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Experimental Estimation of Fundamental Period and Damping Ratio of an Elevated Water Tank Based on Forced Vibration Test

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Abstract

Elevated water tanks are critical lifeline structures whose seismic performance depends strongly on their dynamic characteristics, particularly the fundamental period and damping ratio. Numerical models often rely on simplifications that may not capture real behavior. This study presents an experimental forced vibration test on a 600 m³ reinforced concrete elevated water tank in Rudsar, Iran, to determine its fundamental period and damping ratio under different water levels. A shaker (Pooya5000) was installed on the roof, and harmonic excitation was applied at frequencies up to 8 Hz. Accelerations were recorded, processed using SeismoSignal (bandpass filter 0.5–7 Hz), and compared with finite element (SAP2000) and analytical (Housner-type) models. Results show that the experimentally obtained fundamental periods (0.525–0.554 s for water depths 2.35–3.63 m) are significantly lower than FEM (0.74–0.77 s) and analytical (0.70–0.73 s) predictions. The average damping ratio from free vibration decay was only 0.89%, attributed to the very low excitation amplitude (elastic range). This study highlights the necessity of experimental validation for dynamic analysis and suggests that current code-based period formulas may overestimate flexibility in such structures.

Keywords: Forced vibration test, Elevated water tank, Fundamental period, Damping ratio, SAP2000, Fluid-structure interaction.

1 | Introduction

Elevated water tanks are essential components of urban water supply networks, especially in regions without natural topographic elevation. Their seismic safety is paramount, as failure can lead to loss of potable water, firefighting incapability, and secondary disasters [1], [2]. Past earthquakes (e.g., San Francisco 1906, Mexico City 1985, Kobe 1995) have repeatedly demonstrated the vulnerability of these structures.

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The fundamental period and damping ratio govern the seismic response of any structure. While analytical methods (e.g., Housner's two-mass model) and numerical simulations (FEM) are common, they rely on assumptions such as rigid base, perfect fixity, and linear material behavior. Soil-Structure Interaction (SSI), reinforcement contribution to stiffness, and actual boundary conditions are often simplified or ignored [3], [4].

Forced Vibration Testing (FVT) is a reliable experimental technique to extract dynamic properties by applying controlled harmonic excitation and measuring structural response [5], [6]. However, FVT on large-scale elevated water tanks is rare, especially in Iran.

Fig. 1. Aerial or distant view of the 600 m³ Rudsar elevated water tank.

This study aims to:

I. Determine the fundamental period of a 600 m³ RC elevated water tank under different water levels via FVT.

II. Compute the damping ratio from free vibration decay.

III. Compare experimental results with SAP2000 FEM and analytical calculations.

IV. Propose corrective observations for numerical modeling.

2 | Literature Review

Housner [1], [7] pioneered the two-mass analog: impulsive mass (moving rigidly with the tank) and convective mass (sloshing). This model is still used in codes like ACI 350.3 [8] and Iranian National Building Code (Nashrieh 123). However, these analytical methods assume rigid tank walls and neglect SSI [3].

Numerical studies using SAP2000, ABAQUS, and ANSYS have investigated elevated tanks [9], [10].

Key findings include:

I. Base shear does not always maximize at full tank condition.

II. Near-field earthquakes can excite higher modes.

III. Convective periods can be long, and ignoring them underestimates sloshing forces [4].

Experimental dynamic tests on elevated tanks are scarce. Font [11] performed ambient vibration testing on a steel elevated tank in Arkansas and found good agreement with FEM for the first three modes. Brownjohn et al. [12] used human-induced jumping for footbridge modal analysis, demonstrating low-cost forced vibration. Yu [5] tested a four-story RC building and found that forced vibration gave lower natural frequencies than analytical predictions due to non-structural elements and cracking. To date, no forced vibration test on a large RC elevated water tank in Iran has been reported in international literature. This research fills that gap.

3 | Methodology

3.1 | Test Structure Description

The structure is a 600 m³ reinforced concrete elevated water tank in Rudsar, Gilan Province, Iran (completed 2013). Key properties:

Table 1. Geometric and material properties of the tank.

