*J.Natn.Sci.Foundation Sri Lanka 2022 50 (2): 371 - 386*
DOI: http://dx.doi.org/10.4038/jnsfsr.v50i2.10474

**RESEARCH ARTICLE**

## Structural engineering

# Combined use of non-destructive tests, visual inspection and service life prediction to ensure the reliability of reinforced concrete water tanks

**K Ranasinghe[1*] and S De Silva[2]**
[1] *National Water Supply & Drainage Board, Galle Road, Ratmalana, Sri Lanka.*
[2] *Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna, Hapuagala, Wackwella, Sri Lanka.*

Submitted: 24 March 2021; Revised: 03 September 2021; Accepted: 26 November 2021

**Abstract**: Corrosion of reinforcement is the most significant cause of premature deterioration of reinforced concrete structures. Many of the concrete structures have been exposed to aggressive environments, suffer from durability problems, and fail to fulfil their design service life requirements. Chloride-induced corrosion is one of the deterioration mechanisms that may reduce the service life of reinforced concrete structures. The condition assessment of a reinforced concrete structure over a period of time is useful with routine monitoring. The majority of water supply systems have some form of water storage tanks, most often constructed from reinforced concrete. These tanks are an integral part of the potable water distribution network. To ensure durability and sustainability, they should be adequately inspected and maintained. For effective and durable repairing or retrofitting of reinforced concrete tanks, the use of a suitable condition assessment system may give more sustainable results. This study aimed to propose a system to perform a condition assessment of existing reinforced concrete water retaining structures. The reinforced concrete tanks were selected in Galle, Matara, and Hambanthota districts in Sri Lanka, to perform visual inspections and non-destructive tests. The service life of reinforced concrete structures in marine environments depends on chloride-induced corrosion. Therefore, the development of the chloride penetration model is essential for its assessment. Fick's Second Law of diffusion provides a simple way to predict the chloride penetration in such situations. Therefore, an analytical method is introduced to predict the service life of reinforced concrete water retaining structures taking into account well-known corrosion models such as Fick's Second Law and the Bazant model. Both the predicted service life and the tank soundness score can be used to develop a tank remediation plan more effectively. Therefore, the repair / retrofitting methods proposed based on such assessment will be cost-effective as well as more reliable in enhancing the service life of the water retaining structures. However, modelling the service life of reinforced concrete structures is a complex process as it includes many uncertainties.

**Keywords:** Aggressive environments, chloride induced corrosion, condition assessment, non-destructive test, service life prediction, visual inspections.

## INTRODUCTION

Corrosion of steel embedded in concrete is a serious deterioration problem causing considerable losses to the nation due to maintenance and repair works. Corrosion-induced damage, such as concrete cracking, spalling, delamination, and cross-sectional reduction of the reinforcement, may dramatically affect the long-term performance of reinforced concrete structures, such as a decrease in the load-bearing capacity and, in the worst-case lead to fatal structural consequences, such as failure (ACI, 2008).

The corrosion level of the existing reinforced concrete bridges and buildings has been studied in many types of research. However, a comprehensive level of corrosion study on the water retaining structures in Sri Lanka is

[*] Corresponding author (sudhira@cee.ruh.ac.lk; https://orcid.org/0000-0003-0804-5097)

hardly found. The National Water Supply & Drainage Board in Sri Lanka has many water retaining structures close to the coastal belt. Some of them have been used in service for more than 30 years. Generally, the majority of them are continuously operating without adequate maintenance or any restoration. This investigation finds that they are subjected to spalling, cracks, water leakage, and vegetation on the concrete elements, apart from chloride-induced corrosion damage. Perhaps they hardly achieved the expected design service life of the structure.

The deterioration rate of reinforced concrete structures can be reduced by adopting suitable restoration methods based on continuous monitoring of such structures using visual examination and non-destructive testing. A condition assessment with visual inspection and non-destructive test provides information on its structural performance. Further, to ensure its durable service and select the most appropriate repair method, it is essential to follow up a suitable condition assessment for reinforced concrete water retaining structures.

This study is focused on developing a mechanism to evaluate the current structural condition of existing water retaining structures, based on a visual inspection and non-destructive tests, as well as to predict the service life depending on prevailing mathematical models. For the study, selected reinforced concrete tanks located in the Southern Province in Sri Lanka were used. The locations of the selected water tanks are shown in Figure 1.

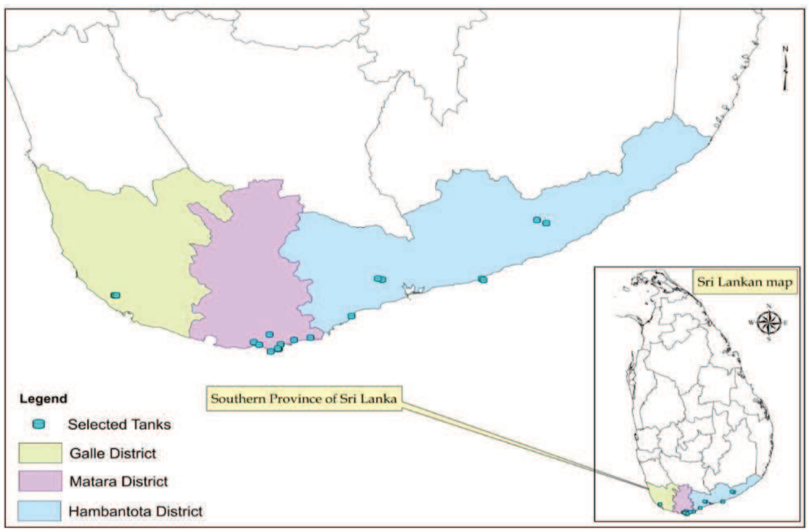


**Figure 1:** Location map of selected water tanks

## MATERIALS AND METHODS

The condition assessment of reinforced concrete water retaining structures is mainly based on the data collected from visual inspection and non-destructive testing. The assessment methodology is developed based on 'Synthesis of National and International Methodologies Used for Bridge Health Indices', published by the Federal Highway Administration (FHWA), US Department of Transportation (Publication no. FHWA-HRT-15-081, 2016) in addition to the past research thesis and papers (Rashidi & Gibson, 2011; Pushpakumara, 2014).

Whether the structure should be repaired, rehabilitated, or replaced can be decided more technically based on remaining service life predictions (Bazant, 1979a; 1979b; Tuutti, 1982; Ming *et al*., 2009). Thereby, the remaining service life is calculated. The structural repair, rehabilitation, or replacement can be selected more technically as well as economically based on the predicted remaining service life. The methodology used here is mainly based on the report, 'ACI 365.1R-00' published by American Concrete Institute (ACI, 2000). The current condition states of 30 existing reinforced concrete tanks were assessed to validate the proposed assessment procedure.

