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Deterioration assessment model for splash zone of marine concrete structures

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ABSTRACT

Concrete exposed to splash zone in partially submerged concrete structures deteriorates rapidly due to reasons such as wetting-drying cycles, the impact of waterborne materials, bio-deterioration, chloride and sulphate attacks. Existing condition assessment and rating systems do not adhere to the interrelation between different performance attributes of splash zones and these models are extremely subjective to the performance of the evaluator. The objectives of this study are to evaluate the effectiveness of parameters that deteriorate marine concrete structures and to develop a new model to predict the rate of deterioration of splash zone in marine concrete structures. The fuzzy Analytical Hierarchy Process (FAHP) was used to develop the model to predict the rate of deterioration. Here, local factors were grouped under five primary parameters as visual inspection, water quality, casual factors, Non-Destructive Tests (NDTs) and crack details. Data relevant to 15 structures were gathered by visual inspection, laboratory and field experiments to validate the proposed model. Attributes of water quality achieved the highest priority for the deterioration of the slash zone of marine concrete structures. Further, numerical values were assigned to this rating model to avoid ambiguity and vagueness of linguistic descriptors in existing rating systems. Finally, the model developed in this study can be used to evaluate the deterioration percentage of the splash zone in structures and according to that appropriate retrofitting and repair work can be done.

1. Introduction

At the present, reinforced concrete has been widely used in coastal and underwater structures in order to construct bridges, jetties, breakwaters and floating structures. However, concrete is more prone to deteriorate due to the aggressive environmental conditions in the atmospheric and splash zone due to chloride content in water, sulphate attacks, abrasion erosion caused by slit, sand and gravel, wetting and drying cycles and due to presence of waste and chemicals in water [5,13]. These environmental parameters will cause cracking, spalling and corrosion which leads to incurring an enormous amount of money on repairing purposes and also this will reduce the structural health and safety of structures [23].

According to researchers, deterioration of concrete structures due to chloride induced reinforcement corrosion is a major problem around the world and reinforcement in partially submerged concrete structures is mainly corroded due to the ingress of chloride ions

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[18,39]. According to Neville [20], a protective oxide layer that consists of γ-Fe_2O_3 is formed on steel which is generated soon after the hydration of concrete has started. Chloride ions that ingress inside concrete can be dissolved in pore solution (free chloride) or bound to the cement hydrates (bounded chloride) and only free chloride contributes to breaking this passive layer which results in corrosion [17]. When the concentration of chloride ions in the pore solution around the steel surface reaches the threshold value this film will be destroyed [4].

According to Tian; and Cohen [31], sulphate attack on concrete is a complex process where the mechanisms are not well understood and these sulphate attacks can be either physical or chemical, whereas chemical attacks can be caused by seawater and groundwater. The main factors that affect the severity of sulphate attack are: C_3A content, $Ca(OH)_2$ content, concentration of sulphates and permeability of the concrete. Water borne sulphates react with C_3A of cement and with calcium hydroxide to form ettringite which is an expansive crystalline product and gypsum [21]

As mentioned by Ting, et al. [33] splash zone is the area which is above and below the mean water level where constant wetting and drying takes place. Concrete is more prone to deteriorate through weathering in this region and also enhances the damage due to chloride attacks, sulphate attacks and salt crystallization. Due to Wetting Drying Action (WDA), the effect of sulphate attacks will increase as it increases the rate of diffusion and capillary absorption [32,41]. Furthermore, the wetting and drying action increased the rate of chloride attacks, with long term exposure there will be high chloride concentration on the surface of the concrete as a result the depth of maximum chloride concentration (conversion zone) will expand [25]. This chloride attack eventually caused corrosion of reinforcement. Corrosion of reinforcement in concrete is an electrochemical process and the differences in electrochemical potentials can occur due to different exposure conditions of concrete [26]. Such as when a part of reinforced concrete is exposed to periodic wetting and drying while another part is permanently submerged in seawater, when there is varying salt concentration or oxygen, electrochemical cells can form [20].

Pushpakumara et al. [24]; Pushpakumara and Thusitha [23]; Wankhade and Landage [36]; Zheng et al. [40] and Dey et al. [10] have used Non-Destructive Tests (NDTs) and visual inspection to assess the condition of existing concrete structures. Rebound hammers, ultrasonic pulse velocity tests, rebar detectors, corrosion resistivity meters, Radioactive methods, etc. are some of the NDTs that can be used for the structural health monitoring processes.

A Multi-Criteria Decision Analysis (MCDA) must be carried out to develop an integrated building assessment system [14,22]. The aim of MCDA is to rank the alternatives for supporting decision making or to find the most desirable alternative. There are many different MCDA methods such as Analytical Hierarchy Process (AHP), Fuzzy Analytical Hierarchy Process (FAHP) and Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) [11]. Out of these techniques, AHP is commonly used in engineering related research in order to make analytic decisions for complex attributes using quantitative or qualitative data [19,35]. AHP is further developed into FAHP using the Fuzzy set theory which was first introduced by Zadeh [37]. The benefits of using FAHP over AHP are, that it can deal with uncertainty and also can represent intermediate judgements [16]. Therefore, the decision makers can make a better judgement using intermediate values. Champiri, et al. [8]; [22,23]; Pushpakumara, et al. [24] and Hopfe, et al. [14] have used FAHP to assess and rating the condition of buildings and other structures.

