SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I7P104

Volume 12 Issue 7, 51-62, July 2025
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Original Article

Non-Destructive Testing for Resilient Water Storage: A Sustainability Perspective for Overhead Reservoirs

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Received: 03 May 2025 Revised: 06 June 2025 Accepted: 05 July 2025 Published: 31 July 2025

Abstract - *The degradation of concrete in above water reservoirs poses intricate issues, requiring diverse in-situ evaluation techniques for accurate structural assessment. A singular Non-Destructive Testing (NDT) approach may be enough for simple situations; nevertheless, the varied circumstances in water reservoirs require a variety of procedures to guarantee precision. Rebound hammer tests may provide incorrect results on wet surfaces or constructions with high carbonation, while Ultrasonic Pulse Velocity (UPV) measurements might fluctuate due to reinforcement. Furthermore, correlations obtained from experimental data are often confined to certain materials, mix ratios, and testing settings, making extrapolation outside defined limits dubious. This research examines the implementation of NDT procedures specified in BIS standards, concentrating on overhead water reservoirs. Case studies involving several overhead tanks demonstrated relationships between different NDT findings, namely between the rebound hammer and UPV tests. These correlations provide precise estimates of structural characteristics and evaluation of corrosion, even with little testing. The results primarily pertain to the cylindrical shaft staging of the above reservoirs, providing insights for sustainable and resilient water infrastructure. This research advances sustainable and climate-resilient water storage solutions essential for urban and rural water management systems by promoting proactive maintenance and improving structural resilience.*

Keywords - *Corrosion, Cylindrical shaft staging, Non-Destructive Testing, Overhead storage reservoir, Sustainable construction.*

1. Introduction

Overhead Reinforced-Concrete (RCC) reservoirs are essential components of both urban and rural water supply systems; however, their structural integrity can decline due to the cumulative effects of ageing, harsh environmental conditions, and seismic activity, resulting in significant safety and sustainability challenges. Non-Destructive Testing (NDT) methods facilitate comprehensive evaluations of condition without damaging the asset, thereby enabling the early identification of flaws and informed decisions regarding maintenance or retrofitting. Consequently, effective disaster-risk governance must implement an integrated, multihazard, and preventive strategy that is rooted in a culture of prevention, preparedness, and prompt response. Preparedness frameworks should prioritize the "build-back-better" principle to ensure that reconstruction initiatives lead to disaster-resilient infrastructures and communities. Considering the substantial societal repercussions of earthquakes, continuous research, systematic post-event assessments, thorough crisis management protocols, and meticulous visual documentation are vital for a thorough evaluation of structural performance and remaining capacity [1, 2]. For cutting-edge research on the materials and design of any structure, a basic structural assessment is essential. Structural assessment gives full command to the engineers to gather all the relevant information of any structural element or the whole structure. Structural assessment is extremely helpful not only in the identification of the probable damage points in any structure, but also in the recognition of the possible reasons behind them. Damage to any structure can be experienced in cracks of varying dimensions, which are considered to be harmful as per the structure's health concern [3]. The existence of cracks in any construction diminishes the strength of its structural components, thereby shortening the total lifespan of the building. Should the existence of cracks indicate potential harm, a thorough visual examination must be conducted, followed by in-situ testing of the concrete surface for compression and an assessment of its reinforcing integrity. Any apparent undesirable corrosion or spalling in a structure, developed and analyzed in accordance with the current requirements of relevant codes, raises significant concerns about the overall strength and durability of the structure among researchers and engineers [4].

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"Overhead Water Tanks" are considered as one of the important infrastructural elements of blended construction of steel and RCC for storing water to utilise the same for the society. The many advantages of using a reinforced concrete tower for water tanks include: they are not affected by changes in climate, are perfectly sealed, have better shape versatility, crack resistant and thus, have an adequate life of the structure. Normal experimental setups are not enough to determine the strength of concrete in compression and the structural adequacy of standing structures. Accordingly, for the structures which are constructed decades ago, such as overhead tanks, a prolific framework is required for the assessment of the durability of the structure in situ. Non – Non-destructive tests can determine the strength properties of the concrete structure by performing various experimental procedures on the concrete surfaces, without harming the structure or causing any detrimental effect on the structure's integrity [5–7]. Various factors are responsible for causing distress in the overhead tanks during their design life. The possibility of the breakdown or complete failure of the structure before its stipulated time is comparatively higher in the scenarios where the structures are located in the dry and hot parts of the earth, accompanied by a high level of humidity, temperature and the existence of traces of basic compounds. If the regular check-ups on the health of the structure are not recorded by any means, the life of the structure will decrease, enhancing the rate of corrosion in the reinforcement and thereby giving way for consequent spalling of the concrete cover [8].