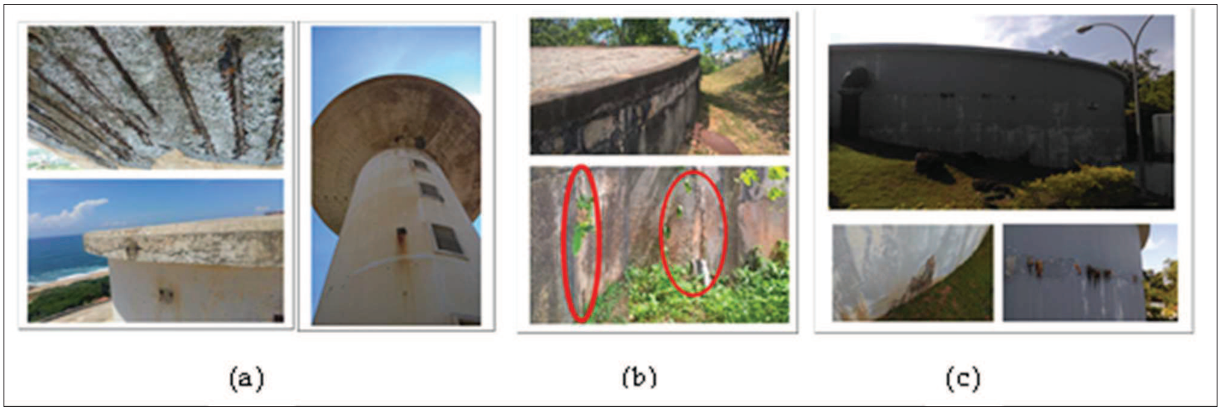


**Figure 2:** Existing reinforced concrete water tanks with corrosion effects: (a) structure no. 13 at Hambantota Sri Lanka; (b) structure no. 02 at Matara Sri Lanka; and (c) structure no. 19 at Galle Sri Lanka

## Data collection from visual inspection

Each square meter of reinforced concrete structure was carefully scrutinized to identify the visual defects and failures. Crack details (i.e., crack type, length, and width), tank element details, vegetation cover (i.e., plant type and area), structural failures, spalling, delamination and reinforcement exposures, water leakages, distance from the coastal belt, the surrounding temperature, and humidity were measured and recorded into the visual inspection sheet. Temperature, humidity, and distance from the coastal belt were used to evaluate the environmental conditions. Apart from that, extra important data of the structures such as age, capacity, dimension, past maintenance details, and information about its past utilization were collected. Some reinforced concrete water tanks with corrosion effects that were observed during the data collection are shown in Figure 2. The formation of subsequent testing programmes was done using non-destructive tests based on an initial indication, which was provided by the visual inspection of reinforced concrete water tanks (ACI, 2008).

### *Visual inspection factor (VIF)*

A rating value for visual inspection parameters, such as vegetation cover, bleed marks with surface staining, spoiling with reinforcement exposures, surface cracks, surface voids, and honeycombing area was introduced.

Rating Values (RV) and priority weights for visual inspection data were used to determine the Visual Inspection Factor (VIF). Rating values were assigned to quantify tank conditions based on visual inspection data shown in Table 1. A higher rating value corresponds to a critical stage of the structure (Pushpakumara, 2014).

**Table 1:** Rating values for visual inspection data

| Rating value (RV) | Vegetation cover (VC) | Bleed marks / water leakage (SB) | Spalling (SP) | Visibility of cracks (CK) | Surface voids and honey combing area (%) (SH) |
|---|---|---|---|---|---|
| 1 | No | No | No | No | No |
| 2 | Moss and algae | Low | Initial stage | Hair cracks | 0–5 |
| 3 | Herbs | High | Concrete cover remove | < 2 mm | 5–10 |
| 4 | Plants | Very high | R/F exposed | >2 mm | >10 |

Table 2 shows the scales for relative importance value (i.e., importance intensity) for different criteria proposed by Saaty (1980). The Analytical Hierarchy Process (AHP) developed by Saaty (1980) can be used to find the priority vector of the visual inspection data (Saaty, 1980; 1988; 1994).

The importance of intensity values is assigned to equation (1). Vegetation Cover (VC) growth significantly influences the deterioration of tank elements compared to Surface Bleed marks (SB). Therefore, compared to VC, Surface Bleed marks (SB), Spalling (SP), and Crack (CK) have intermediate value (i.e., 4), Strong importance (i.e., 5), and Moderate importance (i.e., 3) respectively. Besides, compared to surface voids and Honeycombs (SH), VC is of moderate importance (i.e., 3; refer to Table 2). Further, the Spoiling (SP) indicates the worst condition of an element, which causes failure, compared to VC. Therefore, SP has Strong importance (i.e., 5) compared to VC of elements (Table 2). On the other hand, SP was assessed as an intermediate value (i.e., 2) between two judgments (of equal importance, i.e., 1) to moderate importance (i.e., 3) compared to SB (Table 2). SP has moderate importance (i.e., 3) compared to SH. The results of the comparison of visual inspection data arrange as a comparison matrix.

**Table 2:** Relative importance values introduced by Saaty *et al*. (1980)

| Importance intensity | Explanation |
|---|---|
| 1 | Equal importance |
| 3 | Moderate importance of one over another |
| 5 | Strong importance of one over another |
| 7 | Very strong importance of one over another |
| 9 | The absolute importance of one over another |
| 2,4,6,8 | Intermediate values between the two judgments |
| Reciprocals | Reciprocal for inverse comparison |

The results of the comparison of visual inspection data may be categorized in a reciprocal comparison matrix, as shown in equation (1).

$$\begin{array}{c} \\ VC \\ SB \\ SP \\ CK \\ SH \end{array} \begin{array}{c} \begin{array}{ccccc} VC & SB & SP & CK & SH \end{array} \\ \begin{bmatrix} 1 & \frac{1}{4} & \frac{1}{5} & \frac{1}{3} & 3 \\ 4 & 1 & \frac{1}{2} & 2 & 5 \\ 5 & 2 & 1 & 4 & 3 \\ 3 & \frac{1}{2} & \frac{1}{4} & 1 & 2 \\ \frac{1}{3} & \frac{1}{5} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix} \end{array} \quad ...(1)$$

The priority weights of visual inspection data categories were estimated as a normalized eigenvector by dividing each element by the sum of that column and then computing the average of each row. That gives the priority weight of the corresponding visual inspection data, and the results are tabulated in Table 3 (Ming *et al*., 2009; Rashidi & Gibson, 2011).

**Table 3:** Priority weight of visual inspection data

| Visual inspection parameters | Priority weight |
|---|---|
| Vegetation cover (VC) | 0.097 |
| Surface staining and bleed marks / water leakage (SB) | 0.277 |
| Spoiling (SP) | 0.409 |
| Crack (CK) | 0.146 |
| Surface voids and honeycombs (SH) | 0.071 |

The priority weights of visual inspection data (Table 3) are used as coefficients in equation (2). The rating values assigned based on visual inspection data (Table 1) for equation (2) gives the Visual Inspection Factor (VIF) and it is then rounded off to the nearest whole number (VIF Є 1, 2, 3, 4).

$$VIF = 0.097\ RV_{VC} + 0.277\ RV_{SB} + 0.409\ RV_{SP} + 0.146\ RV_{CK} + 0.071\ RV_{SH} \quad ...(2)$$

where $RV_{VC}$, $RV_{SB}$, $RV_{SP}$, $RV_{CK}$, and $RV_{SH}$ are rating values (Table 1) of Vegetation Cover (VC), Surface Bleed marks (SB), Spoiling (SP), Differential movements or Crack (CK), and Surface voids and Honeycombing (SH) respectively. For example, if VC is found to be 'moss and algae', the value of $RV_{VC}$ should be two. If SB is found to be 'very high', $RV_{SB}$ should be four.