According to Santhanam and Otieno [28], for a concrete structure in a marine environment, there are three main possible exposure conditions. They are atmospheric zone, splash zone or tidal zone and submerged zone. Concrete exposed to the splash zone or tidal zone is usually in the worst deterioration condition of all the exposure categories and it is very important to regularly monitor this zone through a proper assessment method in order to reduce major repairing and retrofitting work. The objectives of this study are to evaluate the effectiveness of parameters that dominate the deterioration of the splash zone of marine concrete structures and to develop a model for rating the condition of the splash zone of underwater concrete structures.

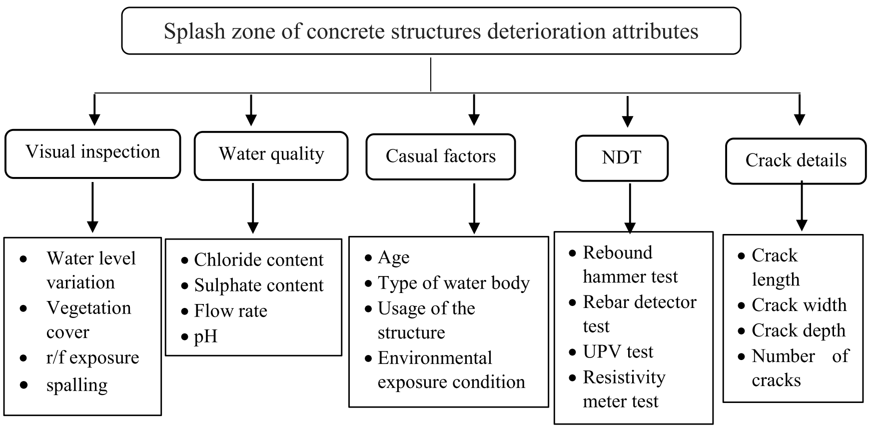

Fig. 1. Main parameters and local factors.

2. Methodology

2.1. Identification of attributes that effect the splash zone of concrete structures

The main attributes and local factors that affect the splash of a structure were identified from past research [23,24,28,32,41]. These studies have focused on different attributes separately. Several studies have used NDTs for their condition assessment tool without considering visual inspection, environmental factors and other casual factors (i.e. type of structure, water quality parameters, age, etc.) [8,36,40,10]. Here to incorporate all these attributes, the local factors were grouped under five main attributes as Visual Inspection (VI), Water Quality (WQ), Casual Factors (CF), Non-Destructive Tests (NDT) and Crack Details (CD) as shown in Fig. 1. Then FAHP model was developed from the information gathered under each attribute of splash zone of marine concrete structures.

2.2. Development of the model

In developing the model, first, a questionnaire was prepared and distributed among 100 experts including researchers and engineers especially those who have experience with marine and coastal structures in order to find the correlation between all the parameters and local factors. The responses collected must be consistent. Therefore, the consistency of the responses was checked by Equation 1 which was proposed by Chang [7] and the Consistency Ratio (CR) of each response should be less than 10 % in order to accept them.

$$CR = \frac{(\lambda_{\max} - n)/(1 - n)}{RI} \quad (1)$$

Where, $\lambda_{\max}$, RI and n are maximum eigenvalue, Random Consistency Index to the number of criteria and number of criteria respectively, as proposed by Chang [7] (Table 1).

Thereafter the responses were collected and converted each of them into standard eigenvector matrices. Here the comparison matrices were in crisp values therefore those values were converted into initial Triangular Fuzzy Number (TFN) matrices using Table 2.

The mean of all the responses give an accurate representation of information. Therefore, after converting all the 100 responses into TFN matrices, a Synthetic Pair-wise Comparison Matrix (SPCM) was developed using the geometric mean method (Eq. 2) proposed by Buckley [6].

$$\widetilde{a_{ij}} = (\widetilde{a_{ij}^{1}} \otimes \widetilde{a_{ij}^{2}} \otimes \widetilde{a_{ij}^{3}} \otimes .... \otimes \widetilde{a_{ij}^{12}}) \quad (2)$$

Where, a_{ij}; the element corresponding to the i^{th} row, j^{th} column in the SPCM, a_{ij}^{1}; the element corresponding to the i^{th} row, j^{th} column in the Initial TFN Matrix of the 1st respondent. Afterwards, fuzzy geometric mean of each row of the SPCM was calculated by using Eq. 3.

$$\widetilde{r_i} = (\widetilde{a_{i1}} \bigotimes \widetilde{a_{i2}} \bigotimes \widetilde{a_{i3}} \bigotimes .... \bigotimes \widetilde{a_{in}})^{\frac{1}{n}} \quad (3)$$