While considering the data regarding disaster studies from past decades, a huge number of overhead RCC water tanks were seriously damaged when seismic waves were experienced worldwide. One of the vital reasons for this profound damage is the inadequacy of the structural arrangement required to support the overhead tank [9]. The damage got even worse in the case of shaft type supporting framework for such overhead tanks. Thus, it can be said that the tower supporting arrangement is more prone to the attachment of seismic forces than the structure of the tank [4]. The effects of the seismic waves on the tower structure will be more severe if the supporting framework has inadequate strength, improper design and reinforcement specification, accompanied by various defects that may develop during its lifetime. Depending upon the topography, India falls under the category of moderately high disaster zones in the world [10]. India is prone to a number of natural disasters such as earthquakes, floods, cyclones, draughts, and landslides, causing huge damage to both life and property. Following the 'Hyogo Framework', India recognizes the need to transition from a reactive approach after disasters to a proactive attitude focused on mitigation and readiness to prevent losses. The Government of India enacted the Disaster Management Act in 2005, established a National Policy on Disaster Management in 2009, and in 2015 entered into three significant agreements: the 'Sendai Framework for Disaster Risk Reduction', the 'Sustainable Development Goals 2015-2030', and the 'Paris Agreement on Climate Change'. The country employs a multihazard and multi-sectoral framework approach, hence fostering national resilience. The evaluation of the damages inflicted by natural disasters, such as the Bhuj Earthquake of 2001 and the Kashmir Earthquake of 2005, is conducted. The observations of such intensive disasters may uncover the critical failure conditions of RCC overhead water tanks of varying capacities. These structures are considered to be a vital infrastructure for providing water to society. Thus, their failure will be a critical situation in post-earthquake scenarios, considering the assertion of human setbacks and the decelerating economic condition of the nation. An overhead reservoir consists of various structural elements, including a water storage tank portion with roof beams and slabs. The staging of such overhead reservoirs is made up of continuous RC columns (IS 11682: 1985). The staging considered for the designing purpose must be able to withstand different types of loads acting on it such as Dead Load, Imposed Loads (consists of Live Load, Wind Loads, Snow Loads; as per IS 875: 2016-Part III), Earthquake Loads (as per IS 1893: 2016 – Part I) and desired suitable combinations of loads [12].

Overhead reinforced-concrete water tanks are essential components of municipal water supply and fire-fighting systems; however, documented failures reveal their susceptibility to seismic forces. The collapse of two elevated tanks in Jabalpur, Punjab, during the earthquake of 1977 resulted in circumferential flexural cracks at the base of the barrel-shaped staging. Similar damage was observed following the 2001 Bhuj earthquake, where many tanks within a 100 km radius of the epicenter experienced partial or complete failure [13]. These occurrences underscore an unacceptable risk, as these structures must remain functional immediately after an earthquake to facilitate fire-fighting and the delivery of essential water. Despite the design provisions outlined in IS 1893-1:2016, which categorize many of these tanks as being in high-hazard Zones IV and V [12], routine visual inspections are inadequate for assessing hidden deterioration or confirming whether aging tanks still meet seismic performance standards. Non-Destructive Testing (NDT) provides a method for identifying internal defects without interrupting service; however, prior research has predominantly concentrated on individual NDT techniques and has rarely connected their outcomes to sustainability initiatives aimed at prolonging service life or minimising embodied carbon. This study seeks to fill this void by (i) integrating acoustic emission and infrared thermography to establish an early-warning system for damage induced by seismic activity, and (ii) linking NDT findings with a sustainable repair approach that utilises Water Hyacinth Ash (WHA) as a partial substitute for cement. Initial material characterization indicates that WHA-modified concrete demonstrates reduced water absorption and improved resistance to acid attack, suggesting its potential for durable and environmentally friendly rehabilitation. By combining advanced diagnostic methods with sustainable material solutions, this research aspires to foster climate-resilient, resource-efficient, and seismically dependable water-storage infrastructure.

The investigation consists of the following objectives: for any structure visually, a systematic approach has to be followed for the purpose of gathering readily existing information regarding the structure under consideration. Additional observations were also noted down during the time of performing the test. Figure 2 shows the deterioration of the tanks. Visual inspection is carried out for gathering the information about the degree of deterioration by making the following observations [11]:

1. Identification of the losses due to concrete cover or spalling
2. Determination of the areas of water seepage
3. Studying the damages because by expansive joints
4. Identification of the occurrence and pattern of both major and minor cracks
5. Identification of scaling or corrosion of Structural steel or reinforcement bars in RC structures
6. Analysing the extent of damages and their probable causes
7. Development of a crack at the concrete–structural steel interface

These observations offer significant initial insights into the structural integrity and assist in pinpointing areas that necessitate additional thorough examination and corrective actions.

2. Literature Review

A significant literature study encompasses the design concerns of overhead water tanks, which have been considerably modified to account for the impacts of seismic forces. The most recent amendment of section II of IS 1893: 2007 [12] delineates the criteria that ensure the structural integrity of water tanks situated in diverse Indian seismic zones. The standard described in the referenced code pertains only to above water tanks. However, the impact of seismic pressures on ground-supported tanks has not been addressed. The current worldwide practices in designing and analyzing tanks with respect to seismic factors reveal many deficiencies in the standards of IS 1893: 1984 [12]. Consequently, until date in India, there have been no genuine standards or codified regulations for evaluating the seismic integrity of fluid storage tanks. The "Guidelines for Seismic Design of Liquid Storage Tanks," which were developed extensively, focused only on the seismic analysis of tanks situated on foundations and 2-DOF idealization systems. It was advised to enhance the lateral rigidity of the tank staging by including beams as bracings [13]. In tanks with shaft staging, the influence of shear stresses may be included, notwithstanding uncertainty about the lateral stiffness of the supplied staging structural components. In seismic analysis, the factor ‘R’ reaches a maximum of 2.5 for the frame staging structure. However, it is 1.8 for the RC shaft construction, attributable to inadequate ductility and a deficiency in redundancy.

While performing the assessment of some tanks on the basis of the response of ground acceleration, it was noted that bolstered portions of the tank and the shell structure of shaft staging are worst affected under tensile straining; notably, maximum in the scenarios of an empty tank. This condition can lead to disastrous impacts if the soil structure interaction is not taken into consideration while doing the structural design. Some of the studies considered the effects, performed the seismic analysis, and recommended repairing techniques for an RC–shaft type Overhead Water Tank [4].

