INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING, MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)
ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

Seismic Behaviour of Elevated Water Tanks – A Review

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DOI: https://doi.org/10.51583/IJLTEMAS.2026.150700070

Received: 29 July 2026; Accepted: 03 August 2026; Published: 13 August 2026

ABSTRACT

Elevated water tanks are the most important lifeline structures which provides access to water for daily utilities to communities and its elevated position ensures smooth and efficient water supply through gravity. The after-earthquake functionality of such water tanks is the major concern as these tanks must ensure its intended purpose of water supply post-earthquake. Previous earthquakes have shown the various failure patterns of elevated water tanks wherein the water tank geometry, shape, height of staging, and the depth of freeboard provided, effect of sloshing waves, underestimation of forces due to Soil-Structure interaction and improper idealization of water tanks have been the major reasons. Compared to conventional buildings elevated water tanks have a huge mass of water supported on a tall staging due to which its seismic behaviour is contradictory when compared with conventional buildings. Hence there is a need to understand the seismic behaviour and assess its vulnerabilities from which Aseismic design of such tanks can be considered. The present study summarizes the past works carried out on assessing seismic behaviour of elevated water tanks considering various parameters that influences its behaviour.

Keywords: Sloshing, Fluid–structure–soil interaction (FSSI), Stratified Soils.

INTRODUCTION

Earthquakes are the most devastating and destructing phenomenon that has troubled mankind over several decades. The poorly designed structured that have failed to comply with seismic Codal provisions have amplified the diastral effect and have caused huge impact on life of humans. Every Earthquake poses a significant challenge to engineers and illustrates the significant need for a need of earthquake resistant design.

Elevated water tanks are considered as a lifeline structure, whose functionality on a daily basis ensures smooth and effective supply of water to communities and its elevated positions is an added advantage to use natural gravity via which water supply process is simplified.

The seismic safety of such tanks shall play a major role on its functionality and they must be designed to withstand such forces during earthquake. In contrast to regular structures, elevated water tanks exhibit unique seismic behaviour since they have a huge water mass supported on a tall staging due to which they are extremely vulnerable to lateral forces. The damages observed during past major earthquakes such as Bhuj (2001) have illustrated the failure pattern of such elevated tanks where improper staging selection and overestimating seismic responses have been the most significant causes [1]. During earthquakes, the behaviour of a structure not only depends on superstructure but is greatly influenced by the response and interaction between super structure and the underlying soil which is the effect of soil—structure interaction (SSI). These effects are usually ignored by adopting fixed base analysis while estimating a structure's seismic response. The conventional approach of fixed base analysis assumes the foundation to be rigid which is contradictory in actual site conditions. conditions. In actuality, the soil structure interaction amplifies the response of the structure resting especially in soft soils and stratified soil deposits compared to stiff soil or rock, and disregarding such a complex interaction has proven to

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

be detrimental to the performance of structures leading to premature collapse during intense ground shaking [2]. In addition to SSI the various failure patterns of elevated water tanks wherein the water tank geometry, shape, height of staging, and the depth of freeboard provided, effect of sloshing waves, and improper idealization of water tanks have been the major reasons. The aseismic design of such tanks demands to account for all these effects and in addition to it, the dynamic effect from sloshing waves. The effect of sloshing waves alters the motion of tanks during ground shaking which was the major cause of failure during the past earthquakes.

A review on the past earthquake demonstrates various failure patterns and the first such vulnerability was observed during Chilean Earthquake of 1960 where the sloshing waves altered the motion of tanks during earthquake and a detailed analysis of failure was done by Housner (1961) which led to the development of Housner model of idealization of water tanks [3].

For instance, in 2001 Bhuj earthquake three elevated tanks were severely damaged (Figure 1) a 265 KL water tank in Chobari village about 20 km from the epicenter collapsed and the tank was half full during earthquake and two staging collapses in Bachau Village and Manfera Village (Figure 2 & 3) these events are evident that there is significant gap in understanding the seismic behaviour of water tanks [1].