Where, r_i denotes the geometric mean of the i^{th} row and n denotes the number of columns in the matrix. The fuzzy weight of each factor was obtained by Eq. 4.

$$\widetilde{w_i} = \widetilde{r_i} \otimes (\widetilde{r_1} \otimes \widetilde{r_2} \otimes \widetilde{r_3} \otimes .... \otimes \widetilde{r_n})^{-1} \quad (4)$$

Then defuzzified the fuzzy weights to get the crisp numerical values. The defuzzification method used here was centre of area.

$$w_i = (u + l + m)/3 \quad (5)$$

u, l and *m* of Eq. 5 represents the upper bound, lower bound and middle ranges of TFN. The defuzzified crisp numerical values were normalized to obtain the final weights. Finally, the rating equations were developed using the priority weights and the priority weights were arranged from highest value to the lowest value.

2.3. Calculation of the deterioration percentage

After calculating the Splash Zone Condition Index (SCI) for each structure the percentage of deterioration was found. For that, first of all the Overall Splash Zone Condition Index (OSCI) was calculated using Eq. 6.

$$OSCI = 2CF \times ESF \times SCI \quad (6)$$

Where, *CF, ESF* are Casual factor (range from 1 to 4) and Element Significant Factor, respectively. Here the *ESF* is 2 for abutments, wing

Table 1
Random consistency index.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.58

Table 2
TFN values and their reciprocals.

Relative Significance	Fuzzy Number	FAHP Value	
		TFN	Reciprocal
Equal Importance	1	(1,1,1)	(1,1,1)
Intermediate judgement	2	(1,2,3)	(1/3,1/2,1)
Moderate Importance	3	(2,3,4)	(1/4, 1/3, 1/2)
Intermediate judgements	4	(3,4,5)	(1/5, 1/4, 1/3)
Strong Importance	5	(4,5,6)	(1/6, 1/5, 1/4)
Intermediate judgements	6	(5,6,7)	(1/7, 1/6, 1/5)
Very Strong Importance	7	(6,7,8)	(1/8, 1/7, 1/6)
Intermediate judgements	8	(7,8,9)	(1/9, 1/8, 1/7)
Absolute Importance	9	(8,9,10)	(1/10, 1/9, 1/8)

walls and 4 for piers [27] and *SCI* was round off to the nearest whole number (SCI $\in$ 1,2,3,4).

Then the Highest Overall Splash Zone Condition Index (*HOSCI)* which represent the highest *OSCI* was calculated using the Eq. 7. This was developed using Eq. 6. Where *CF* and *SCI* are equal to 4 (worst case).

$$HOSCI = 32 \times ESF \tag{7}$$

The Splash Zone Condition Score was calculated using Eq. 8.

$$SCS = \frac{HOSCI - OSCI}{HOSCI} \times 100 \tag{8}$$

Finally, the deterioration percentage was calculated using the *SCS*.

2.4. Field and laboratory tests

2.4.1. Visual inspection

Visual inspection provides information on the condition of the structures and this is very helpful in predicting the future condition of a structure. The NDTs that should be carried out on the structures were identified by visual inspection and through observation, the surface condition of the structures was identified. Under visual inspection, information about vegetation cover, reinforcement exposure (area), spalling (area), water level variation (measured by the measuring tape), crack details and type of water body were gathered. First identified the critical area (i.e. average length or area of splash zone) of the elements of the marine structure then water level variation, vegetation cover, r/f exposure and spalling were observed and when taking the water level average of three values were taken. The vegetation covers and r/f exposure percentages were calculated by considering the total area of the splash zone of critical elements of the structure. The spalling amount (length and width) was measured using a measuring tape. Furthermore, two inspectors were involved in this process.

Fig. 2. Velocimeter.

2.4.2. Determining the flow velocity

The portable Electromagnetic Velocity Meter (Fig. 2) was used to take the velocity measurements of the water bodies according to EN14154 and ISO4064. This equipment consists of two parts: electromagnetic velocity sensor and the display unit. Here, the velocity sensor was put into the water body and the readings were recorded.

2.4.3. Non-destructive tests

Non-destructive tests are used to identify the deterioration that has happened to the structures. Rebound hammer, rebar detector/ cover meter, Ultrasonic Pulse Velocity (UPV) tester and resistivity meter were used as non-destructive test equipment for condition assessment of splash zone of existing underwater concrete structures.