### *Crack detail factor (CDF)*

The number of cracks, crack width (using a crack gauge) and crack length are recorded during visual inspection. Then based on the above-recorded data, the final rating values for crack width, number of cracks, crack length, and crack depth can be determined (Rashidi & Gibson, 2011; Pushpakumara, 2014).

**Table 4:** Rating values for crack details

| Rating values (RV) | Crack details | | | |
|---|---|---|---|---|
| | Number of cracks (N) | Crack width (mm)(W) | Crack length (mm) (L) | Crack Depth (mm) (D) |
| 1 | No cracks | | | |
| 2 | 1–2 | 0.25–1 | < 100 | < 10 |
| 3 | 2–3 | 1–2 | 100–300 | 10–20 |
| 4 | > 3 | > 2 | > 300 | > 20 |

The AHP is used to develop the reciprocal comparison matrix of crack details and priority weights of crack detail. The priority weights of crack detail are assigned as coefficients in equation (3). The rating values assigned to Equation 3 are based on collected data as shown in Table 4.

Then the equation gives the Crack Details Factor (CDF) and it is then rounded off to the nearest whole number (CDF Є 1, 2, 3, 4).

$$CDF = 0.489\, RV_N + 0.138\, RV_W + 0.235\, RV_L + 0.138\, RV_D \qquad \dots (3)$$

where $RV_N$, $RV_W$, $RV_L$, and $RV_D$ are rating values for the number of cracks, crack width, crack length, and crack depth, respectively.

### *Element significant factor (ESF)*

Based on the element significant factor used by the researchers for the analysis of concrete bridges (Rashidi & Gibson, 2011; Pushpakumara *et al*., 2017), the new ESFs were introduced similarly for the main elements of reinforced concrete water tanks, as shown in Table 5. The lower rating value reflects the minor significant element, and higher rating values refer to the most significant element in the water tank.

**Table 5:** Element significant factor

| Element | (ESF) |
|---|---|
| Roof | 1 |
| Walls | 2 |
| Base slab | 3 |
| Shaft, columns. beams, foundation | 4 |

### *Causal factor (CF)*

Aggressive environmental conditions, age, and maintenance level may be directly involved with the overall condition of a water tank (Pushpakumara, 2014;

**Table 6:** Rating values for each parameter of the causal factor

| Rating value | Age of the structure (A) | Type of exposure (E) | Maintenance level (M) | Quality of inspection (I) |
|---|---|---|---|---|
| 1 | Recently build | Mild | Satisfactory level | Very high |
| 2 | New | Moderate | Moderate satisfactory | High |
| 3 | Old | Severe | Poor level | Medium |
| 4 | Very Old | Very severe | Very poor level | Low |

Pushpakumara *et al*., 2017). Further, the standard of the inspection contributes to the condition assessment of water tanks. Therefore, the above factors are also considered during the calculation of overall tank condition and are commonly named the causal factor (CF). Table 6 shows the rating values for causal factors. The higher rating value reflects the worst situation (Ming *et al*., 2009; Rashidi & Gibson, 2011).

The AHP is used to develop the reciprocal comparison matrix of causal factors and priority weights of causal factors are determined. The causal factor (CF) is calculated by using equation (4).

$$CF = 0.225\ RV_A + 0.471\ RV_E + 0.189\ RV_M + 0.115\ RV_I \quad \ldots (4)$$

$RV_A$. $RV_E$, $RV_M$, and $RV_I$ represent the rating value for age, exposure condition, maintenance level, and quality of inspection, respectively (CF Є 1, 2, 3, 4).

***Element construction type factor (ECTF)***

The type which is used for the construction of the water tank is another important factor. Table 7 shows the construction type and their vulnerability for the tank condition assessment developed based on past research studies (Rashidi & Gibson, 2011; Pushpakumara, 2014). The higher construction type factor reflect more vulnerability.

**Table 7:** Element construction type factor (ECTF)

| Construction type | ECTF |
|---|---|
| Precast concrete | 1 |
| Pre-stressed concrete | 2 |
| Steel | 3 |
| Reinforced concrete | 4 |

**Non-destructive test factor (NDF)**

The non-destructive tests such as rebound hammer test, cover meter survey, concrete resistivity test, and crack gauge are used to investigate the structural condition of the reinforced concrete tanks. The rebound hammer is a surface hardness tester that indicates the quality and soundness of the concrete surface. The cover meter is used to investigate the precise concrete cover depth as well as pinpoint the exact location of the rebar in the reinforced concrete water tank. The corrosion resistivity meter is used to assess the possible rate of corrosion in embedded reinforcing steel. Figure 3 indicates a few photographs of data collection in the field.


**Figure 3:** Data collection by NDT: (a) record data from visual inspection; (b) rebound hammer test; (c) concrete resistivity test; and (d) cover meter survey

The past studies (Ming *et al*., 2009; Rashidi & Gibson, 2011) indicate, the corrosion rate is a more critical parameter than the rebound number and concrete cover. The corrosion rate gives a hint about the corrosion status of the particular reinforced concrete structural element. The rebound number evaluates the compressive strength of the concrete surface. The minimum cover should be maintained to ensure the safe transmission of bond forces, durability, and fire resistance of the reinforced concrete members. Hence, the cover is one indicator of a durable structure. Therefore, from the above facts, as well as past studies (Pushpakumara, 2014), the priority weight for Corrosion Rate (CR), Rebound Number (RN), and Concrete Cover (CC) can be assigned as 0.5, 0.3, and 0.2, respectively. The Non-destructive Test Factor (NTF) is calculated from equation (5).

$$NDF = (0.5 \times \alpha) + (0.3 \times \beta) + (0.2 \times \gamma) \quad \ldots (5)$$

where $\alpha$ is the rating value of concrete resistivity, $\beta$ is the rating value corresponding to the rebound number, and $\gamma$ is the rating value for concrete cover. NDF ranges from 1 to 4. The rating values were proposed for average concrete resistivity, quality of concrete surface related to average rebound number, and precise concrete cover depth, as shown in Tables 8, 9, and 10, respectively. The results of UNDP Disaster Risk Management Programme (2007), which have been developed for buildings, as well as past research papers and a thesis, were studied and assigned values accordingly for rating purposes (UNDP Disaster Risk Management Programme, 2007; Rashidi & Gibson, 2011; Pushpakumara, 2014; Pushpakumara *et al*., 2017). The rating values from 1 to 4 in Table 8 indicate the possible rate of corrosion in the reinforced concrete element (NDT James Instrument Inc., 2021).

**Table 8:** Possible corrosion rates for resistivity and rating values

| Resistivity (k Ohms cm) | Possible corrosion rate | Rating value ($\alpha$) |
|---|---|---|
| > 20 | Insignificant | 1 |
| 10–20 | Moderate to low | 2 |
| 5–10 | High | 3 |
| < 5 | Very high | 4 |

The rating values from 1 to 4 in Table 9 show the quality of the concrete surface related to the average rebound number (Pushpakumara, 2014; Pushpakumara *et al*., 2017).