Fig.1 Water tank of 265 KL in Chobari village   Fig.2 Staging Collapse in Bachau village

Fig.3 Staging Collapse in Manfera village

Many such damages have been observed during past earthquakes which has led to an extensive number of studies on evaluating the seismic performance and responses of elevated water tanks considering various parameters, this paper summaries a few of the studies which have contributed majorly in the aseismic design of elevated water tanks.

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LITERATURE REVIEW

The dynamic analysis of water tanks has been the subject of a significant number of studies to date and these studies have examined a wide variety of parameters, including the impact of sloshing waves, the performance of the staging pattern during ground shaking, the effect of subsoil, or soil-structure interaction (SSI), and its impact on seismic behaviour. Here are a few of them presented below.

George Housner (1963) considered the Chilean earthquake that took place in 1960.In this paper the relation between the motion of water in tank with respect to tank and motion of whole structure with respect to ground is considered. Three basic conditions were considered for the analysis. He said that if water tank is fully filled i.e. Without freeboard then the sloshing effect of water is neglected, if the tank is empty then no sloshing, as water is absent. In the above two cases water tower behaves as one-mass structure. But in third case i.e., water is partially filled, the sloshing effect must be considered. In that case the water tower will behave as a two-mass structure. In case of partially filled water tanks, there is a free surface available for water movement and during earthquake ground shaking, the liquid exerts hydrodynamic pressure. The water in the tank gets divided into two different masses. The liquid in the lower region of the tank behaves like a mass that is rigidly connected to tank and is termed as impulsive mass. The liquid in the upper region of the tank moves in the direction opposite to the movement to tank and is termed as convective mass. The convective mass is the sloshing mass or sloshing wave which alters the dynamic behaviour of container. Finally, he concluded that when the fully filled tank is compared with the partially filled tank then it is seen that the maximum force to which the half-filled tank is subjected may be significantly less than half the force to which the full tank is subjected. The actual forces may be as little as $1/3^{rd}$ of the forces anticipated on the basis of completely full tank. This study highlighted the effect of sloshing waves and the concept of convective mass.

Boyce 1973 in his work titled **– "Vibration tests on a simple water tower"** conducted an experimental and studied three parameters such as Design lateral force, Time period and Hydrodynamic pressure on walls and the study showed that the performance factor 'K' value considered to compute the design lateral force is too low and suggested to introduce suitable value based on supporting structure used and suggested to use K = 3 until further revision of Code. In case of Time period, IS1893 suggested Single mass model for water tanks and when experimental study was conducted to verify the same the results showed large variation and it was suggested to consider two mass model idealization and when verified experimentally the results yielded closer agreement. In case of Hydrodynamic pressure, the code suggested not to account for convective pressure by only considering impulsive pressure but the study suggested to considered both convective and impulsive pressure and also indicated that convective pressure can be the dominant factor during earthquakes. It was finally concluded that IS1893 requires major revision and the above discussed changes to be implemented in revised version as per Housner's model.

Sudhir K Jain and Sajjad Sameer U (1993) in their work **"A Review of requirements in Indian codes for aseismic design of elevated water tanks"** reviewed IS 1893:1984, compared it to other international seismic codes, and recommended a number of modifications. The subsequent modifications were made after the study was completed in order to put Boyce's (1973) recommendations into practice.

- **a.** The equation for determining the design lateral force for raised tanks may be modified to include a suitable performance factor value, such as 3.0. The lateral design force required by IS: 1893-1984 is significantly low due to the lack of a performance factor for raised towers.
- **b.** The two-mass representation may be used in place of the IS code's one-mass model.
- **c.** Details of Housner's mechanical model may be incorporated to the formulas for hydrodynamic pressure distribution in the tank.
- **d.** The code may include an equation for determining the water's sloshing height.
- **e.** The lateral stiffness of the tank's supporting system must take the bracing beam flexibility into account.
- **f.** The inclusion of the effect of accidental torsion was suggested.
- **g.** The impact of convective hydrodynamic pressure must be taken into account in the seismic analysis.
- **h.** For tank wall stress analysis, a simplified hydrodynamic pressure distribution was recommended.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