The rebound hammer test was used to find out the surface compressive strength of concrete and this is a rapid and convenient test. In this study, the digital display rebound hammer was used. First the abrasive stone, which provided with the equipment, was used to smooth the surface of concrete to test. The plunger is then held perpendicular to the concrete surface and body pushed towards the concrete. Then a button on the side of the body is pushed to lock the plunger into the retracted position and the rebound number and compressive strength is read from the digit display. Locations, having very low rebound number, indicate weak surface of concrete. A rebar detector was used on concrete structures to determine the location and diameter of reinforcement and the concrete cover. An Ultrasonic Pulse Velocity (UPV) tester was used to measure the velocity of propagating ultrasonic pulses through concrete. Using this instrument, the crack depth (for known pulse speed and length) and internal quality of the concrete were obtained. Initially, the trance-meter and the receiver were kept at 0.3 m interval length and the travelling time to the pulse was measured. Then pulse velocity was calculated by known distance and time. A resistivity meter was used to determine the possible rate of corrosion in embedded reinforcing steel of the selected concrete bridges by using electrical resistivity. Here two holes (50 mm apart) with the diameter of 6 mm and the depth of 8 mm were drilled on the surface of concrete. The two holes were filled with dispenser conductive gel. This was necessary to create good contact between concrete and resistivity meter probes, which, was inserted in to holes. Resistivity of concrete (in kΩcm) was measured and the possible corrosion rate of steel reinforcement was determined by referencing the resistivity ranges included in the instruction manual of resistivity meter.

2.4.4. Crack gauge test

The crack gauge was used to measure crack width and this can measure crack widths from 0.05 mm to higher values with 0.05 mm intervals. Using this, crack widths in the splash zone of underwater elements were measured and recorded.

2.4.5. Laboratory experiments

In order to perform the experiments, first water samples were collected from the water bodies where the structures are located and labelled them from 1 to 15 (Fig. 3(a)). Then pH [2], chloride ion content [3] and sulphate content [1] of the water samples were measured at laboratory conditions.

The chloride content of water samples was evaluated by titrating against silver nitrate. Each collected sample was filtered in order to remove solid matter such as sand or weeds. Then 20 ml of the sample was diluted by pipetting it into a 100 ml volumetric flask and made it up to the mark with distilled water. Then 10 ml of diluted sample was added to a conical flask and two drops of chromate indicator were added. The resulting solution was titrated against 0.1 $moll^{-1}$ Silver Nitrate. The colour change from faint lemon-yellow colour to red brown colour was observed and the volume at the endpoint was recorded. This procedure was repeated three times and took the average of it. Finally, the chloride ion concentration was determined using the silver nitrate volume consumed to the endpoint. A pH meter is an electronic device used to measure the pH of a solution. First, the pH meter was calibrated against a known standard buffer solution to ensure the accuracy of the reading. Then the electrode was rinsed with distilled water and wiped it using a

(a) (b)

Fig. 3. Analysis of water quality (a) Collected water samples (b) Measuring pH of a water sample.

tissue. Thereafter, the pH of the water samples was measured as shown in Fig. 3(b). In order to determine the sulphate concentration, the spectrophotometer was used. This device measures how much a chemical substance absorbs light by measuring the intensity of light as it passes through a sample solution. First, the spectrophotometer was calibrated then 10 ml of water sample was filled to each of the two glass specimens and then a chemical (SulfaVer 4 powder) was added to one of the glass specimens and kept for 5 min. After that, both the specimens were placed in the spectrophotometer and the reading of the sulphate concentration was recorded.

3. Results and discussion

3.1. Visual Inspection (VI)

Under visual inspection, Water Level variation (*WL*), Vegetation Cover (*VC*), Reinforcement Exposure (*RE*) and Spalling (*S*) were considered as subcategories and the responses of the experts were collected as standard eigenvector matrices.

The relative importance of each parameter in accordance with the responses was gathered and mean values were calculated to develop Table 3. The response is accepted only if the Consistency Ratio (CR) is less than 10 % and it was calculated from Equation 1. The calculated CR value for Matrix 1 is 2.1 % which is less than 10 %. Then the Synthetic Pair-wise Comparison Matrix (SPCM) was developed using the geometric mean method considering the responses of the 100 experts as shown in Table 3.

Finally, Eq. 9 was used to calculate the priority weight of subcategories under Visual Inspection (VI).

$$VI = 0{\cdot}438RV_{RE} + 0{\cdot}394RV_{S} + 0{\cdot}096RV_{WL} + 0{\cdot}072RV_{VC} \quad (9)$$

Where RV_{RE}, RV_{S}, RV_{WL} and RV_{VC} are the rating values of reinforcement exposure, spalling, water level variation and vegetation cover, respectively and the coefficients of each term in Eq. 9 represent the priority weights. When reinforcement is present in the splash zone exposed to the atmosphere, the corrosion process accelerates due to reasons such as chloride ion attacks, contact with oxygen and this can be considered the most vulnerable thing that can happen to a structure. Similarly spalling can also accelerate the deterioration of concrete structures. According to the rating equation, reinforcement exposure has the highest priority weight while spalling has the second highest priority weight. Water level variation and vegetation cover have low priority weights.

In order to find out the *VI* value, Rating Values (*RV*) and priority weights were used. Table 4 was developed by referring to past research and visual inspection information gathered and it represents the rating values for each local factor. A greater rating value reflects the condition observed by visual inspection is worst.