The rating values from 1 to 4 in Table 10 show the effect of the concrete surface relative to the precise concrete cover depth (Pushpakumara, 2014).

**Table 9:** Quality of concrete surface and rating value for average rebound number

| Average rebound number | Quality of concrete surface | Rating value ($\beta$) |
|---|---|---|
| > 40 | A very good hard layer | 1 |
| 30–40 | Good layer | |
| 20–30 | Fair | 2 |
| < 20 | Poor concrete | 3 |
| 0 | Delaminated | 4 |

**Table 10:** Proposed rating values for the cover of the concrete

| Concrete cover (mm) | Rating value ($\gamma$) |
|---|---|
| > 50 | 1 |
| 30–50 | 2 |
| 10–30 | 3 |
| < 10 | 4 |

## Proposed reinforced concrete tank rating procedure

Every 1 $m^2$ of the elements of a tank was inspected separately. Then, using these visual and detailed inspection data and non-destructive test results, Visual Inspection Factor (VIF). Crack Details Factor (CDF), and Non-Destructive Test Factor (NDF) were calculated for each square meter of the elements.

The visual inspection provides a wide range of information (i.e., vegetation cover, surface staining and bleed marks, structural failures, different movements, surface voids and honey combing areas, and reinforcement exposures) compared to crack inspection (i.e., crack width, length, depth, and the number of cracks) and non-destructive tests (i.e., concrete strength and corrosion behaviour). Further, crack details are more critical than the non-destructive tests to identify the current condition of tanks. Therefore, it is considered that the VIF, CDF, and NDF have priority values of 0.5, 0.3, and 0.2, respectively (Pushpakumara, 2014; Pushpakumara *et al*., 2017). Based on the above information, the Condition Index (CI) was calculated from equation (6) for all the elements separately. Each calculated CI value was rounded off to the nearest whole number (CI Є 1, 2, 3, 4).

$$CI = (0.5 \times VIF) + (0.3 \times CDF) + (0.2 \times NDF) \qquad \ldots(6)$$

where,
VIF is the Visual Inspection Factor,
CDF is the Crack Detail Factor, and
NDF is the Non-Destructive Test Factor.

Areas with equal *CI* values are separately accumulated, and the element condition was calculated using Equation 7 as the Element Condition Index *(ECI).*

$$ECI = \frac{\sum(q_i \; x \; CI)}{\sum q_i} \qquad \ldots(7)$$

where,
*CI* is the Condition Index of the selected area, and
$q_i$ is the area of an element reported in the condition index (*CI*).

The overall condition of a water tank is calculated using equation (8) as the overall Tank Condition Index (*OTCI*). The higher *OTCI* value reflects the worst case of a reinforced concrete tank.

$$OTCI = \frac{CF \sum(ESF_i \; x \; ECTF_i \; x \; ECI_i)}{n} \qquad \ldots(8)$$

where,
$ESF_i$ is the Element Significant Factor of i $^{th}$ element,
*CF* is the Causal Factor,
$ECTF_i$ is the Element Construction Type Factor of the i$^{th}$ element (ranging from 1 to 4),
$ECI_i$ is the Element Condition Index of the i$^{th}$ element, and n is the number of elements.

**Table 11:** Tank soundness score (TSS) ranges and physical condition of the tanks

| *TSS* (%) range | Expected condition of reinforced concrete tank | Overall tank safety condition | Tank condition rating |
|---|---|---|---|
| 75 < *TSS* ≤ 100 | The tank shows no deterioration. There may be discoloration, efflorescence, and/or superficial cracking but without effect on strength and/or serviceability. | Good condition | 1 |
| 50 < *TSS* ≤ 75 | Minor cracks, spalls, bleeding marks, and algae may be present with moderate to low levels of corrosion of steel reinforcement and no deterioration of the system. | Satisfactory / fair condition | 2 |
| 25 < *TSS* ≤ 50 | Some delamination and/or spalls may be present. Corrosion of steel reinforcement may be present with loss of bar sections and the strength may be lost and need repairing and retrofitting of element or tank. | Poor condition | 3 |
| 0 ≤ *TSS* ≤ 25 | Delamination, spalls, herbs and algae, and corrosion of steel reinforcement are prevalent. Element displacements and movements are present. The entire structure needs to be replaced. | Serious / failure condition | 4 |

Tank Soundness Score (*TSS*) is calculated as a percentage by using equation (9).

$$TSS = \frac{(HOTCI - OTCI)}{HOTCI} \; x \; 100 \qquad \ldots(9)$$

Lower *TSS* value reflects the worst case of a tank.

*HOTCI* is the highest *OTCI* valve (i.e., worst case) of any tank which is calculated by using equation (10).

In equation (10), it is considered that the *ECI* valves of all elements are equal to 4 (i.e., worst case) and *CF* is also equal to 4 (i.e., worst case).

$$HOTCI = \frac{16 \sum(ESF_i \; x \; ECTF_i)}{n} \qquad \ldots(10)$$

Table 11 shows the *TSS* ranges and status relevant to the physical condition of a tank proposed based on similar studies that have been carried out for the Bridge Soundness Score (Pushpakumara, 2014; FHWA, 2016;).

**Evaluation of current condition state of an existing reinforced concrete water tank**

The structural condition of thirty existing reinforced concrete water tanks was assessed using both visual inspection and non-destructive tests. Figure 4 represents a flow diagram of the methodology of the assessment of reinforced concrete water tanks. The assessment methodology was developed based on 'Synthesis of National and International Methodologies Used for Bridge Health Indices' published by the Federal Highway Administration (FHWA), US Department of Transportation (2016), the standard ACI 365.1R-08 published by the American Concrete Institute, and some past research studies (Rashidi & Gibson, 2011; Pushpakumara, 2014). Table 12 shows the calculation of TSS for a reinforced concrete water tank located in Hambantota (structure no. 13).

**Table 12:** Calculation of Tank Soundness Score (TSS) for a water tank (Structure no. 13)

| Element | Total area ($\sum q_i$) ($m^2$) | $ECI_i$ | $ESF_i$ | $ECTF_i$ | $ECI_i \times ESF_i \times ECTF_i$ |
|---|---|---|---|---|---|
| Roof slab | 152 | 2.88 | 1 | 4 | 11.54 |
| Tank walls | 295 | 2.90 | 2 | 4 | 23.23 |
| Tank base slab | 62 | 2.36 | 3 | 4 | 28.34 |
| Shaft / column | 245 | 2.13 | 4 | 4 | 34.13 |
| Foundation | 133 | 1.98 | 4 | 4 | 31.68 |
| $\sum (ESF_i \times EMF_i \times ECI_i)$ | | | | | 128.92 |
| Causal Factor (CF) | A | E | M | I | 3.66 |
| | 3 | 4 | 4 | 3 | |
| Number of elements (n) | | | | | 5 |
| Overall tank condition index (OTCI) | | | | | 94.37 |
| Highest overall tank condition index (HOTCI) | | | | | 179.20 |
| Tank soundness score (TSS) | | | | | 47.34% |