Durgesh C Rai (2003) reviewed the performance of elevated water tanks during the Mw 7.7 Bhuj earthquake of January 26, 2001, with particular emphasis on the damage sustained by their supporting structures. The study reported that a large number of elevated water tanks experienced severe damage, while at least three tanks collapsed due to inadequate seismic performance of their staging systems. The investigation identified that shaft-type staging, which was widely used in the affected region, suffered from poor ductility, low redundancy, and inadequate toughness, leading to circumferential flexural cracking near the base. Similarly, frame-supported staging exhibited damage in the form of weak brace–column joints and inadequate member strength. A strength evaluation of the damaged shaft-supported tanks revealed that although they satisfied the design requirements of IS 1893:1984, they were deficient when compared with the provisions of the International Building Code (IBC). The study concluded that the seismic design forces specified in IS 1893:1984 were insufficient for elevated water tanks and underestimated the seismic demand by nearly a factor of three. The author emphasized the need for revising seismic design provisions and improving the ductility and redundancy of supporting staging systems to enhance the earthquake resistance and post-earthquake functionality of elevated water tanks.

Livaoğlu and Doğangün (2006) presented a comprehensive review of simplified seismic analysis procedures for elevated water tanks by incorporating fluid–structure–soil interaction (FSSI) effects. The study evaluated ten simplified mechanical and finite element models commonly used for the seismic analysis of elevated tanks and examined their applicability using general-purpose structural analysis software. The fluid–structure interaction was represented using an added mass approach, while the soil–structure interaction was modelled using massless foundation and substructure approaches for four different soil classes. A reinforced concrete elevated Intze tank with a frame-supported staging was considered to compare the seismic responses predicted by the different models. The results showed that single lumped-mass models underestimated the base shear and overturning moment, which could lead to unsafe seismic designs. The study further demonstrated that the distributed added-mass model with sloshing mass-produced results that closely matched more rigorous finite element analyses and was therefore recommended for practical seismic design of elevated water tanks. The authors concluded that simplified modelling techniques can effectively capture fluid–structure–soil interaction effects and provide reliable seismic response predictions without the need for specialised fluid or soil finite elements.

Nishigandha R. Patil and Rajashekhar S. Talikoti (2015) studied the seismic behavior of elevated water tank having different staging configurations. Four Rectangular tank models of capacity 170m^3 supported on a staging of height 12m in seismic zone II was considered for the study. The analysis was carried out finite element software ETABS. Parameters such as Displacement and base shear was considered.

Model I: Staging with conventional system braced at 3m c/c along height.
Model II: Staging with diagonal shear wall in plan.
Model III: Staging with shear wall at corner.
Model IV: Staging with diagonal bracing in elevation.

The study showed that Shear walls situated in the centre core component of staging can greatly improve staging resistance under lateral loading. Lateral displacement of (Model -1) water tank with the conventional bracing system is 5 to 6 times greater tank the other three models, but it has the lowest base shear due to its lower seismic weight.

Suyash Nerkar and Chittaranjan Nayak (2016) has studied the seismic behaviour of elevated RC water tank. Rectangular and circular water tanks with different water levels (0%, 25%, 50%, 75% and 100%) were considered for study. Static and dynamic analysis of time history (Bhuj earthquake) was performed using SAP2000 software. Base shear variation and time period are the parameters studied. It was concluded that as water level increases the time period increases and base shear was maximum for the circular tank compared to the rectangular tank.

Swathi Naik and M.S. Bhandiwad (2016) made an effort on the study of seismic analysis of an elevated rectangular water tank with mid frame staging and is compared with different seismic zones as per IS1893:2002 (part 2) and wind speed for different soil conditions (soft, medium and hard soils). The tank is modelled in finite element software ETABS, and parameters such as base shear, displacement, overturning moment is compared.

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It was concluded that displacement is more in soft soil and least in hard soil and maximum displacement was observed in zone V. The base shear remained same and was maximum for soft and medium soil and least for hard soil. The overturning moment is more in case of soft soil and has maximum value when the tank is located in Zone V. The overturning moments increase as the seismic zone increases.