3.2. Water quality (WQ)

Similar procedure (i.e. mentioned under Section 3.1) was used to developed the priority weight based equation (Eq. 7) for water quality parameter. First, SPCM matrix (Table 5) for water quality parameter was developed by using 100 experts' views and Eq. 4 was used to develop the priority weight equation for water quality parameter. Chloride ion concentration (*Cl*), Sulphate Concentration (*SC*), Flow rate (*F*) and *pH* were considered as sub-categories under water quality parameter.

Then the priority weights were calculated and the rating equation (Eq. 10) for water quality was developed.

$$WQ = 0{\cdot}620RV_{Cl} + 0{\cdot}180RV_{SC} + 0{\cdot}108RV_{pH} + 0{\cdot}092RV_{F} \quad (10)$$

Where RV_{Cl}, RV_{SC}, RV_{pH} and RV_{F} are rating values of chloride concentration, sulphate concentration, pH and flow rate, respectively. According to Zhang, et al. [39] and Pushpakumara and Thusitha [23], chloride ion induced corrosion can cause critical damage to the concrete and as a result the service life of the structure would be reduced, similarly sulphate attacks also can cause severe damage due to formation of ettringite which is an expansive crystalline product which can cause cracking, expansion and spalling. According to the rating equation highest priority weight is obtained by chloride concentration. Sulphate concentration, pH and flow rate have received priority weights in descending order.

Table 6 shows the rating values developed by the authors referring literature for water quality parameter.

3.3. Casual factors (CF)

Age of the structure (*A*), Type of water body (*T*), Environmental exposure (*E*) and Usage of the structure (*U*) were considered under casual factors. Table 7 illustrates the SPCM which was formed from the responses collected for casual factors.

Eq. 11 illustrates the rating equation for Casual Factors (*CF*).

Table 3
SPCM of visual inspection parameter.

	WL			VC			RE			S		
WL	1	1	1	1.516	2.141	2.862	0.136	0.157	0.187	0.175	0.213	0.275
VC	0.349	0.467	0.66	1	1	1	0.179	0.221	0.290	0.173	0.209	0.265
RE	5.335	6.346	7.354	3.438	4.522	5.573	1	1	1	0.74	1.084	1.644
S	3.641	4.682	5.706	3.776	4.782	5.785	0.608	0.922	1.351	1	1	1

Table 4
Rating values for visual inspection.

Index	Local factor	Rating value (RV)				Reference
		1	2	3	4	
WL	Water level variation (mm)	$x \leq 100$	$100 < x \leq 500$	$500 < x \leq 900$	$x > 900$	Developed by author with reference to Champiri, et al. [8]
VC	Vegetation cover	Spread ≤ 5 % of the element area	5 % of the element area < Spread ≤ 15 % of the element area	15 % of the element area < Spread ≤ 25 % of the element	Spread > 25 % of the element area	Lagat et al., ($year$) [15]
RE	r/f exposure area (%)	No	$0 < RE \leq 5$	$5 < RE \leq 10$	$RE > 10$	Pushpakumara et al., ($year$) [24]
S	Spalling	immeasurably small or no spalling	Holes bigger than Pop outs	≤ 150 mm in length and width	> 150 mm in length and width	USACE ($year$) [34]

Table 5
SPCM of water quality parameter.

	Cl			SC			F			pH		
Cl	1	1	1	4	5	6	5.966	6.971	7.974	4.183	5.185	6.188
SC	0.181	0.222	0.287	1	1	1	1.149	1.820	2.550	1.888	2.930	3.949
F	0.244	0.283	0.331	0.392	0.549	0.871	1	1	1	0.33	0.477	0.715
pH	0.162	0.193	0.239	0.253	0.341	0.53	1.398	2.096	3.031	1	1	1

Table 6
Rating values for water quality.

Index No.	Local factor	Rating Value (RV)				Reference
		1	2	3	4	
Cl	Chloride concentration (g/L)	$Cl^- < 12$	$12 \leq Cl^- < 18$	$18 \leq Cl^- < 25$	$Cl^- \geq 25$	Costa & Appleton [9]
SC	Sulphate concentration (g/L)	$SO_4^{2-} < 2.0$	$2.0 \leq SO_4^{2-} < 2.5$	$2.5 \leq SO_4^{2-} < 3$	$SO_4^{2-} \geq 3$	Fugler, et al. [12]
pH	pH	pH ≥ 10 (no corrosion)	7 ≤ pH < 10 (constant rate of corrosion)	4 ≤ pH < 7 (constant corrosion)	pH < 4 (rapid corrosion)	Developed by author with reference to [38]
F	Flow rate (m/s)	Still water	$0 < F \leq 0.3$	$0.3 < F \leq 1$	$F > 1$	Developed by author

Table 7
SPCM of casual factors.

	A			T			U			E		
A	1	1	1	1	1.516	1.933	3.031	4.076	5.102	1.149	2.1689	3.178
T	0.517	0.66	1	1	1	1	3.031	4.076	5.102	1	1.7411	2.408
U	0.196	0.245	0.33	0.341	0.422	0.542	1	1	1	0.231	0.301	0.435
E	0.315	0.461	0.871	0.415	0.574	1	2.297	3.323	4.338	1	1	1

Table 8
Rating values for Casual factors.