The tank is exposed to a very severe environment since it is located very close to a coastal belt (i.e., $RV_E = 4$). The tank could be considered an old structure since it is older than 30 years (i.e., $RV_A = 3$). Then, the causal factor was calculated from equation 4 by assigning rating values for maintenance level and quality of inspection as 4 and 3, respectively. VIF (Equation 2), CDF (Equation 3), and NDF (Equation 5) were calculated separately for each element of the tank, such as the roof, tank wall, base slab, tank shaft, and foundation. Similarly, CI was calculated by using Equation 6. The ECI values for each element were calculated by Equation 7. The product of '$ECI_i \times ESF_i \times ECTF_i$' was calculated for each tank element, and the sum was obtained. Next, the Overall Tank Condition Index (OTCI) was calculated by using Equation 8. These values were used to calculate the Highest Tank Condition Index (HOTCI) by using equation 10. Next, the Tank Soundness Score (TSS) was calculated as a percentage by using Equation 9. Finally, the tank remediation actions can be proposed based on the TSS value. The calculations are listed in Table 12.

**Prediction of the service life of reinforced concrete water tanks**

Prediction of the service life of existing reinforced concrete water tanks would give an idea about the remaining service life period, deterioration rate, and the identification of the appropriate time to initiate the repairing and retrofitting. The corrosion process consists of three time periods: initiation time, de-passivation time, and propagation time (Tuutti, 1982). From the calculated corrosion initiation phase with the duration of de-passivation time and propagation phases, the overall service life of a reinforced concrete structure can be estimated. Such estimated values can be used to select an optimum design service life for a new structure as well as optimum repair and rehabilitation solutions for existing structures. The rate of diffusion of chlorides through the concrete cover and the critical chloride threshold value of the embedded steel reinforcement significantly influence the duration of the corrosion initiation phase. Initiation time ($t_c$) can be predicted using equations 11 and 12 according to Fick's Second Llaw (Bazant, 1979a; 1979b; Ming *et al*., 2009; Pillai, 2011).

$$C(x,t) = C_o erfc \frac{x}{\sqrt{4D_c t_c}} \quad ...(11)$$

where
*C(x,t)* is the chloride concentration at depth × after time t,
$C_o$ is the concentration of chloride ions in pores of concrete at the surface,
*erfc* is the complementary error function,
*x* is the concrete cover at various times t relevant to the required design life,
$t_c$ is the initiation time, and
$D_c$ is the diffusion coefficient.
The diffusion coefficient ($D_c$) can be determined by using Equation 12

$$D_c = \beta \frac{kTLV\left(\frac{dc}{dt}\right)}{ZeECA} \quad ...(12)$$

Where,
$D_c$ is the diffusion coefficient (given in $cm^2/s$),
β is the corrosion factor for ionic interaction (varies from 1.22 to 1.7 based on the chloride concentration from 0.1 M to 0.5 M NaCl),
k is the Boltzmann constant,
($k = 1.38 \times 10^{-16}$ ergs/K/ion)
T is the temperature (K),
Z is the chloride valence (Z is 1 for NaCl),
e is the charge of the proton ($4.8 \times 10^{-10}$ e.s.u.),
E is the applied electrical potential (V),
L is the specimen thickness (cm),
V is the volume of the chloride collection tank ($cm^3$),
C is the initial chloride concentration in chloride source solution ($mol/cm^3$), and
dc/dt is the steady-state migration rate of chloride ion ($mol/cm^3.s$).

Bazant *et al.* (1979a) established two classical formulas for calculating the de-passivation time ($t_p$) and propagation time (corrosion time, $t_{corr}$). The de-passivation time can be calculated by averaging the values of the Bazant method and Ming's proposed method (Bazant, 1979a; 1979b; Ming *et al*., 2000).

When the de-passivation time is calculated from Ming's proposed method by using equation (14), the result is three times larger than the results from equation (13) according to the Bazant method. Ming *et al*. (2009) explained that this difference is caused by the different declined mechanisms of chloride ion concentration. Ming's proposed method, a declined straight line is used, while the Bazant method uses a declined parabolic curve. However, the real phenomenon may be a declined parabolic curve occurs and then, subsequently, a declined straight line (Ming *et al*. 2000, 2009). Therefore, to estimate a more precise value for de-passivation time, we get the average of the proposed Ming's and Bazant methods (Ming *et al*. 2000, 2009).

$$t_p = \frac{1}{12D_c}\left[\frac{L}{1-\sqrt{\frac{C^*}{C_0}}}\right]^2 \quad ...(13)$$

$$t_{p'} = \frac{1}{4D_c}\left[\frac{L}{1-\sqrt{\frac{C^*}{C_0}}}\right]^2 \quad ...(14)$$

where,
$t_p$ is the de-passivation time,
$D_c$ is the diffusion coefficient,
L is the cover thickness,
$C^*$ is the threshold value of the chloride concentration, and
$C_o$ is the concentration of chloride ions in pores of concrete at the surface.

Propagation time ($t_{corr}$) can be calculated by using the modified Bazant method (Bazant, 1979a; 1979b). Equations 15, 16, and 17 were used to calculate propagation time.

$$t_{corr} = \rho_{cor} \frac{D}{s} \frac{\Delta D^*}{j_r} \quad ...(15)$$

where $\Delta D^*$ is given by

$$\Delta D^* = f_t' \left[2\left(\frac{L}{D}+1\right)\right] \delta_{pp} \quad ...(16)$$

where $\delta_{pp}$ is given by

$$\delta_{pp} = \frac{D}{E_{ef}}(1+\vartheta) + \frac{2D^3}{s^2 E_{ef}} \quad ...(17)$$

where,
$\rho_{cor}$ is the density of the corrosion product,

s is the space of the steel bar,
D is the steel diameter,
$j_r$ is the rate of rust production per unit area of the plane,
$f_t^{/}$ is the tensile strength,
L is the cover thickness,
$\delta_{pp}$ is the bar hole flexibility,
$\vartheta$ is Poisson's ratio ( $\vartheta$ and, and
$E_{ef}$ is the effective elastic modulus.