The ‘Structural Survey’ is a term that is allotted for the examination of the ‘health’ of an existing structure. This survey includes a critical survey of both non-structural and structural accessible components of the structure. Depending on the structural survey (critical visual survey) observations, reconnaissance and a detailed study have been carried out to determine and approve the degree of damage or distress, by conducting some in situ experiments, because of rusting, creep or any other possible reason. Non Destructive Tests prove to be an aid in assessing the structure’s non-structural and structural components, stretching from the outer surface to inner complex conditions [14]. Two of the major reasons for the possibility of distress in any structure are environmental conditions and the stress induced. The cracks that occur in the structure are classified into five different categories on the basis of severity of damage: very severe, severe, moderate, slight, and insignificant. There are various factors that are responsible for the advancement in the rate of corrosion, which relies upon the identification of the micro cracks caused by climate, particularly environmental contamination level and atmospheric moisture [15, 16]. The ideal solution for the same on the exposed surface of steel structures is providing suitable treatment to innovate the framework of the plan, which thereby includes the provision of coating on the structure to increase its durability. A proper planning and ductile designing of a structure can enhance the durability of all defensive covering applications [17].

2.1. Corrosion in Overhead Tanks

Small, shop-fabricated tanks have different protective choices than bigger, field-erected tanks. Smaller tanks are usually easier to maintain with a consistent degree of corrosion protection. Small tank isolation by mounting a horizontal tank on saddles or setting a vertical tank on structural elements, shop-fabricated tanks for aboveground applications can effectively isolate the tank from the soil. Because the tank is kept away from the conductive electrolyte, the only corrosion issues that need to be addressed are atmospheric, which are normally addressed with suitable coatings. If the tank is to be built on a conductive base, it can be simply coated with a durable dielectric coating to minimize soil contact. It has widely been remarked that putting a tank in the wrong place can be disastrous. This is correct in theory, but the concrete pad must be built to move liquids away from the tank and not accumulate water between the tank bottom and the pad. If water gathers, corrosion will most likely develop, resulting in a tank that has a shorter life than one that has been set on sand bedding. The pad must also be in good condition, with no cracks that could allow dirt contact. If the tank is set on soil, the best long-term corrosion control option is a good quality coating paired with cathodic protection. Galvanic anodes are a low-cost, low-maintenance corrosion management solution if the tank can be electrically separated. The critical points taken into consideration consist of the access of the application of coat, circumvention of garbage traps and dampness; provision of ventilation and drainage and most importantly, a cautious contact administration with other materials and provisions for safety and durability requirements. Overhead tanks built on shaft-type staging and experiencing spillage of water over longer periods will show corrosion of reinforcing bars. For better durability, unique assessments need to be done. Use of Corrosion Inhibitors is recommended in concrete for durability as it forestalls quickened rusting of the structural steel, and suitable climate-appropriate coatings might be applied for the concrete surface's durability. But, in existing tanks, Half Cell Potential tests are conducted to judge the extent of corrosion [18].

2.2. Assessment of Structural Adequacy

The judgment of the structural adequacy of any water tank and the choice of retrofitting technique depend upon the results of Non-Destructive Testing (NDTs), which includes the experiments with Ultrasonic Pulse Velocity (UPV) and Rebound Hammer (RH). These tests estimate the condition of the concrete used in tanks. The results from the UPV test give a detailed observation regarding the quality of concrete, differentiating the locations with delamination and interior breaking; and the extent of occurrence of cracks and splitting of concrete. Some of the studies [19] were based on testing the concrete samples to determine their mechanical properties by employing NDTs as per IS 516:1959 [20] and IS 13312:1992. Wankhede used the Analytical Hierarchy Process (AHP) to determine the health condition of the overhead water reservoirs in the region of Karad, located in the Indian state of Maharashtra. He used NDTs such as the UPV Test, Half–Cell Potential Testing, and Surface Hardness Test to rank the overhead water reservoirs. NDTs can also be used to discover the presence of water and the dying procedure [11 – Binda] after the occurrence of floods; which holds an impact in providing the supreme level of treatment in post disaster scenarios [21].

The advancement in framework verification [12 – Latif] employs sensors at a macro scale and integrates framework validation with advanced corrosion and cover degradation testing. This framework comprises a unit combined with a linear polarization approach for identifying corrosion locations and measuring strain at the micro-testing level. The recommendations from the most recent edition of IS 1893: 2002 (Part II) have not been implemented in overhead water reservoirs constructed before the 1990s, unless a vulnerability assessment was conducted along with the corresponding measures. This research examined the three overhead water reservoirs in the tiny city of Faridabad, Haryana, India, which has around 20 such reservoirs that have been operational for the previous 50 years. "These overhead tanks vary in age, and due to several factors, their structural integrity is generally acceptable; however, some are nearing the end of their lifespan while others are yet to be utilized." This study focuses on the evaluation of the structural durability of a selected overhead tank. The research would be beneficial for consultancies and organizations in designing overhead structures to provide adequate strength and durability, facilitate maintenance, and extend the lifespan of overhead tanks [14, 17, 23].