Index	Local factor	Rating Value (RV)				Reference
		1	2	3	4	
U	Usage of the structure	undefined	Used by people only (footbridge)	Hydraulic structures	Used for vehicle transportation	Pushpakumara & Thusitha [23]
A	Age of the structure	<20 yrs	21–40 yrs	41–60 yrs	>60 yrs	Fugler et al., ($year$) [12]
T	Type of water body	Still water	Water streams/ Rivers	lagoon	Sea	Developed by author with reference to Pushpakumara and Thusitha [23]
E	Environmental exposure condition[a]	$E > 1000$ m	$100 \text{ m} < E \leq 1000$ m	$0 < E \leq 100$ m	0	Developed by author

[a] E represents the distance from the sea. E = 0 means that the structure is located in the sea and when E increases the distance from the sea increases.

$$CF = 0{\cdot}389RV_A + 0{\cdot}307RV_T + 0{\cdot}216RV_E + 0{\cdot}088RV_U \quad (11)$$

Where RV_A, RV_T, RV_E and RV_U represent the rating values of age of the structure, type of water body, environmental exposure and usage of the structure, respectively. Here, environmental exposure condition means the surrounding environment of the structure. According to Eq. 11, highest priority is obtained by the age of the structure because when a structure continuously exposed to extreme environmental conditions (wetting and drying, abrasion erosion, chloride attacks, etc.) the structural health of it would be reduced and also it effect the integrity and bearing capacity of the structure [23] and lowest priority is obtained by usage of the structure. The CF value can be obtained by the priority weights and rating values which is illustrate in Table 8 and the CF value ranges from 1 to 4.

3.4. Non-destructive tests (NDTs)

NDTs are very important as it give the most accurate information about the structures and also Non-destructive tests can be used to find out crack details. Rebound Hammer (*RH*), Ultrasonic Pulse Velocity (*UPV*) tester, Rebar Detector (*RD*) and Resistivity meter (*R*) were considered under NDT. The SPCM of NDTs is shown in Table 9.

Eq. 12 represents the rating equation obtained for NDT.

$$NDT = 0{\cdot}465RV_{RH} + 0{\cdot}287RV_{UPV} + 0{\cdot}153RV_R + 0{\cdot}095RV_{RD} \quad (12)$$

Where RV_{RH}, RV_{UPV}, RV_C and RV_{RD} represent the rating values of rebound hammer, UPV, resistivity meter test and rebar detector test, respectively. Here, rebound hammer test has obtained the highest priority weight due to reasons such as: it gives the compressive strength of concrete which is very important, simple to use and this instrument is often used in the field. Second highest priority weight is obtained by UPV. This can be used to determine the crack depth and compared to rebound hammer test this required experience operators to use the device. Resistivity meter test and rebar detector test have obtained lower priority weights. Pushpakumara and Thusitha (2022b) have observed similar patterns for priority values of NDTs. Table 10 shows the rating values for NDTs.

3.5. Crack details (CD)

Number of cracks (*N*), crack width (*W*), crack length (*L*) and crack depth (*D*) were considered as crack details. Table 11 represent the SPCM developed based on geometric mean method for crack details parameter.

After the SPCM was developed the rating equation of Crack Details (*CD*) was built which is illustrated by Eq. 13.

$$CD = 0{\cdot}365RV_W + 0{\cdot}322RV_D + 0{\cdot}199RV_N + 0{\cdot}114RV_L \quad (13)$$

Where RVw, RV_D, RV_N and RV_L represent the rating values of crack width, depth of the crack, number of cracks and crack length respectively. Highest priority weight is obtained by crack width as it is the most important parameter that affect the corrosion of reinforcement [29] which is 0.365 and the lowest priority weight is obtained by crack length which is 0.114. Table 12 represents the rating values for each local factor and when the rating value increases, the condition become worst. The value of CD ranges from 1 to 4.

3.6. Development of the rating equation based on selected parameters

After developing the rating equations for Visual Inspection (*VI*), Water Quality (*WQ*), Casual Factors (*CF*), NDT and Crack Details (*CD*) a rating equation to find the amount of deterioration was formed with respect to the above mention parameters. Table 13 illustrates the SPMC of the overall deterioration of the splash zone of the underwater structures.

After developing the SPCM, the rating equation was built up to calculate Splash zone Condition Index (*SCI*) of the splash zone of underwater structure (Equation 14).

$SCI = 0.363WQ + 0.287VI + 0.179CF + 0.13CD + 0.041NDT$ Equation 14.