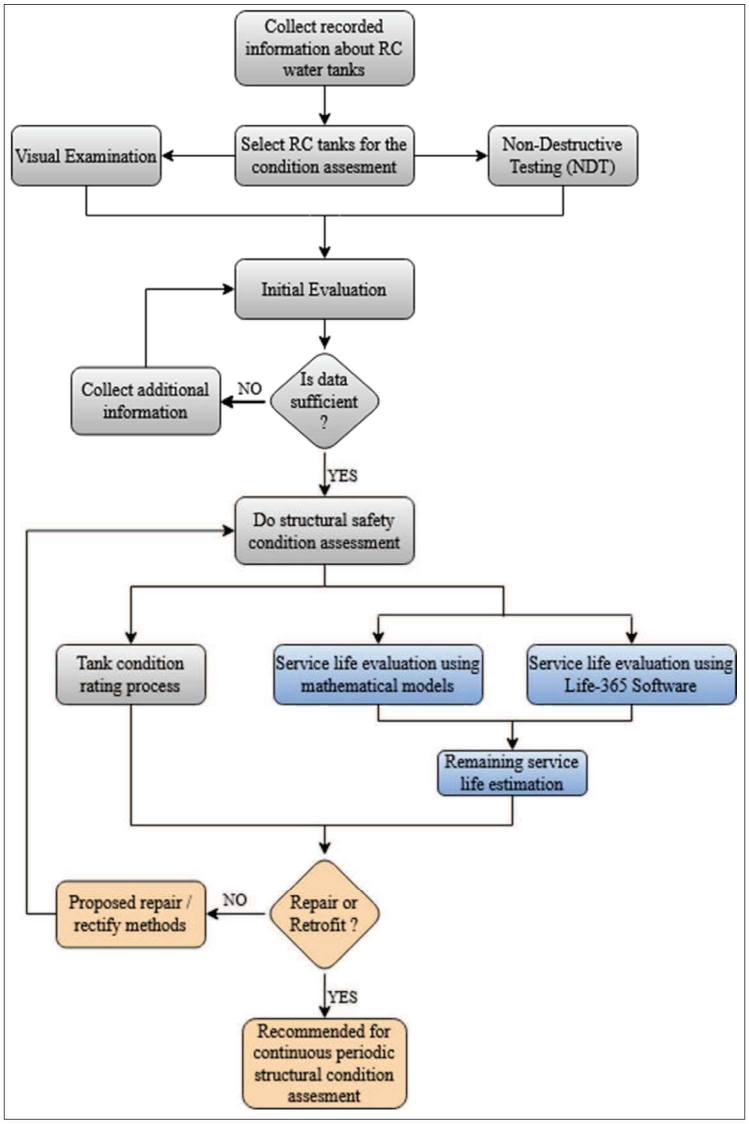


**Figure 4:** Flow diagram for assessment of the current condition of a reinforced concrete tank

The effective elastic modulus can be determined by using equation (18).

$$E_{ef} = \frac{E_c}{1 + \varphi_{cr}} \quad ...(18)$$

where,
$\varphi_{cr}$ is the creep coefficient of concrete, and,
$E_c$ is the modulus of elasticity.
The modulus of elasticity of concrete ($E_c$) can be determined by using equation (19).

$$E_c = 4700\sqrt{f_c^{/}} \qquad ...(19)$$

where,
$f_c^{/}$ is the average compressive strength of concrete.

The total service life of reinforced concrete structure can be expressed as,

$$t = t_c + t_p + t_{corr} \qquad ...(20)$$

$t_c$ and $t_p$ are the initiation and de-passivation times, respectively,

$t_{corr}$ is Propagation time, and ($t_p + t_{corr}$) can be considered as the propagation period.

**Table 13:** The assessment output of 30 structures

| Structure No | Service life (years) | | | | | TSS % | Overall tank safety condition/rating |
|---|---|---|---|---|---|---|---|
| | From empirical formula | | | Predicted (total) | | | |
| | Initiation time ($t_c$) | De-passivation time ($t_p$) | Propagation time ($t_{corr}$) | $t_{emp}$ | $t_{life-365}$ | | |
| 1 | 25.65 | 44.83 | 4.65 | 75 | 81 | 69 | 2 |
| 2 | 19.38 | 34.37 | 4.81 | 59 | 60 | 41 | 3 |
| 3 | 22.50 | 39.46 | 5.06 | 67 | 68 | 46 | 3 |
| 4 | 25.65 | 44.83 | 4.65 | 75 | 80 | 70 | 2 |
| 5 | 40.08 | 70.04 | 5.48 | 116 | 123 | 83 | 1 |
| 6 | 25.65 | 44.83 | 4.65 | 75 | 81 | 53 | 2 |
| 7 | 26.95 | 47.1 | 4.73 | 79 | 83 | 69 | 2 |
| 8 | 25.65 | 44.83 | 4.65 | 75 | 80 | 67 | 2 |
| 9 | 23.15 | 40.46 | 4.48 | 68 | 72 | 61 | 2 |
| 10 | 24.38 | 42.62 | 4.56 | 72 | 75 | 60 | 2 |
| 11 | 25.65 | 44.83 | 4.65 | 75 | 81 | 81 | 1 |
| 12 | 28.28 | 49.42 | 4.81 | 83 | 86 | 79 | 1 |
| 13 | 15.86 | 28.14 | 5.69 | 50 | 51 | 47 | 3 |
| 14 | 20.31 | 36.03 | 4.90 | 61 | 65 | 57 | 2 |
| 15 | 21.38 | 37.36 | 4.65 | 63 | 68 | 56 | 2 |
| 16 | 25.65 | 44.83 | 4.65 | 75 | 81 | 78 | 1 |
| 17 | 28.28 | 49.42 | 4.81 | 83 | 86 | 75 | 2 |
| 18 | 31.04 | 54.24 | 4.98 | 90 | 96 | 75 | 2 |
| 19 | 25.65 | 44.83 | 4.65 | 75 | 81 | 73 | 2 |
| 20 | 25.65 | 44.83 | 4.65 | 75 | 81 | 77 | 1 |
| 21 | 25.65 | 44.83 | 4.65 | 75 | 81 | 67 | 2 |
| 22 | 22.25 | 39.46 | 5.06 | 67 | 69 | 66 | 2 |
| 23 | 13.52 | 23.98 | 4.65 | 42 | 46 | 56 | 2 |
| 24 | 25.65 | 44.83 | 4.65 | 75 | 81 | 58 | 2 |
| 25 | 22.25 | 39.46 | 5.06 | 67 | 70 | 60 | 2 |
| 26 | 32.46 | 56.74 | 5.06 | 94 | 98 | 60 | 2 |
| 27 | 22.25 | 39.46 | 5.06 | 67 | 68 | 59 | 2 |
| 28 | 32.46 | 56.74 | 5.06 | 94 | 97 | 60 | 2 |
| 29 | 22.25 | 39.46 | 5.06 | 67 | 70 | 60 | 2 |
| 30 | 32.47 | 56.74 | 5.06 | 94 | 98 | 61 | 2 |