Parameter	Value
Tank capacity	600 m³
Shaft height	33.5 m
Shaft outer/inner diameter	8.0 / 7.0 m
Shaft wall thickness	0.5 m
Tank outer diameter (including cornice)	18.4 m
Tank wall thickness	0.3 m
Tank net height	7.35 m
Foundation	1.2 m thick circular raft, 20 piles (d=1 m, L=25 m)
Concrete compressive strength (fc')	30 MPa (field tests)
Elastic modulus (E)	26.15 GPa

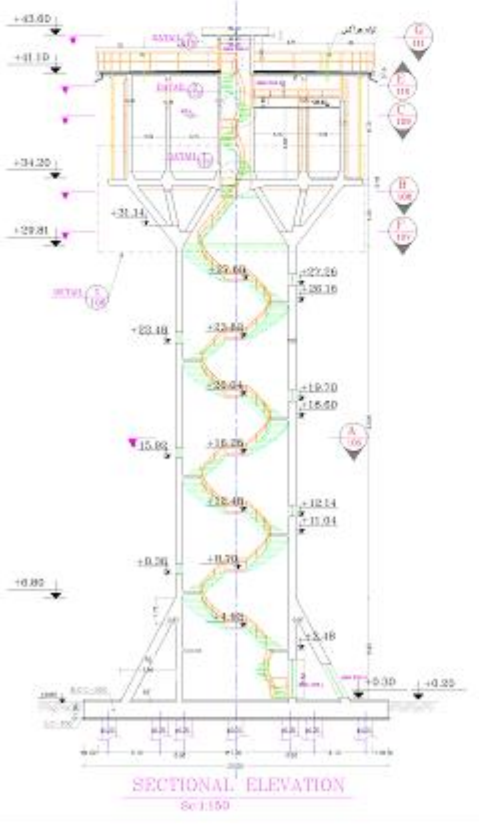


Fig. 2. Longitudinal section of tank and shaft.

3.2 | Forced Vibration Test Setup

A Pooya5000 eccentric mass shaker was installed on the roof slab near the center of mass (slight offset due to roof access). The shaker has two rotating masses (each up to 13.2 kg total) with adjustable eccentricity. The excitation frequency was varied from low values up to ~8 Hz. The horizontal harmonic force is:

$$P_t = 2me\omega^2 \ \sin\omega t,$$

where m = total rotating mass, e = eccentricity, ω = angular frequency.

Four wireless triaxial accelerometers (BeanAir AX-3D-2G, sampling 100 Hz) were placed on the roof. Calibration was performed before each test series.

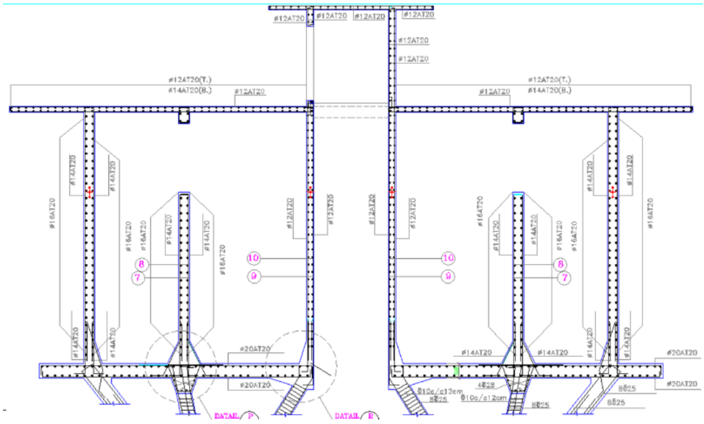


Fig. 3. Shaker (Pooya5000) details.

3.3 | Test Program

Water levels were continuously monitored via a float sensor. Tests were conducted at five water heights: 2.35 m, 2.80 m, 3.19 m, 3.63 m, and also analyzed for empty (0 m) and full (4.17 m) from FEM/analytical. Each test consisted of 60 s operation: first 30 s forced excitation, then shaker turned off to record free decay for damping estimation.

3.4 | Signal Processing

Raw acceleration records were processed using SeismoSignal (Seismosoft, 2022). Processing steps:

I. Baseline correction to remove drift

II. Bandpass Butterworth filter (0.5–7 Hz) to eliminate high-frequency noise and very low-frequency trends

III. Fast Fourier Transform (FFT) to obtain frequency spectra

Damping ratio calculated using logarithmic decrement method from free vibration portion:

$$m\ddot{u} + c\dot{u} + ku = p_0 \,\text{Sin}\,\omega t = (2m_e e\omega^2)\,\text{Sin}\,\omega t.$$

3.5 | Numerical and Analytical Models

FEM (SAP2000): a 3D shell-element model (1172 four-node shell elements) was created. The added mass approach (Westergaard) was replaced by an alternative concentrated mass method at 32 points (16 inner + 16 outer tank walls) at the center of mass height, distributing water mass proportionally to water level. Piles and SSI were ignored (rigid base assumption).

Analytical: simple cantilever beam formula

$$I_{\text{shaft}} = \frac{\pi}{64}\left(D_{\text{ext}}^4 - D_{\text{int}}^4\right),$$

where P = total weight (structure + water), $L_{\text{shaft}} = 33.6$ m, $I_{\text{shaft}} = \frac{\pi}{64}\left(D_{\text{ext}}^4 - D_{\text{int}}^4\right)$.