V.J. Ghadage et al. (2016) performed Soil structure interaction Analysis of Elevated water storage tanks. A circular elevated tank of 4,00,000 litres supported on a staging of height 16m from ground level located in seismic zone III was considered for the study. The analysis was performed considering three soil conditions (Soft soil, medium soil and soft rock soil). Displacement and Modal parameters were the parameters considered for the study. The analysis was carried out using Staad Pro software. It was concluded that time period and displacement was maximum in case of soft soil compared to medium and soft rock soil.

Ayub Patel and Sourabh Dashore (2017) has studied the seismic behaviour of elevated square and circular RCC water tanks having different capacities of storage. For this purpose, square and circular elevated water tanks of capacities 1 lakhs and 2 lakhs are considered to analyse under seismic forces. Heights of staging considered are 12m, 18m and 24m for square and circular tanks for both the capacities. All the models are analysed for zone III, zone IV and zone V using STAAD.Pro v8i software. The response parameters selected are lateral displacement and base shear. From the analysis result parameters such as deflection and base shear of the water tanks increases from lower to higher zones because the magnitude of intensity will be more for higher zones.

Sayed Habiburahman et al. (2017) made an attempt to study the seismic behaviour of R.C elevated rectangular water tank considering different staging height. The water tank has a capacity of 300 m3 and staging height such as (6m, 9m, 12m, 15m, 18m and 21m) and also different seismic zones such as II, III, IV & V were studied and analysis was carried out using STAAD.pro. Parameters such as maximum displacement, maximum base shear, maximum base moment was studied. It was observed that base shear, displacement and base moment increased with Seismic zones and staging height.

Mor Vyankatesh and More Varsha (2017) conducted a Comparative Study on Dynamic Analysis of Elevated Water Tank with Frame Staging and Concrete Shaft. The main objective was to study the hydrodynamic effect with different supporting system in different seismic zones. Four tanks of capacity $150m^3$,$250\ m^3$,$500\ m^3$ and $750m^3$ with a staging of height 12m,14m,18m and 21m respectively were considered for the study. The analysis was carried out using Staad.pro software. The results showed that, Base shear for elevated tanks, supported on concrete shaft is greater than that of elevated tanks supported on frame staging, time period in impulsive mode for shaft supported tanks and frame supported tanks differ subsequently. But for convective mode the difference is less comparatively and Sloshing wave height is approximately same for the tanks with different supporting system, but it differs for tanks as the capacity increases.

Boshra Eltaly et al. (2018) have conducted an experimental and FE modal study on elevated steel water tanks. The dynamic parameters (frequencies and mode shape) of scaled models were experimentally determined. Two different scaled models of elevated cylindrical steel water tanks tank 1 and tank 2 were chosen in this study to identify their modal parameters using ANSYS. The measured and simulated values differ by less than 5% for all modes except for the third mode of tank 2, is slightly higher giving difference of 5.46%. These variations are considered to be minor and they concluded that the constructed models can serve as a baseline model in structural dynamics for future analysis to be representative of the real structures.

Sai Ramya et al. (2019) have studied the seismic response of elevated rectangular water tank with different staging patterns and different water level condition (full, half and empty). Four types of bracing systems such as normal bracing, diagonal bracing, V bracing and cross bracing are considered for the analysis. A total of 12 combinations were analysed and base shear, base moment and roof displacement for the fixed models using SAP2000. The tank has a capacity of 108000 litres is supported on RC staging of height 20m supported on 8 columns in seismic zone V. They concluded that diagonal bracing is most effective and provides minimum value of displacement, base shear and base moment for empty, half and full condition.

Sagar T Mane and Prashant M Kulkarni (2019) have performed time history analysis of circular and rectangular elevated water storage tank using baffle wall. The concrete baffle wall has been used to reduce sloshing effect of the water tank. Koyna earthquake (1967) acceleration time history data is used. The tank responses such as maximum displacement, base shear, time period was compared with tank walls with and without baffle walls. The tank dimensions are 9m x 4.5m x 4m with free board of 0.3m and staging height was 16m with 6 columns, and size of baffle wall was 180mm in seismic zone IV and medium soil. They observed that top nodal displacement decreases by 14.55% with baffle wall in empty condition and 6.24% in full tank condition and time period for both empty and full tank condition increases with baffle wall compared to without baffle walls.