**Table 14:** Sample calculation of service life for a water tank (structure No. 13)

| Corrosion process | Equation | Parameters & calculations | Calculated time period (Years) |
|---|---|---|---|
| Initiation time ($t_c$) | $C(x,t) = C_o erfc \frac{x}{\sqrt{4D_c t_c}}$ | $C(x,t)$ = 8 kg/m$^3$<br>$C_0$= 34.84 kg/m$^3$<br>x= 38 mm<br>$D_c$= 1 × 10$^{-12}$ m$^2$/s<br>$D_c$= 31.54 mm$^2$/y<br>$erfc \frac{x}{\sqrt{4D_c t_c}} = 0.2296$<br>Hence,<br>$\frac{x}{\sqrt{4D_c t_c}} = 0.8495$ | 15.86 |
| De-passivation time ($t_p$) | $t_p = \frac{1}{12D_c}\left[\frac{L}{1-\sqrt{\frac{c^*}{c_0}}}\right]^2$<br>$t_{p\prime} = \frac{1}{4D_c}\left[\frac{L}{1-\sqrt{\frac{c^*}{c_0}}}\right]^2$ | L = 38 mm<br>c* = 8 kg/m$^3$<br>$t_p$ = 14.07 years<br>$t_{p'}$ = 42.20 years | 28.14 |
| Propagation time ($t_{corr}$) | $t_{corr} = \rho_{cor} \frac{D}{s} \frac{\Delta D^*}{j_r}$<br>$\Delta D^* = f_t^/ \left[2\left(\frac{L}{D}+1\right)\right] \delta_{pp}$<br>$\delta_{pp} = \frac{D}{E_{ef}}(1+\vartheta) + \frac{2D^3}{s^2 E_{ef}}$ | D = 16 mm<br>$E_{ef}$ = 9,908 N/mm$^2$<br>$\vartheta$ = 0.18<br>S = 100 mm<br>$f_c^/$ = 40 N/mm$^2$<br>$f_t^/$ = 3.48 N/mm$^2$<br>L = 38 mm<br>$j_r$ = 1.5 × 10$^{-7}$ g/m$^2$s<br>$j_r$= 1.5 × 10$^{-13}$ g/mm$^2$s<br>$\rho_{cor}$ = 3,600 kg/m$^3$<br>$\delta_{pp}$ = 0.00199mm$^3$N<br>$\Delta D^*$= 0.0467 mm<br>$E_c$= 29,725 N/mm$^2$ | 5.69 |
| Estimated Total service life ($t = t_c + t_p + t_{corr}$) | | | 50 |
| Age of the structure | | | 36 |
| The estimated remaining service life of the structure | | | 14 |

## Results and prediction of service life of water tanks

### *Evaluating service life of the water tanks*

According to the proposed condition assessment procedure, structure no. 02 (a groundwater tank at Matara in Sri Lanka) shows the minimum TSS value of 41%, and it has spent 56% of the expected service life. The tank is located close to the coastal belt with an approximate distance of 420 m. In addition to that, the quality of the construction techniques adopted seems to be very poor. Furthermore, with the sea breeze, the tank has been exposed to direct winds with high salt concentrations. The prevailing physical condition of this tank is the worst compared to other structures used for the study.

Structure no. 05, a ground reinforced concrete tank in the Southern Province of Sri Lanka, has the maximum TSS value (i.e., 83%), and it has completed 11% of its expected physical service life (Refer to Table 13). The tank is located at a considerable distance from the coastal belt (approximately 4,175 m). According to the visual inspection, there are no structural failures, minor cracks, vegetation cover, or any other visual defects.

Hence it can be understood that the prevailing physical state of the structure is in good condition. Therefore, it can be identified that the deviation of the actual from the predicted structural condition is not significant.

For this type of analysis, many parameters should be known to use the mathematical models mentioned in section 4 to estimate the service lives of a reinforced concrete tank. The steel diameter D, the space of the steel bar, **s** (100 mm), and cover thickness, L (38 mm), were obtained from field observation. Other parameters were extracted from literature published by the researchers, such as the diffusion coefficient of chloride ions, $D_c = 1 \times 10^{-12}$ m$^2$/s (Clifton, 1993; Angst & Vennesland, 2007), the threshold value of the chloride concentration, $C^* = 8$ kg/m$^3$ (Hope & Ip, 1987; Angst & Vennesland, 2007), the concentration of chloride ions in pores of concrete at the surface, $C_0 = 34.84$ kg/m$^3$ (Pushpakumara, 2014), creep coefficient of concrete, $\varphi_{cr} = 2.0$ (ACI 365.1R-08, 2000), Poisson's ratio, $\vartheta = 0.18$ (Angst & Vennesland, 2007), the rate of rust production per unit area of the plane, $j_r = 1.5 \times 10^{-15}$ g/m$^2$s (Bazant, 1979a; 1979b), the density of the corrosion product, $\rho_{cor} = 0.0036$ g/mm$^3$ (Bazant, 1979a; 1979b) and the average compressive strength of concrete, $f_c^{/} = 40$ N/mm$^2$ (ACI 365.1R-08, 2000).

By inserting these parameters into previously discussed formulas, values for $t_c$, $t_p$, and $t_{corr}$ for a reinforced concrete tank can be calculated. A sample calculation of the service life for a water tank (structure no. 13) in Hambantota, Sri Lanka, is tabulated in Table 14.

The predicted service life values from both the empirical formula and Life-365 software, as well as TSS values for 30 reinforced concrete tanks are tabulated in Table 13. The selected sample of tanks (30 numbers) is located in the southern province of Sri Lanka. Lower TSS values reflect the tanks with the worst condition.

Assessing the degree, severity, and importance of each case of damage identified during the assessment process provides a detailed picture of the tank. When compared to that information, the calculated TSS values match the actual status of most tanks well. That indicates that the proposed assessment procedure can be used to assess the structural health condition of the tank more efficiently and accurately.

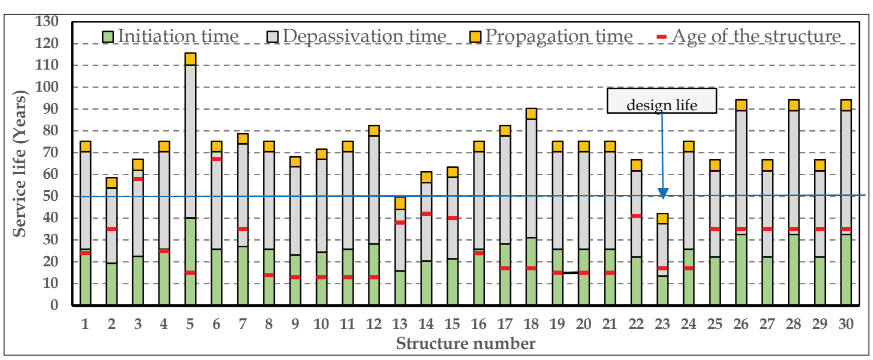


**Figure 5:** Variation of age with predicted service life and design life of the structures

**Variation of tank age and service life**

The design life of a reinforced concrete water tank should be in the range of 40–60 years, according to the BS 8007. Generally, the service life of the reinforced concrete water tank is assumed to be 50 years for the structural design as an average value. Structure numbers 13 and 23 indicate less service life than the expected design value. However, the expected service life of both of the tanks exceeds 40 years. These two structures are located very close to the sea and exposed to direct wind with high salt concentration. Therefore, such a relatively low service life is indicated due to the aggressive environmental conditions.

Further, Figure 5 indicates that some structures are within the De-passivation period. Among them, Tank nos. 3, 6, and 13 are very close to the propagation period. Hence, immediate repair or retrofitting works are needed for those tanks.