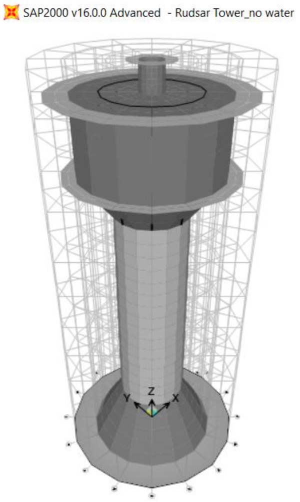
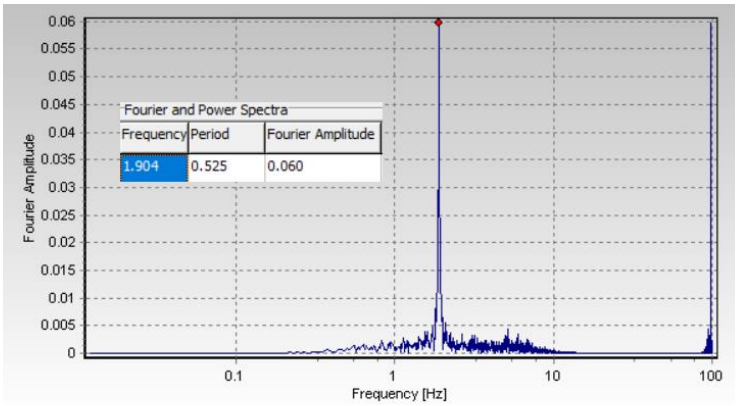


Fig. 4. SAP2000 model mesh.

4 | Results

4.1 | Fundamental Period from Forced Vibration

For each water level, the peak in the frequency-domain response corresponded to the fundamental mode. Example for Hw=2.35 m: peak frequency = 1.904 Hz → T = 0.525 s.



Fourier and Power Spectra

Frequency	Period	Fourier Amplitude
1.904	0.525	0.060

Fig. 5. Sample acceleration time history and FFT for Hw=2.35 m.

Table 2. Experimental periods for different water levels.

Water Level Hw (m)	Experimental T (s)	Frequency (Hz)
2.35	0.525	1.904
2.80	0.532	1.880
3.19	0.539	1.855
3.63	0.554	1.831

As water level increases, the period increases (more mass), but the change is relatively small due to dominant shaft stiffness.

4.2 | FEM and Analytical Periods

Table 3. Comparison of periods from FVT, FEM.

Hw (m)	FVT T (s)	FEM T (s)	Analytical T (s)
0	–	0.69	0.64
2.35	0.525	0.74	0.70
2.80	0.532	0.75	0.71
3.19	0.539	0.76	0.72
3.63	0.554	0.77	0.73
4.17	–	0.78	0.74

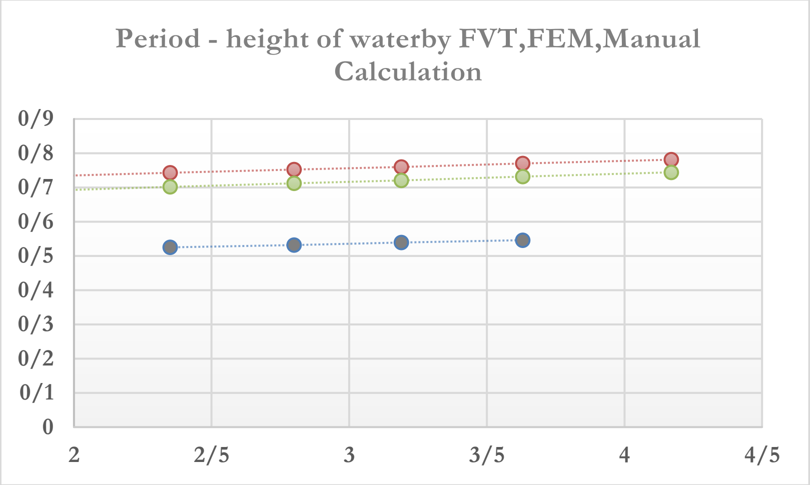


Fig. 6. Comparative period vs. Water level plot.

Observation: experimental periods are consistently 25–30% lower than FEM and analytical predictions. This indicates that real stiffness is significantly higher than modeled.

4.3 | Damping Ratio

From free decay after shaker turn-off, the average damping ratio was:

$$\xi = \frac{1}{2\pi\, m} \ln \frac{U_n}{U_{n+m}}.$$

This is much lower than typical 2–5% for RC structures. The reason: excitation amplitude was very small (peak acceleration ≈ 0.0035g), keeping the structure in the perfectly elastic range with no micro-cracking or friction damping. Under a real strong earthquake, damping would be higher (2–5%).

4.4 | Empirical Period Equation

A power-law fit to experimental data (Hw from 2.35 to 3.63 m) gives:

$$T = 0.485H^{0.0906}.$$

Extrapolating to empty tank (Hw=0) gives T ≈ 0.486 s, close to the trend of FEM/analytical but still lower.