2.3. Contributions and Comparative Advantages

The novelty of this study lies in its dual approach, which integrates advanced Non-Destructive Testing (NDT) techniques with sustainable material application to assess and enhance the seismic resilience of overhead Reinforced Concrete (RCC) water reservoirs. Unlike prior studies that focus solely on damage detection using single-method NDT approaches, this research combines Acoustic Emission (AE) and Infrared Thermography (IRT) to provide a comprehensive and real-time structural health assessment. The synergistic use of these techniques offers deeper insight into both surface and internal flaws, especially crack initiation and propagation under stress, which are often overlooked in traditional methods like the rebound hammer or ultrasonic pulse velocity alone.

Furthermore, the study introduces the use of Water Hyacinth Ash (WHA) as a partial cement replacement in concrete repair strategies, a sustainable innovation not explored in previous works. WHA is assessed for its mechanical and durability performance, showing improved resistance to water absorption and acid attack, two critical factors in prolonging the service life of RCC tanks in harsh environments.

In summary, this research is distinguished by the following research gaps from the literature:

1. Multi-modal NDT integration (AE + IRT) for enhanced diagnostic accuracy.
2. Linking NDT outputs to sustainable rehabilitation, thereby supporting long-term structural performance.
3. Introducing and validating WHA as a green material for eco-efficient structural retrofitting.
4. Addressing seismic vulnerability specifically in high-risk zones (Zones IV and V) with practical implications for disaster-resilient infrastructure.

3. Methodology

The study examined the evaluation of NDTS in three overhead water reservoirs situated at distinct sites in Faridabad: Location 1: Boosting Station in a Housing Colony at Sector 29, Location 2: Hanuman Mandir at Sector 28, and Location 3: Raghunath Mandir at Sector 28. All overhead water reservoirs possess a circular configuration supported by shaft-type reinforced concrete staging. All three overhead water reservoirs are about 50 years old, with a single, broken reinforced concrete stairway constructed around the edge of each reservoir. Visual examination readily reveals stresses and fissures, necessitating a comprehensive structural evaluation, including the necessity for repairs and rehabilitation.

A comprehensive methodology was employed to assess the influence of creep on the longevity of overhead water reservoirs, commencing with extensive data collection from various visual inspections, subsequently followed by the execution of non-destructive tests on diverse structural elements of the reservoirs. Non-Destructive Tests (NDTs) are conducted to assess the strength of the concrete structural elements of the staging, using the Rebound Hammer Test, Ultra-Pulse Velocity Test, and Core Extraction Methods. The assessment of deterioration or damage is based on the results of the visual examination and non-destructive tests, guiding the implementation of required rehabilitation or retrofitting methods. Figure 1 presents a flowchart of the process.

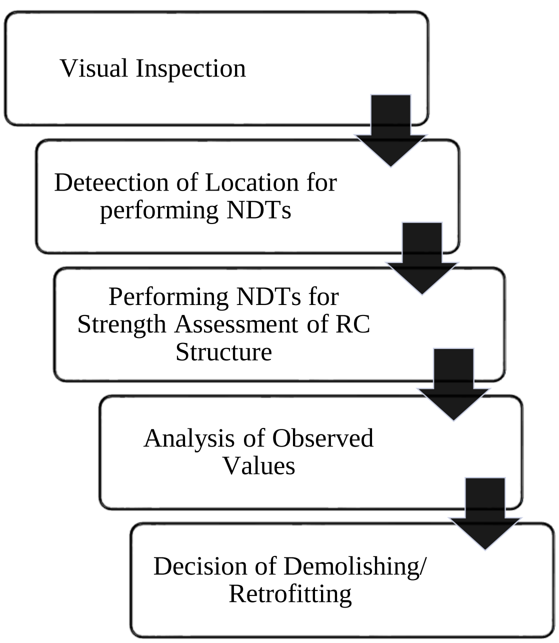

Fig. 1 Methodology adopted

In all three cases, the tanks were thoroughly inspected. A common pattern observed in all the tanks is that there is an undesirable extent of deterioration on the bottom of the tanks. Also, the staging of the structures was damaged to the extent that corroded bars are clearly visible and spalled, along with the presence of fouled concrete because of seepage. To determine the structural strength of the overhead water reservoirs, the Rebound Hammer (RH) Test, Ultrasonic Pulse Velocity (UPV) Test and Core Cutting Test were performed. One of the widely used tests to gather the characteristics of hardened cementitious composites without causing any harm to any structural element is the RH Test. Strength and durability are hardened concrete's two most important properties when considered in built–up RC structures. The RH test is employed to determine the strength of concrete in compression, considering the suitable relationship between strength and Rebound Number [2].

The basic advantage of RH is that it gives a clue about the quality of concrete as it is observed on the surface. The size of aggregates, carbonation, moisture content, age of concrete, texture of aggregates, and concrete mix design characteristics are the factors that influence the readings of the Rebound Hammer and its observation. The accuracy of the determination of the strength by RH is 25 percent. A sample size of 100 x 100 mm was prepared by the application of carborundum stone.

Six readings were taken at a single location, while the RH transducer was placed on the surface prepared by covering one–third of the shaft structure. After performing the test, the average of the Rebound Number is taken. These readings obtained were used to determine the strength with the help of a calibration graph. No necessary corrections were considered since the rebound hammer is placed on specified locations.

The velocity of an ultrasonic pulse is independent of the dimensions of the structural components, but is dependent on properties of the material under Hooke's Law; thereby, it is necessarily dependent on the concrete mix and material used. The standard of the UPV Test is grounded on the fact that velocities higher in magnitude and time reduction in the reception of pulse are gathered for a concrete of the best quality with no internal cracks and a homogeneous structure.