Water Quality (*WQ*) has received the highest priority weight as water quality effect the most, on deterioration of the splash zone in underwater structures. The effect of chloride and sulphate ions, pH and flow rate were considered under the water quality. These factors accelerate the corrosion process of marine structures [15,18]. In the splash zone wetting and drying cycles occurs and it accelerate the chloride intrusion [8,23]. Further, variation in the height of the splash zone was considered under visual inspection. Variation in height of the splash zone indicates the availability of drying and wetting processes (Pushpakumara and Thusitha, 2022b). Visual inspection, casual factors, crack details have received priority weights in the descending order. NDT has received the lowest priority weight as these tests are common for any structure.

Table 9
SPCM of NDTs.

	RH			UPV			RD			R		
RH	1	1	1	1.149	1.888	2.551	4	5	6	2	3	4
UPV	0.392	0.53	0.871	1	1	1	2	3	4	1.149	2.169	3.178
RD	0.167	0.2	0.25	0.25	0.333	0.5	1	1	1	0.488	0.608	0.871
R	0.25	0.333	0.5	0.315	0.461	0.871	1.149	1.644	2.048	1	1	1

Table 10
Rating values for NDTs.

Index	Local factor	Rating Value (RV)				Reference
		1	2	3	4	
RH	Rebound hammer	a > 30	20 < a < 30	a < 20	0	Developed by author with reference to [24]
UPV	UPV (km/sec)	b > 3.5	3 <b< 3.5	2 < b < 3	b <2 or reading fluctuating	Pushpakumara et al., ($year$) [24]
R	Resistivity meter test (k Ohms cm)	c > 20	10 < c< 20	5 < c < 10	c <5	Shekarchizadeh, et al. [30]
RD	Rebar detector test (clear cover/mm)	Clear Cover > 60	40 < Clear Cover ≤ 60	20 < Clear Cover ≤ 40	Clear Cover ≤20	Pushpakumara et al., ($year$) [24]

Table 11
SPCM of crack details.

	N			W			L			D		
N	1	1	1	0.37	0.506	0.758	2	3.064	4.095	0.322	0.422	0.574
W	1.32	1.974	2.702	1	1	1	2.433	3.155	4.193	1	1.320	1.552
L	0.425	0.561	0.822	0.238	0.317	0.411	1	1	1	0.28	0.389	0.542
D	1.741	2.371	3.104	0.644	0.758	1	1.844	2.572	3.565	1	1	1

Table 12
Rating values of Crack details.

Index	Local factor	Rating Value (RV)				Reference
		1	2	3	4	
N	Number of cracks[a]	No cracks	1 ≤ N < 2	2 ≤ N < 3	N ≥ 3	Developed by author with reference to [24]
W	Crack width (mm)	Immeasurable	0.25 ≤ W< 1	1 ≤ W< 2	W ≥ 2	Pushpakumara, et al. [24]
L	Crack length(mm)	Immeasurable	L< 100	100 ≤ L< 300	L ≥ 300	Pushpakumara, et al. [24]
D	Crack depth (mm)	Immeasurable	D < 10	10 ≤ D < 20	D ≥ 20	Pushpakumara, et al. [24]

[a] Consider no. of cracks on the critical element.

4. Case study

The structural health of fifteen marine concrete structures was evaluated using the developed rating model. Here in order to cover various environmental conditions, marine concrete structures located in rivers, lagoons, inland and structures located near to the sea were taken into consideration. Furthermore, when selecting the structures, the flow rate of the water body, age of the structure and the usage of the structure were also taken into consideration. After selecting the structure, the splash zone of each structure was identified and all the analysis was done only to the splash zone. The analysis was carried out for all the 15 structures. The Sections 4.1 and 4.2 elaborate the background details of two marine concrete structures and the values obtained for each attribute and the final deterioration percentage.

4.1. Veyangoda (B208) Bridge

Veyangoda Bridge (Fig. 4) was constructed 50 years ago and is located 4.17 km (i.e. distance from the seashore) away from Negombo lagoon, Sri Lanka. According to Road Development Authority (RDA) - Sri Lanka, the identification number of the bridge is B208.

The structure has mainly deteriorated due to abrasion erosion caused by high flood flow during the rainy season. The chloride concentration of water is very low which is 0.177 g/l. During flood seasons the water level raises up to 1500 mm. Furthermore, there are no visible cracks and vegetation cover. According to the NDT results the bridge is in good condition.

The values obtained for Visual Inspection (*VI*), Crack Detail (*CD*), Water Quality (*WQ*), *NDT* and Casual Factors (*CF*) are 1.288, 1, 1.308, 1.248 and 2.915, respectively. Using these values, the *SCI* was obtained as 1.547. Then, calculate the deterioration (i.e. 63.6 %) as a percentage. According to the calculation, the level of deterioration of the splash zone of the structure is 36.4 %. This structure has received a lower percentage because in this structure there is no visible cracks, therefore no corrosion occurred due to external factors and also is located far away from the coastline. It can be concluded that the percentage obtained is accurate with respect to visual inspection information and NDT results.

Table 13
SPCM for deterioration of splash zone of underwater structures.