5 | Discussion

5.1 | Why Are Experimental Periods Lower?

The FEM and analytical models overestimate the period (i.e., underestimate stiffness) due to:

I. Reinforcement contribution ignored in SAP2000 – The steel rebar increases effective stiffness, especially in the elastic range.

II. Piles and SSI – The 20 piles (25 m deep) and surrounding soil provide additional lateral restraint not modeled.

III. Tank walls and partitions – The internal division walls add stiffness that was lumped only as mass.

IV. Non-structural elements – Staircase, parapet, and roof elements contribute to actual stiffness.

This finding aligns with Yu [5] who found forced vibration frequencies 25–30% higher than analytical for an RC building.

5.2 | Implications for Seismic Design

Using code-based or FEM-derived periods without calibration may lead to:

I. Overestimation of spectral acceleration (if period is overestimated, Sa might be lower or higher depending on spectrum shape).

II. In the case of stiff soil and low periods (<0.6 s), Iranian code 2800 (4th ed.) has increasing Sa with period; thus overestimating T gives unconservative lower forces.

Therefore, experimental calibration is essential, especially for retrofitting existing tanks.

5.3 | Very Low Damping

The measured 0.89% damping is realistic for small-amplitude vibration. For seismic design, higher damping (e.g., 3–5%) should be used, as recommended by ACI 350.3 [8] and Eurocode 8.

6 | Conclusion

FVT successfully determined the fundamental period of a 600 m³ RC elevated water tank at various water levels.

Experimental periods (0.525–0.554 s for Hw=2.35–3.63 m) are significantly lower (by ~25–30%) than FEM (SAP2000) and analytical predictions. Real stiffness is higher due to reinforcement, piles, and non-structural elements.

Damping ratio from small-amplitude forced vibration was only 0.89% – much lower than seismic design values (3–5%) because the structure remained perfectly elastic.

Empirical equation $\mathrm{T} = 0.485\mathrm{H}_{\mathrm{w}}^{0.0906}$ was derived for this tank type.

Numerical models without experimental calibration may overestimate periods and lead to unconservative seismic forces for stiff, short-period tanks.

References

[1] Housner, G. W. (1954). *Earthquake pressures on fluid containers*. https://authors.library.caltech.edu/records/eewgr-ay603

[2] Haroun, M. A., & Housner, G. W. (1981). Seismic design of liquid storage tanks. *Journal of the technical councils of asce*, *107*(1), 191–207. https://doi.org/10.1061/JTCAD9.0000080

[3] Bahreini Toussi, I. (2016). *Experimental and numerical investigation of liquid storage tanks under seismic excitation* [Thesis]. http://dx.doi.org/10.20381/ruor-266

[4] Shakib, H., & Alemzadeh, H. (2017). The effect of earthquake site-source distance on dynamic response of concrete elevated water tanks. *Procedia engineering*, *199*, 260–265. https://doi.org/10.1016/j.proeng.2017.09.020

[5] Yu, E. (2005). *Forced vibration testing and analytical modeling of a four-story reinforced concrete frame building* [Thesis]. https://www.proquest.com/openview/e2e03c6bd3093a3769e5a44566a05122/1?pq-origsite=gscholar&cbl=18750&diss=y

[6] Jacobsen, E. D. (2011). *Forced vibration testing and analysis of pre-and post-retrofit buildings* [Thesis]. https://www.proquest.com/openview/22a9409808e9e168fde8cd77450e396a/1?pq-origsite=gscholar&cbl=18750&diss=y

[7] 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

[8] American Concrete Institute. (2020). *ACI 350.3-20 seismic design of liquid-containing concrete structures*. https://studylib.net/doc/27979290/aci-350.03-2020-analysis-and-desing-of-liquid-containing-...

[9] Purnama, A. Y., Rifa'i, A., & Hardiyatmo, H. C. (2018). Fuel tank foundation improvement system on soft soil layer based on 3D numerical simulation. *GEOMATE journal*, *14*(41), 13–18. https://geomatejournal.com/geomate/article/view/3198

[10] Patel, J. J., Patel, C. N., & Patel, H. S. (2014). Fluid-structure interaction approaches for seismic behavior of elevated water tank. *National conference on recent advances in civil and structural engineering (racse-14)*. ADIT & BVM. https://studylib.net/doc/25714140/fluid-structure-interaction

[11] Font, A. M. (2014). *Dynamic testing of an elevated water tank* [Thesis]. https://scholarworks.uark.edu/etd/2373/

[12] Brownjohn, J., Bocian, M., & Hester, D. (2017). Forced vibration testing of footbridges using calibrated human shaker and wireless sensors. *Procedia engineering*, *199*, 417–422. https://doi.org/10.1016/j.proeng.2017.09.134