For instance, in the detection of a crack in the concrete element, the transmitted pulse gets weakened and thus moves in different directions, which, in turn, increases the distance. Thus, these pulses will be received after the stipulated time, hence showing the lower magnitudes of wave velocity. The basic setup of the UPV Test is to measure the travel time of the wave through concrete. The velocity is calculated by the distance travelled by the wave with respect to travel time. The velocity is reported in km/s, which subsequently determines the quality of concrete. The values so obtained are used to examine the condition of the concrete in terms of the presence of voids, its integrity and homogeneity. The quality of the concrete can be reported as: "Excellent", "Good", "Medium" and "Doubtful", depending on the measured values of UPV, cited in IS 13311: 1992 [13].

Fig. 2 Completely deteriorated side of the tank

In this study, three overhead water reservoirs are taken into consideration and are being tested for the Rebound Hammer Test and UPV Test. A core cutting test is also performed to determine the strength of the concrete sample.

Since no direct relation is established between the above three stative NDTs for overhead water reservoirs, this study aims to fulfil the necessary requirement, which will help the engineers carry out their necessary on-site research and thus, may save time in achieving the same.

4. Results

4.1. The Test Results Obtained from Schmidt's Rebound Hammer Test, UPV Test and Core Cutting Test for The Different Points at Three Different Locations

4.1.1. For the Overhead Water Reservoir located at the Boosting Station in a Housing Colony at Sector – 29, Faridabad, India:

Table 3 gives a brief description of 10 rebound hammer values at 6 different points, as well as the average rebound number and estimated cube compressive strength in (N/mm2). The ultrasonic pulse velocity readings for 20 concrete samples and their corresponding concrete quality grading based on IS:13311(P-1) standards, are presented in Table 1.

Core test findings in Table 2 show variance in ultimate load and cylinder strength among core samples. Table 4: Half Cell Potential Results show that the core sample length-to-diameter ratio and ultimate load are correlated.

Ultrasonic Pulse Velocity (UPV) testing was performed in compliance with IS: 13311 (Part 1) to evaluate the quality of concrete. The findings reveal that most of the measurements are categorized as 'Doubtful', with merely three locations exhibiting 'Medium' quality. There were no readings identified as 'Good' or 'Excellent', indicating considerable variation and potential deterioration in the concrete integrity throughout the examined areas.

Table 1. Ultrasonic pulse velocity readings

S. No.	Requirement as per IS:13311(P-1)	Result	Concrete Quality Grading
1	> 4.5: Excellent 3.5 to 4.5: Good 3.0 to 3.5: Medium < 3.0: Doubtful	2.69	Doubtful
2		1.00	Doubtful
3		3.84	Medium
4		2.54	Doubtful
5		1.12	Doubtful
6		0.87	Doubtful
7		1.43	Doubtful
8		0.99	Doubtful
9		3.14	Medium
10		2.35	Doubtful
11		0.96	Doubtful
12		1.65	Doubtful
13		1.79	Doubtful
14		2.88	Doubtful
15		2.33	Doubtful
16		1.16	Doubtful
17		1.78	Doubtful
18		3.44	Medium
19		1.67	Doubtful
20		2.44	Doubtful

Table 2. Core test results

Core No.	Length (mm)	Diameter (mm)	L/D	Ultimate Load (KN)	Cylinder Strength (N/mm^2)
1	161.30	93.59	1.7234	100.2	14.57
2	117	67	1.7463	67.3	19.0887
3	122	67	1.8209	53.8	15.2596
4	113	67	1.6866	74.5	21.1309
5	116.6	67	1.7403	42.5	12.0545

Rebound Hammer testing was conducted to assess the surface hardness and compressive strength of concrete. The average rebound values varied from 31.00 to 35.50, which correspond to estimated compressive strengths ranging from 31 N/mm^2 to 39 N/mm^2.

The moderate strength discrepancies in the values indicate localized variations in concrete compaction or surface condition.

Table 3. Rebound hammer test readings

S. No.	Rebound Hammer Values						Average rebound no.	Estimated Cube Compressive Strength (N/mm^2)
	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6		
1	33	37	38	35	31	39	35.50	35
2	35	34	32	36	36	38	35.17	34
3	35	29	39	34	38	38	35.50	39
4	33	33	35	36	31	35	33.83	31
5	37	31	30	36	37	30	33.50	32
6	34	31	29	33	33	39	33.17	33
7	36	32	35	34	31	35	33.83	34
8	32	31	36	36	35	30	33.33	33
9	34	29	30	33	31	29	31.00	31
10	37	33	33	27	32	35	32.83	33

Table 4. Half cell potential results

S. No.	Half Cell Reading	Risk of Corrosion
1	-415	90
2	-415	90
3	-410	90
4	-377	90
5	-413	90
6	-451	90

Table 5. Ultrasonic pulse velocity readings

S. No.	Requirement as per IS:13311(P-1)	Result	Concrete Quality Grading
1	> 4.5: Excellent 3.5 to 4.5: Good 3.0 to 3.5: Medium < 3.0: Doubtful	1.98	Doubtful
2		1.45	Doubtful
3		4.12	Medium
4		2.56	Doubtful
5		1.45	Doubtful
6		0.55	Doubtful
7		1.46	Doubtful
8		1.11	Doubtful
9		3.21	Medium
10		1.21	Doubtful
11		2.22	Doubtful
12		1.36	Doubtful
13		2.57	Doubtful
14		1.47	Doubtful
15		2.44	Doubtful
16		1.17	Doubtful
17		1.58	Doubtful
18		3.67	Medium
19		1.19	Doubtful
19		1.19	Doubtful
20		0.87	Doubtful

4.1.2. The Overhead Water Reservoir is located at Hanuman Mandir in Sector-28, Faridabad, India.

Table 6 presents the average rebound number and estimated cube compressive strength of 10 concrete samples, along with the rebound hammer test readings. The ultrasonic pulse velocity readings for 20 concrete samples and their corresponding concrete quality grading based on IS:13311(P-1) standards, are presented in Table 5. The results of core testing, which include the length, diameter, length-to-diameter ratio, ultimate load, and cylinder strength of four concrete core samples, are presented in Table 7. Table 8 displays the half-cell potential readings for six concrete samples and the corresponding corrosion risk.