	VI			WQ			CF			NDT			CD		
VI	1	1	1	0.415	0.574	1	1.32	2.352	3.366	5.102	6.118	7.13	2.759	3.68	4.704
WQ	1,	1.741	2.408	1	1	1	1.741	2.766	3.776	5.533	6.544	7.553	3.031	4.162	5.223
CF	0.297	0.425	0.758	0.265	0.361	0.574	1	1	1	3.482	4.514	5.533	1.319	2.352	3.365
NDT	0.14	0.163	0.196	0.132	0.153	0.181	0.181,	0.222,	0.287	1	1	1	0.212	0.271	0.378
CD	0.213	0.320	0.5	0.192	0.24	0.33	0.297	0.425	6	2.639	3.680	4.704	1	1	1

Fig. 4. Veyangoda (B208) Bridge.

4.2. Mankuliya (B425) Bridge

Mankuliya Bridge (Fig. 5) is located on Negombo lagoon (near to seashore), Sri Lanka and this has been exposed to extreme environmental conditions for over 100 years.

As the structure is located in the lagoon area the water contains a high level of chloride ions (9.13 g/l). Therefore, chloride ion induced corrosion can be seen. The flow velocity is very high. In this structure, severe structural distresses such as spalling of greater than 150 mm in length and width and cracks greater than 300 mm in length were observed. Moreover, the *NDT* results show poor structural integrity.

The values obtained for *VI*, *CD*, *WQ*, *NDT* and *CF* are 3.664, 4, 1.508, 4 and 3.693, respectively. The *SCI* was obtained as 2.94. Then, calculate the deterioration as a percentage (i.e. 69.2 %).

Table 14 shows the deterioration percentages of 15 structures. The data were collected by using visual inspection, NDT and laboratory tests (i.e. from water samples) for these fifteen bridges and the proposed rating model was used to evaluate the condition of the splash zone of the bridges.

The model was developed based on five parameters (i.e. water quality, visual inspection, causal factors, NDT and crack details). From these parameters, water quality has the highest effect. According to Liu et al. [17] structures located within 100 m distance from the coastline have the highest risk of deterioration, due to the high surface chloride concentration. Due to chloride ions and other external factors, the deterioration of the splash zone is high compared to the underwater and atmospheric zone. Furthermore, when reinforced steel is exposed it accelerates corrosion as there are alternately wetting and drying cycles. This model was validated using laboratory experiments, visual inspection and NDT results. According to the results it is observed that structures located close to the coastline have higher deterioration rates.

5. Conclusions

In this study, a rating model was developed to predict the rate of deterioration of the splash zone of marine concrete structures and the model was validated by assessing the current condition of 15 existing marine concrete structures. The model was developed based

(a) **(b)**

Fig. 5. Mankuliya Bridge (a) Spans and piers (b) visible cracks.

Table 14
Percentage of deterioration of the selected structures.

	Bridge name	WQ	VI	CF	CD	NDT	Deterioration (%)
1	Kimbulapitiya (B321) Bridge	1.292	1.192	2.349	1.000	1.713	14.39
2	Veyangoda (B208) Bridge	1.308	1.288	2.915	1.000	1.248	36.40
3	Canal Bridge	1.402	1.320	3.020	2.190	1.400	25.68
4	Main Street Bridge	1.352	3.234	3.052	3.451	3.452	51.85
5	Kothalawala Bridge	1.416	1.000	3.693	2.834	1.713	30.02
6	Mankuliya (B425) Bridge	1.508	3.664	3.693	4.000	4.000	69.20
7	St. Nicholas Bridge	1.630	3.102	2.945	2.963	3.257	50.93
8	Nainamadama Bridge	1.292	1.096	2.738	2.512	1.465	22.01
9	Kotugoda Bridge	1.292	1.192	2.738	1.792	1.153	19.38
10	Pamunugama Bridge	1.356	1.264	2.845	2.013	1.561	23.00
11	Hendala Bridge	1.200	1.168	1.960	2.000	1.248	14.43
12	B596 Bridge	1.292	3.058	1.960	2.834	2.688	39.20
13	Aththanagalu Oya Bridge	1.283	1.213	2.416	1.000	1.693	14.86
14	Thoduwawa Bridge	1.200	1.096	3.088	1.000	1.000	15.80
15	Chillaw Bridge	1.508	3.496	3.088	2.957	3.000	53.70

on FAHP and numerical definitions were used to avoid subjectivity of evaluators. According to the model, water quality has the highest priority for the deterioration of the splash zone of the structure and visual inspection, causal factors, crack detail and NDT have priority weights in the decreasing order. The proposed method can be used to rate the deterioration percentage of existing marine concrete structures in tropical countries and according to the results obtained from the model, proper remediation can be done. As future research work in this domain, freeze-thaw action can be taken into consideration in order to modify this model.

CRediT authorship contribution Statement

BHJ Pushpakumara: Conception of the work, Data analysis and interpretation, Wrote the paper, Critical revision of the article. MSGM Fernando: Conducted the experiments, Data analysis and interpretation, Wrote the paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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