Sagar T Mane and Prashant M Kulkarni (2019) conducted Comparative Analysis of Circular and Rectangular Elevated Water Storage Tank Using Different Types of Bracing System. The capacity of the tank was 1.65lakh litres supported on a staging of height 16m.The different types of steel bracing like single diagonal, X-type, V-type, chevron bracing of section (ISMB250) and 180 mm concrete baffle wall was used. In both circular and rectangular water tanks, six-column staging has been considered for the study in seismic zone III and soil condition was medium. The numerical analysis was carried out for the two tanks with and without bracing systems by using the SAP 2000 software as per IS provisions. Parameters such as maximum top node displacement and base shear was considered. It was concluded that X-type bracing gives minimum value of displacement in rectangular and circular water tank for both empty and full condition and also baffle walls with simple staging system showed similar reduction in displacement values.

Sutanuka Nath and Atanu Kumar Dutta (2020) investigated the influence of soil–structure interaction (SSI) on the seismic response of elevated reinforced concrete water tanks, emphasizing that the conventional fixed-base assumption may not accurately represent the dynamic behaviour of tanks founded on deformable soils. The study considered two Intze-type elevated water tanks with identical storage capacities, one supported on frame staging and the other on shaft staging, and analysed their seismic performance using ANSYS Workbench. The supporting soil was modelled as a three-dimensional elastic continuum, considering hard, medium, and soft soil conditions, while nonlinear time-history analyses were performed using three earthquake ground motions. The results demonstrated that soil flexibility significantly influences the seismic response of elevated water tanks, with lateral displacement increasing as soil stiffness decreases. The study further revealed that the magnitude of seismic response depends not only on the supporting soil condition but also on the staging configuration and the frequency characteristics of the input ground motion. The authors concluded that neglecting soil–structure interaction may lead to underestimation of seismic demands, particularly for tanks founded on soft soils, and recommended the explicit consideration of SSI in seismic analysis and design.

Pranitha Jogi and B. R. Jayalekshmi (2021) investigated the effect of soil–structure interaction (SSI) on the seismic response of an elevated Intze water tank. A finite element model of the coupled tank–soil system was developed to study the influence of supporting soil flexibility under different soil conditions and water levels. The seismic response was evaluated in terms of parameters such as lateral displacement, base shear, overturning moment, and sloshing displacement. The study reported that the displacement and base shear of the elevated water tank increased with increasing flexibility of the supporting soil. The results also showed that the response of the tank was influenced by both the supporting soil condition and the water level in the tank. The authors concluded that soil–structure interaction has a significant effect on the seismic behaviour of elevated water tanks and should be considered in seismic analysis and design for obtaining realistic structural response

Sahana and Deepu (2023) studied the seismic vulnerability assessment of a baffled elevated water tank by considering fluid–structure–soil interaction (FSSI) and different staging configurations. Performance based design technique was employed, taking into account various spectrum acceleration data, and displacement was measured at the top of the tank. The analysis was performed using FEM based software tool SAP2000. Water tanks models were developed by varying the water level (empty, half-filled, and full) and staging configuration (basic, radial, and cross bracing) while incorporating fluid–structure–soil interaction. Nonlinear dynamic analysis was carried out as per FEMA P695 guidelines using five earthquake ground motions with gradually increasing intensity levels through Incremental Dynamic Analysis (IDA). Fragility curves corresponding to different performance limit states was plotted, and collapse margin ratios were identified to assess the seismic safety of the tank. The results showed that the staging with Cross-bracing are more resistant against earthquake forces, approximately 32.5% greater than the radial and basic staging configurations. The study also evaluated SSI effects on seismic performance and the results indicated that tanks resting on hard soil have 99% higher safety margin when compared to tanks resting on soft soil, while medium soil provided about 25% higher safety than soft soil. The study also evaluated the effect of fluid-structure interaction and the results highlighted the importance of sloshing waves where the half -filled tank showed higher vulnerability than full and empty tank condition.

