Materials Today: Proceedings xxx (xxxx) xxx

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

A systematic conditional assessment of strength and durability damage of concrete structures in marine environments

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Marine environment
Concrete structures
Durability
Corrosion
Design
Conditional assessment

ABSTRACT

The marine environments reduce the working life of the concrete structures owing to the severe exposure to the chemical ingress, and continuous contact with the humid air, and saline soil conditions. A scientific investigation and the conditional assessment of the existing structures may be helpful to learn the damage mechanism. This article represents the scientific conditional assessment of some existing old concrete structures in the coastal areas of Jamnagar and Dwarka of Gujarat. The objective of the study was to collect information on the types and severity of the damagesin the existing structures and preparing an assessment rubric mentioning the significance of modes of marine environment resulting in a specific damage type. To evaluate the severity of the damages, the parametric approach and a root cause analysis including the experimental investigations on the collected samples has been utilized. The outcomes revealed several interesting observations those have been classified into three major attributes namely material limitations, structural design and third as the gross environmental impacts. The study encouraged the authors to dig deeper in the area of work and showed potential of the methodology to understand the damages caused by the marine environments to the on-shore concrete structures.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Advances in Construction Materials and Structures.

1. Introduction

The marine exposure condition imposes a challenging environment on concrete as a material, structures and member. The long-term performance of concrete in marine environment is observed to be subjected on a complex integrated physical and chemical mechanisms [1]. The marine environment is not always regarded as the sea water, but it is the combination of the marine sand / ground, air and temperature at and around the coastal regions and the shallow as well as deep sea water together. In such cases, the damage occurred on the concrete structures needs to be evaluated or assessed for the damage with a systematic approach. Therefore, conditional assessment of the marine structures is merely not similar to the other structures. In fact, how to assess the damages of concrete in marine environments is a challenge because the nature of degradation and skill of damage varies with the location of marine structure. The concrete in the marine environment along with the reinforcements of steel bars shows damages namely corrosion, efflorescence, staining, erosion, cracking, mortar spalling and surface losses, lump mass losses, and many others. Regarding reinforced concrete in particular, chloride ingress by diffusion is probably the most important mechanism of deterioration, leading to corrosion of the embedded reinforcing steel. However, the overall situation is complicated by concomitant deterioration of the material itself by sulfate attack and physical effects such as salt crystallization and mechanical action of the waves.There are references available to refer on the topic of assessment of damage in marine environments. Use of common methods of assessment includes use of rebound hammers, porosity meters, carbonation tests on the samples [1] providing preliminary damage information, use of non-destructive tests methods and visual inspections [2,3], on site assessment of the strength parameters of the concrete [4], use of permeability apparatus for fluid ingress, destructive tests on samples at the site and chemical analysis of the samples in laboratories [5,6], assessment of the degree of the distresses in the concrete due to marine environment by visual and analytical inspections of the sites [7], applications of electromagnetic methods on the existing structures [8], the corrosion detection of the damages structures in the repaired structures by.

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https://doi.org/10.1016/j.matpr.2023.03.188
2214-7853/
Selection and peer-review under responsibility of the scientific committee of the International Conference on Advances in Construction Materials and Structures.

both destructive and non-destructive methods [9], by exploring the transport mechanism within the damaged concrete samples [10], assessment based on the life-cycle evaluation of the concrete structures in the marine environment [11], using time-dependent prediction model of ingress of chlorides in concrete [12], by carrying out the reliability and sensitivity analysis of the existing structures subjected to the marine environments [13], by assessing the chloride diffusion in off shore structures and their profiles from the different sources for the laboratory investigations [14], evaluation and prediction of the service life span of the bridge deck system of the marine bridge using time-dependent ingress of corrosion inducing chemicals in the samples [15], and laboratory studies on the concrete samples consisting the chloride ion penetrations in the mass and exploring the micro structural formation of the disintegrations and loss of binders in the mass due to the corrosion of the sea waters [16] are available to refer and understand how the damage scenario of the concrete may be evaluated. In this study the authors have made efforts to prepare a systematic guidelines directing to a firsthand overall damage detection in marine structures. The suggested methodology is based on the case studies of the existing damaged marine structures. A questionnaire was prepared as a checklist and the data were collected form the real marine structure sites and placed in to the assessment sheet from which it was possible to quantify the amount, intensity and type of damage of the structures. Moreover, the method includes several real time parameters those are influencing the damage. All three impacting environments namely air, water and soil at the marine site have been explored and studied to what extent they have created the damage in the concrete as well as reinforced concrete structures located in the coastal areas. The authors look forward for the effective utilization of the suggested step by step conditional assessment of the marine structures for the damage detection.