Table 6. Rebound hammer test readings

S. No	Rebound Hammer Values						Average rebound no.	Estimated Cube Compressive Strength (N/mm2)
	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6		
1	31	39	36	37	28	42	35.50	35
2	32	35	29	39	38	37	36.67	37
3	34	32	36	37	35	38	35.33	35
4	30	34	33	34	29	36	32.67	33
5	35	30	30	36	37	30	33.00	33
6	33	33	35	36	31	35	33.83	31
7	37	31	30	36	37	30	33.50	32
8	34	31	29	33	33	39	33.17	33
9	36	32	35	34	31	35	33.83	34
10	32	31	36	36	35	30	33.33	33

Table 7. Core test results

Core No.	Length (mm)	Diameter (mm)	L/D	Ultimate Load (KN)	Cylinder Strength (N/mm2)
1	181.30	93.69	1.935	47.40	6.877
2	152.77	93.40	1.635	98.60	14.398
3	152.71	93.80	1.628	94	13.61
4	151.36	93.59	1.617	73.60	10.702

Table 8. Half cell potential results

S. No.	Half Cell Reading	Risk of Corrosion
1	-461	90
2	-423	90
3	-385	90
4	-322	90
5	-405	90
6	-466	90

The primary test outcomes reveal low compressive strengths, varying from 6.88 N/mm² to 14.40 N/mm², which are markedly beneath acceptable thresholds, indicating significant deterioration in the strength of the concrete. The L/D ratios fall within permissible limits, thereby ensuring the reliability of the testing process. Moreover, half-cell potential measurements consistently surpass -300 mV, suggesting a 90% likelihood of active corrosion in the reinforcement. Collectively, these findings confirm severe.

Degradation in both the quality of the concrete and the condition of the embedded steel necessitates prompt remedial measures.

4.1.3. The Overhead Water Reservoir is located at Raghunath Mandir in Sector 28, Faridabad, India.

The results of the rebound hammer test, including the average rebound number and estimated cube compressive strength, are shown in Table 9. The data pertains to ten different concrete samples. Twenty samples of concrete were tested for ultrasonic pulse velocities, and their associated quality grades were listed in Table 10 according to the IS:13311(P-1) specifications for concrete. Four concrete core samples were tested for several parameters, including ultimate load, cylinder strength, length-to-diameter ratio, diameter, and length, and the findings are shown in Table 11. The half-cell potential values and associated corrosion risk for six different concrete samples are shown in Table 12.

The results of the Rebound Hammer Test show average rebound values between 31.50 and 35.33, which correspond to estimated compressive strengths ranging from 31 N/mm² to 35 N/mm². These figures indicate a relatively consistent and moderate level of surface concrete strength, with no notable anomalies detected. The findings imply that the surface layer of the concrete is in acceptable condition, although additional correlation with core test data is required for a thorough structural evaluation. Most readings are within the anticipated range for aged concrete, suggesting uniform surface hardness across the tested areas. However, as the rebound hammer primarily evaluates surface characteristics, it may not adequately reflect internal deterioration.

Table 9. Rebound hammer test readings

S. No.	Rebound Hammer Values						Average rebound no.	Estimated Cube Compressive Strength (N/mm2)
	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6		
1	30	32	31	35	29	32	31.50	32
2	32	34	28	31	34	35	32.33	32
3	33	32	35	30	36	36	33.67	34
4	30	33	31	32	29	34	31.50	32
5	32	33	28	32	34	36	32.50	33
6	33	32	29	34	32	39	33.17	33
7	36	32	36	33	31	35	33.83	34
8	34	31	37	37	36	39	35.33	35
9	30	34	33	35	30	36	32.67	33
10	33	34	35	35	30	36	33.83	31

Table 10. Ultrasonic pulse velocity readings

S. No.	Requirement as per IS:13311(P-1)	Result	Concrete Quality Grading
1	> 4.5: Excellent 3.5 to 4.5: Good 3.0 to 3.5: Medium < 3.0: Doubtful	1.54	Doubtful
2		1.23	Doubtful
3		3.89	Medium
4		2.10	Doubtful
5		0.76	Doubtful
6		1.14	Doubtful
7		2.65	Doubtful
8		0.77	Doubtful
9		3.16	Medium
10		1.45	Doubtful
11		2.65	Doubtful
12		2.56	Doubtful
13		1.87	Doubtful
14		1.34	Doubtful
15		1.65	Doubtful
16		2.98	Doubtful
17		2.11	Doubtful
18		1.37	Medium
19		1.98	Doubtful
20		1.53	Doubtful

The results of the Ultrasonic Pulse Velocity test, according to IS:13311 (Part 1), indicate that most values are categorized as 'Doubtful', which signifies inadequate concrete quality. Only three measurements are classified.

