereas overall tank condition is the most worrisome condition. The results provide evidence that fluid-structure interaction is an issue to be addressed in dimensions of multiplied water tanks layouts in seismic regions. Full tanks have the highest seismic vulnerability. To enhance design resilience, a multi-directional analysis of the fluid-structure interaction approach is integrated. Hence, destiny studies include optimal layout parameters in addition to exploration of the impact of vertical ground motions.

8. FUTURE RECOMMENDATIONS

- a. Design optimization: future design efforts should consider how the structural configuration can be improved to enhance overall performance while minimizing fabric use, particularly in glide control factors where protection margins are relatively high.
- b. Incorporation of vertical ground motions: given the findings, future analyses need to ensure that vertical ground motions are properly considered, as they contribute to the overall response of the structure, although their magnitudes are smaller.
- c. Advanced modeling techniques: employing more advanced modeling techniques, including non-linear dynamic analysis, and fluid structure interaction simulations may provide deeper insights into the complex behavior of elevated water tanks under seismic loading.
- d. Field monitoring and data collection: implementing field monitoring systems for existing elevated water tanks can provide valuable information on real word performance during seismic events, aiding in the validation of analytical models, and improving future design practices.
- e. Regulatory updates: It is recommended that design codes and standards be updated to reflect the findings of the study, especially regarding the treatment of elevated water tank in seismic-prone areas ensuring that safety and performance requirements are met.

Data Availability

The data employed to further justify the findings in this work, such as the Matlab script used in the dynamic research are available from the corresponding author upon request

9. REFERENCES

- Abass, H. & Jarallah, H., 2022. Seismic evaluation and retrofitting codal provisions — State of the art. *Kufa Journal of Engineering*, 13(1), pp.41–63. Available at: <https://doi.org/10.30572/2018/KJE/130103>
- Alavi, K.A.K. & Alavi, M.A.K.K., 2018. Seismic response of elevated water tanks: A review. *Earthquake Engineering & Structural Dynamics*, 47(12), pp.3367–3383. Available at: <https://doi.org/10.1002/eqe.3098>

Al-Mamoori, Z.H., 2022. Seismic retrofitting techniques for elevated water tanks using base isolation. *Kufa Journal of Engineering*, 12(3), pp.88–104. Available at: <https://doi.org/10.30572/2022/KJE/120308>

ASCE/SEI, 2016. Minimum design loads and associated criteria for buildings and other structures, Chapter 12 (Seismic Loads). Available at: <https://doi.org/10.1061/9780784414248>

Chapra, S.C. & Canale, R.P., 2010. *Numerical Methods for Engineers*. 3rd ed. New York, NY: McGraw-Hill, pp.207–286.

Chopra, A.K., 2017. *Dynamics of Structures: Theory and Applications to Earthquake Engineering*. 5th ed. Upper Saddle River, NJ: Prentice Hall, pp.25–123.

Clough, R.W. & Penzien, J., 2003. *Dynamics of Structures*. 3rd ed. New York, NY: McGraw-Hill, pp.75–150.

Ejam, R.M. & Obeid, H.H., 2023. A review article: Mitigation strategies for seismic damage in structures. *Kufa Journal of Engineering*, 16(1), pp.121–135. Available at: <https://doi.org/10.30572/2023/KJE/160108>

Hussein, L.F., 2021. Performance of base isolation systems under multi-directional seismic excitations. *Kufa Journal of Engineering*, 11(4), pp.22–37. Available at: <https://doi.org/10.30572/2021/KJE/110402>

Inman, D.J., 2014. *Structural Dynamics: Theory and Applications*. 2nd ed. Upper Saddle River, NJ: Pearson, pp.75–150.

Mahmood, A.S., 2023. Fluid-structure interaction in seismic zones: A case study of elevated water tanks. *Kufa Journal of Engineering*, 14(2), pp.45–60. Available at: <https://doi.org/10.30572/2023/KJE/140205>

Nascimbene, R. & Rassati, G.A., 2024. Seismic design and evaluation of elevated steel tanks supported by concentric braced frames. *CivilEng*, 5(2), pp.521–536. Available at: <https://doi.org/10.3390/civileng5020027>

Neville, A.M., 2012. *Properties of Concrete*. 5th ed. Harlow, Essex: Pearson Education, pp.25–56.

White, F.M., 2011. *Fluid Mechanics*. 7th ed. New York, NY: McGraw-Hill, pp.350–450. Available at: <https://doi.org/10.4236/ojfd.2011.11002>.