Sangeetha et.al (2024) investigated the seismic behaviour of an elevated reinforced concrete water tank by incorporating a comprehensive soil–structure interaction (SSI) assessment under both level and sloping ground conditions. A 3 m × 3 m × 3 m elevated water tank supported on a 6 m high staging was modelled in SAP2000 v22, and seismic analyses were performed using the Response Spectrum Method in accordance with IS 1893 (Part 1): 2016 for Seismic Zones II and III. The study considered soft, medium, and hard soil conditions, empty and full tank configurations, and ground slopes varying from 0° to 30°. Both fixed-base and flexible-base (SSI) analyses were carried out to evaluate parameters such as natural frequency, time period, lateral displacement, and base shear. The results indicated that soil flexibility significantly increased the displacement and base shear of the elevated water tank compared to the fixed-base condition. It was also observed that base shear increased with increasing ground slope, whereas the displacement generally decreased due to the increase in structural stiffness with ground inclination. However, in soft soil under SSI conditions, displacement decreased up to a 15° slope and increased thereafter, indicating a transition towards greater soil flexibility. The study concluded that soil–structure interaction has a significant influence on the seismic performance of elevated water tanks and should be considered in seismic analysis and design to obtain realistic structural responses, particularly for tanks located on sloping ground.

Jayadeep and Govindaraju (2025) Investigated the influence of stratified soil deposits on the seismic response of elevated water tanks, taking into account various stratified soil. A Square tank of dimension 3m x 3m x 3m with freeboard of 0.3m supported on a staging of height 9m above ground level was considered for the study and the analysis was carried out using SAP2000 V18.2 software tool using the Bhuj (2001) earthquake acceleration as the input ground motion. Six different stratified soil profiles were considered to evaluate the effect of soil layering on the dynamic response. Initially, the soil profiles were analysed independently, without the superstructure, using the Elastic Continuum Approach to understand the influence of soil stratification and the variation of acceleration across different soil layers. The results showed that Soil Profile C3 exhibited the lowest natural frequency among the considered profiles. Since displacement response is predominantly associated with low-frequency characteristics, the C3 profile was expected to produce higher displacement values. Subsequently, the elevated water tank was analysed considering each stratified soil profile, and the seismic responses were evaluated. The results indicated that the water tank resting on the C3 stratified soil profile showing maximum displacement compared to the other soil profiles, highlighting the significant influence of soil stratification on the seismic performance of elevated water tanks. The study also evaluated the height if sloshing waves for different seismic zones and the maximum sloshing wave was observed for Seismic Zone V. Furthermore, the results established a clear relationship between the natural frequency of the supporting soil mass and the structural response, indicating that lower soil natural frequencies lead to higher displacement demands, thereby confirming the inverse relationship between natural frequency and displacement.

CONCLUSION

The reviewed literature highlights that the seismic performance of elevated water tanks is governed by the combined effects of fluid–structure interaction (FSI), soil–structure interaction (SSI), and the dynamic characteristics of the supporting system. Earlier studies primarily focused on evaluating the seismic behaviour of elevated water tanks under fixed-base conditions and identifying deficiencies in existing design practices. Subsequent research emphasized the importance of incorporating SSI and FSSI in seismic analysis, demonstrating that soil flexibility significantly influences critical response parameters such as displacement, base shear, overturning moment, natural frequency, and sloshing behaviour. Recent investigations have extended the analysis to different staging configurations, soil conditions, and seismic vulnerability assessments, confirming that soft soils and flexible foundations amplify the seismic response of elevated water tanks.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VII, July 2026

However, most of the existing studies have considered homogeneous soil deposits, while only limited attention has been given to stratified soil profiles, which are more representative of actual field conditions. Furthermore, the influence of layered soil deposits on the dynamic characteristics of the soil–tank system, particularly the relationship between the natural frequency of stratified soils and the resulting seismic response, remains inadequately explored. Therefore, there is a need for a comprehensive investigation into the seismic behaviour of elevated water tanks supported on stratified soil deposits to develop more realistic and reliable seismic design recommendations.

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