Within the 'Medium' range, no readings achieve the 'Good' or 'Excellent' standards. This implies considerable degradation in the internal structure of the concrete, highlighting the necessity for a more thorough investigation and potential remedial measures.

Table 11. Core test results

Core No.	Length (mm)	Diameter (mm)	L/D	Ultimate Load (KN)	Cylinder Strength (N/mm2)
1	165.62	94	1.7619	158	22.779
2	166.66	93.80	1.7767	65.8	9.527
3	169.04	93.5	1.8079	105.8	15.417
4	172.14	95.8	1.7968	110.7	23.326

Table 12. Half cell potential results

S. No.	Half Cell Reading	Risk of Corrosion
1	-421	90
2	-429	90
3	-444	90
4	-403	90
5	-389	90
6	-437	90

Overall, the findings suggest a significant degree of internal deterioration in the concrete, with only a limited number of regions exhibiting satisfactory quality. The persistently low UPV values underscore the necessity for structural rehabilitation. These results emphasize the critical need to incorporate both non-destructive and destructive testing methods for precise evaluation and informed decision-making.

4.2. Correlation between the Test Values

Figure 3 illustrates the association between the rebound hammer test results and the ultrasonic pulse velocity (UPV) test data for the examined overhead tanks. Figure 4 illustrates the relationship between the half-cell potential test values and the rebound hammer test results. The results from the UPV and half-cell potential tests show a favourable correlation, as seen in Figure 5. The outcomes of the core-cutting test and the rebound hammer test are correlated, as seen in Figure 6.

Rebound Hammer and UPV Test: y = 0.0865x

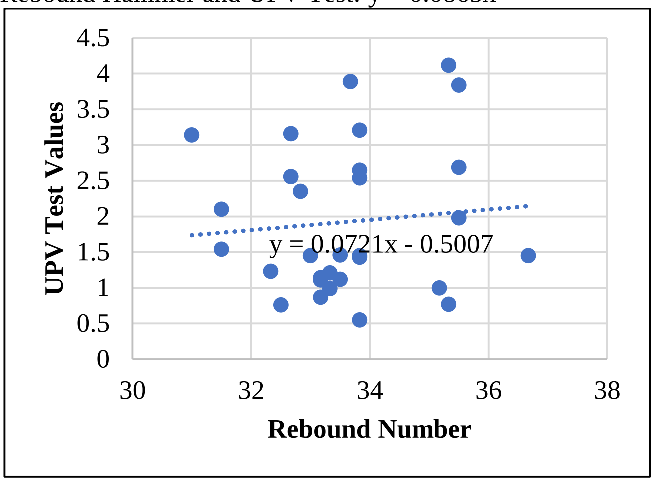

Fig. 3 Relationship between rebound hammer test value (x) and UPV test (y)

The overhead tanks under study were built more than 50 years ago and have been experiencing seepage and leakage of water. As per the plotted values, there is a weak correlation between Ultrasonic Pulse velocity values and rebound hammer readings. Though the estimated compressive strength from the rebound hammer is above 30N/mm2, the UPV values are in a doubtful range, which clearly shows that the concrete has delaminated from inside, whereas the surface concrete is hard. The hardness of surface concrete can also be attributed to carbonation, as the tanks are situated in a highly inhabited and traffic congested area.

Rebound Hammer and Half–Cell Potential Test:
y = -0.1702

A negative and weak correlation exists between Rebound Hammer values and Half Cell Potential values. The risk of corrosion in the rebars is as high as 90%.

Half–Cell and UPV Test: y = 0.1097x

Positive correlation between UPV and Half Cell potential clearly reflects the increased risk of corrosion, as ‘Doubtful’ and ‘Medium’ Concrete quality grading has degraded the passive alkaline layer over the rebars. So, it can be inferred that weakly graded ultrasonic pulse velocity weakly graded concrete will show higher risks of corrosion. In case of tanks, weak concrete also indicates that permeability has increased, and seepage/leakage water will have a greater ingress to reinforcement bars.

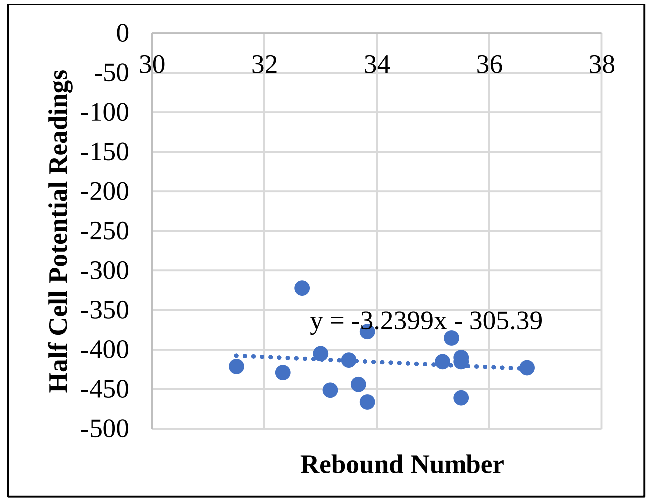

Fig. 4 Relationship between rebound hammer test value (x) and half–cell test (y)