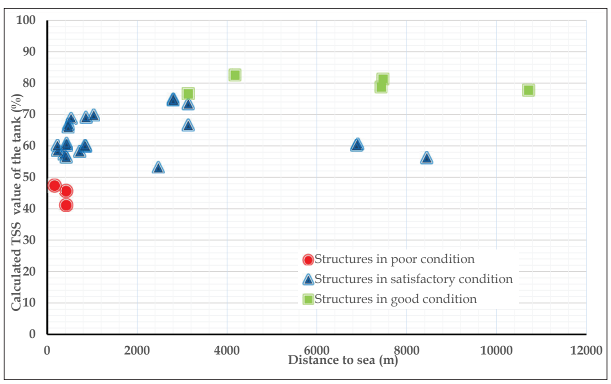


**Figure 6:** Variation of Tank sound score and overall tank safety condition with distance to the coastal belt

Salt spray can be carried by wind and settle on the surface of the reinforced concrete tank. The surface chloride concentration of a reinforced concrete water tank is increased over time due to constant exposure to the sea breeze. Hence the structures can deteriorate within a shorter time than expected at the design stage. Therefore, the distance from a coastal belt is an important factor that should be taken into account for the durable structural design of such structures. According to Figure 6, most of the structures which have comparatively low safety conditions (i.e., with low TSS) can be seen within 2 km of the coastal belt. The structural condition of a reinforced concrete water tank also depends on ageing, material quality, excessive loads, carbonation effects, and poor workmanship at the construction stage. Therefore, few structures that are not in good condition but are in satisfactory condition can be seen at a considerable distance from the coastal belt (within the distance of 7.0–8.5 km), as shown in Figure 6.

## CONCLUSIONS

Every water supply system has some form of a water storage tank most often constructed from reinforced concrete. These tanks are an integral part of the potable water distribution network but are often taken for granted from a maintenance and condition assessment point of view. To ensure durability and sustainability, they should be adequately inspected and maintained. To effectively achieve these objectives, a suitable assessment system should be implemented.

The objective of the paper was to introduce a suitable condition assessment system for reinforced concrete water tanks.

Both visual inspection and non-destructive data are used to calculate a Tank Soundness Score. It provides a more objective evaluation of the structural condition because it reduces reliance on the inspector's judgment for rating the tank condition. An element-level inspection enables inspectors to capture both the severity and extent of any problems that may influence the integrity of the structure. Such information is valuable for planning maintenance, repair, and rehabilitation programmes.

The service-life prediction method used here is mainly focused on the effect of one degradation process. However, more degradation processes usually occur simultaneously on structures. Hence, assessment becomes more complicated.

Both the predicted service life and the tank soundness score can be used to develop a tank remediation plan more effectively. Therefore, the repair/retrofitting methods proposed based on such assessment will be cost-effective as well as more reliable in enhancing the service life of the water retaining structures. Further, it can be shown that the deviation of the actual from the predicted structural condition of the thirty selected sample structures did not significantly change.

Hence, the proposed combined use of non-destructive tests, visual inspection, and service life prediction to ensure the reliability of the reinforced concrete water tank is more effective. In addition to that, it is a valuable tool for assessing its structural and functional health.

The graphical analysis indicates the durability of a reinforced concrete water tank constructed on standard practices depends on both exposure conditions and the distance from the coastal belt. Also, this study revealed that the quality of concrete materials, workmanship, and routine maintenance strategies, directly and indirectly, affected the service life of the reinforced concrete water tanks. Therefore, the use of impermeable denser concrete mixers and the application of a suitable protective sealer or coating to the surfaces of the water tank just after completing the construction activity are some of the major recommendations to ensure good structural and functional health for the reinforced concrete water tanks.

## REFERENCES

ACI (2000). *Service-Life Prediction—State-of-the-Art Report-ACI 365.1R-00*. American Concrete Institute (ACI), Farmington Hills, Michigan, USA.

ACI (2008). *Guide for Conducting a Visual Inspection of Concrete in Service -ACI 201.1R-08*. American Concrete Institute (ACI), Farmington Hills, Michigan, USA.

Angst U. & Vennesland Ø. (2007). *SINTEF Report (SP 4.2)-Critical Chloride Content.* Concrete Innovation Centre (COIN), Trondheim, Norway.

Bazant Z.R. (1979a). Physical model for steel corrosion in concrete sea structures - theory. *Journal of Structural Division* **105**(6): 1137–1153.
DOI: https://doi.org/10.1061/JSDEAG.0005168

Bazant Z.R. (1979b). Physical model for steel corrosion in concrete sea structures - application. *Journal of Structural Division* **105**(6): 1155–1166.
DOI: https://doi.org/10.1061/JSDEAG.0005169

BSI (1987). *British Standard Code of Practice for Design of Concrete Structures for Retaining Aqueous Liquids -BS 8007:1987.* British Standards Institution, London, UK.

Hope B.B. & Ip A.K.C. (1987). Chloride corrosion threshold in concrete. *ACI Materials Journal* **84**(4): 306–314.
DOI: https://doi.org/10.14359/1617

Ming-Te L., Ran H., Shen-An F. & Chi-Jang Y. (2009). Service life prediction of the pier for the existing reinforced concrete bridges in the chloride-laden environment. *Journal of Marine Science and Technology* **17**(4): 312–319.
DOI: https://doi.org/10.51400/2709-6998.1988

NDT James Instrument Inc. (2021). *OhmCorr™ Test System - Resistivity Meter For Concrete (manual).* Available at *https://www.ndtjames.com/Ohmcorr_Test_System_Resistivity_Meter_p/c-rm-8000.htm*, Accessed 27 August 2021.

Pillai R.G. (2011). *Corrosion and Service Life Prediction of Reinforced Concrete Structure*. Building Technology & Construction Materials Division, Dept. of Civil Engineering, IIT Madras, Chennai, India.

Pushpakumara B.H.J. (2014). Condition Assessment, Repair and Retrofitting of Existing Bridges in Sri Lanka due to Chloride Effect*. M.Phil. Thesis*, University of Ruhuna, Sri Lanka.

Pushpakumara B.H.J., De Silva S. & De Silva S. (2017). Visual inspection and non-destructive tests-based rating method for concrete bridges. *International Journal of Structural Engineering* **8**(1): 74–91.
DOI: https://doi.org/10.1504/IJSTRUCTE.2017.081672

Rashidi M. & Gibson P. (2011). Proposal of a Methodology for Bridge Condition Assessment. *Proceedings of The 34th Australasian Transport Research Forum (ATRF)*, 28–30 September. Adelaide, Australia, pp. 1–13.

Saaty T.L. (1980). *How to Make a Decision: The Analytic Hierarchy Process*. McGraw-Hill International, New York, USA.
DOI: https://doi.org/10.13033/isahp.y1988.042

Saaty T.L. (1988). *Multicriteria Decision Making: The Analytic Hierarchy Process*. RWS Publications, Pittsburgh, USA.

Saaty T.L. (1994). *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*. RWS Publications, Pittsburgh, USA.

Tuutti K. (1982). *Corrosion of steel in concrete- Report No. 4.82.* Swedish Cement and Concrete Research Institute, Stockholm, Sweden, pp.1-469.

UNDP Disaster Risk Management Programme (2007). *Condition Assessment of Building for Repair and Upgrading*. National Disaster Management Division, Ministry of Home Affairs, New Delhi, India.

US Federal Highway Administration (FHWA) (2016). *FHWA-HRT-15-081 - Synthesis of National and International Methodologies Used for Bridge Health Indices.* U.S. Department of Transportation, Washington D.C., USA.