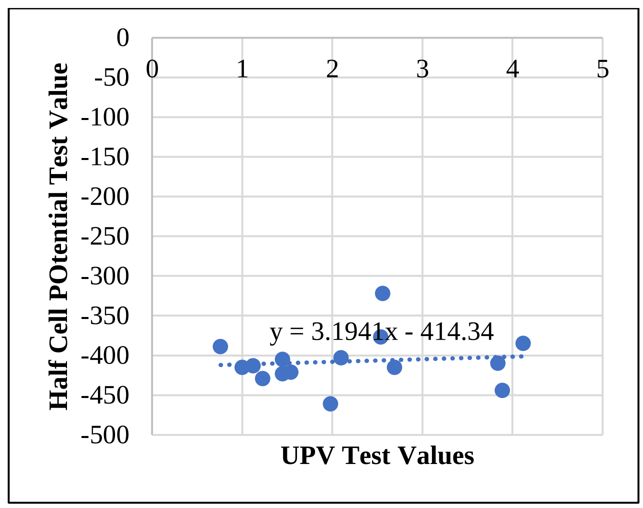

Fig. 5 Relationship between UPV test (x) and half–cell test (y)

Rebound Hammer and Core – Cutting test: **y = -0.2842x**

While Rebound Hammer measurements reflect the in-situ compressive strength of concrete, the data acquired from the tank staging reveal an inverse association between the compressive strength of removed cores and the Rebound values.

This unexpected outcome may be ascribed to the tank staging being in a saturated condition, yielding implausible rebound number values that corroborate the unreliability of the estimated strength, as indicated in the BIS code ‘IS 13311-2 (1992): Method of non-destructive testing of concrete- methods of test, Part 2: Rebound hammer [CED 2: Cement and Concrete].

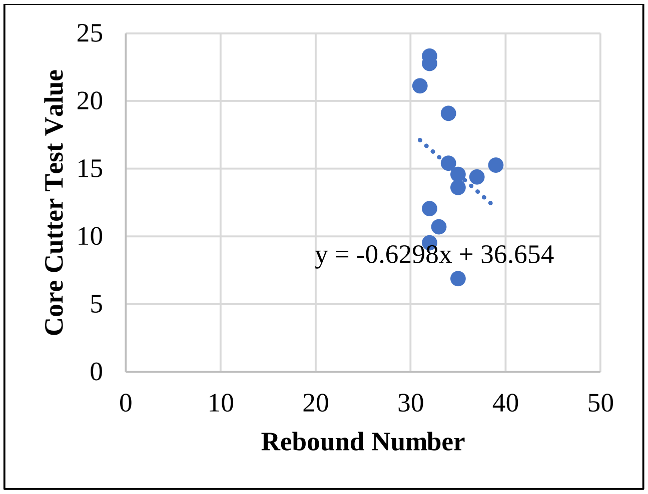

Fig. 6 Relationship between rebound hammer test (x) and core–cutting test (y)

The correlation analysis indicates discrepancies between surface hardness and the internal quality of concrete, as rebound hammer results frequently overstate the true condition of the concrete. The weak or negative correlations observed with UPV and core test values emphasize the drawbacks of depending exclusively on surface-based tests, particularly in structures influenced by moisture, such as overhead tanks. Furthermore, the positive correlation between UPV and half-cell potential underscores the heightened risk of corrosion in compromised concrete, thereby reinforcing the necessity for comprehensive assessment methods to guarantee precise evaluation and efficient maintenance planning.

4.3. Discussion

The same patterns were observed in the Non-Destructive Tests (NDT) and core cutting experiments conducted on three overhead water reservoirs in Faridabad, India. The Ultrasonic Pulse Velocity (UPV) test results (Tables 1, 5, and 10) indicated doubtful quality grading, implying internal defects or deterioration, while the rebound hammer test results (Tables 2, 6, and 9) indicated moderate to high compressive strength. The concrete's ultimate load and cylinder strength were found to vary significantly in the core test results (Tables 3, 7, and 11), suggesting a broad spectrum of concrete strengths. Tables 4, 8, and 12 demonstrate that the half-cell potential test results indicate a high risk of corrosion (90%) in all test locations. Furthermore, the correlation between the test results was examined, revealing modest correlations between the rebound hammer and UPV test values (Figure 3) and the rebound hammer and half-cell potential test values (Figure 4). A positive correlation was observed between the half-cell potential test values and UPV (Figure 5), suggesting that the risk of corrosion in unstable graded concrete is elevated. The rebound hammer and core-cutting test values exhibited a negative correlation (Figure 6). The findings emphasize the necessity of integrating multiple testing methods to accurately evaluate the condition of overhead water reservoirs, particularly in damp conditions, and underscore the limitations of rebound hammer testing.

5. Conclusion

The three overhead water reservoirs in Faridabad, India, were subjected to Non-Destructive Tests (NDT) and core cutting tests, which disclosed consistent patterns of moderate to high compressive strength, internal defects or deterioration, and a high risk of corrosion. The feeble correlation between rebound hammer test values and UPV test values, as well as between rebound hammer test values and half-cell potential test values, implies that rebound hammer testing may not be a reliable method for evaluating the internal condition of the concrete or the risk of corrosion. The positive correlation between UPV test values and half-cell potential test values suggests that the risk of corrosion in feeble graded concrete is elevated. In conclusion, the study underscores the significance of integrating a variety of testing methods to accurately evaluate the condition of aerial water reservoirs and guarantee their structural integrity.

Credit Authorship Contribution Statement

Ram Prakash: Conceptualization, Methodology, Review, Writing, Investigation, and Visualization,

Senthil Vadivel T: Conceptualization, Methodology, Review, Writing, Investigation, Visualization, Editing, and Supervision.

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