1.1. Research significance

The damage of marine structures consists wider scope of initial investigations and therefore requires well framed or structured methodology where a step wise process may be adopted and followed to obtain the qualitative severity of the damage. Many a times, availability of the information of the damage scenario proves to be very useful in the absence of the preliminary data to the stakeholders. The authors have prepared a frame work through which, systematically conditional assessment of the affected concrete structures in marine environments can be carried out and the tool may get fitted at any of the stages of repair, rehabilitation, strengthening or even in the life cycle assessment process as well. This novel model has been prepared on the basis of datasets collected by the authors from the actual marine sites within the coastal region of the western India and the state of Gujarat in the past six months. The model also includes the combined use of technical inspections, visual observations and to an extent the laboratory investigation and test results before reaching to the conditional assessment of the damaged structures.

2. Methodology and survey modules

2.1. Methodology

The damage detection methodology for the marine structures a little innovative approach in assessment practices as observed and understood by the authors upon the visits of the sites. There may be similarities in the type of damage namely visual cracks, loss of cover of concrete, corrosion in the reinforcement bars and concrete mass, however, the causes of such damages are not found similar to that of the non-marine environment induced damages to the structures. Therefore, as shown in Fig. 1 a unique approach for conditional assessment has been implemented towards the methodology. The method includes site visits being the most significant and important factor for assessment. Visual inspection of structure has been focused in the methodology with the innovative approach of registering the scenario by classified work strategy. This includes the use of an assessment rubric proposed by the authors. The rubric is explained in detail in section 3 and 4 with an example of the areal case study carried out by the authors. The method as can be observed is based on the qualitative and quantitative assessment projected together. The third stage of method includes bifurcation of the samples' study with analytical and experimental approaches. On one hand, the qualitative analysis is proposed to obtain the damage scenario by external and evidently available conditions of the structures. While on the other hand, if required the samples may be taken to the relevant laboratories for structural investigations which eventually can support the damage interpretation of the structures.

The authors visited several coastal sites and performed a case study within the coastal areas of western side of Gujarat state from Jamnagar to Dwarka districts. The site visit photographs have been shown in Figs. 2 to 6 respectively for different locations. It is to be noted that the visit was based on the location of the structures, namely near shore area, submerged structures, partial submerged areas, far located structures and small nonstructural components. During the visit, it was observed that marine environment in any form like water, soil and air creates significant distresses in the concrete and steel as a material. The damage caused to the materials eventually results in to the structural damage. Therefore, distance of structures from the source of marine environment becomes an important criterion in assessment and unfortunately which is largely ignored while conducting the assessment. This is one of the innovative outcomes of the survey and that is why it has been incorporated in the assessment rubric also. Some of the concrete surfaces were partially damaged by erosion and loss of material however, not fit for retrofitting or repairs by any means. Therefore, the damage scenario has to be studied with respect to the degree of degradation with visual inspection preliminarily. Fig. 2 shows location and contact based damage of the structures in marine environments. Fig. 2(c) specially interesting as it indicates all three attributes of marine environments together on a single structure type. Fig. 3 shows the structural components those are in continuous and permanent contact of the marine water largely, causing greater value of damage in relatively shorter span. This again encouraged to include the time of contact as one of the rubric parameters. Fig. 4 shows completely degraded rein-

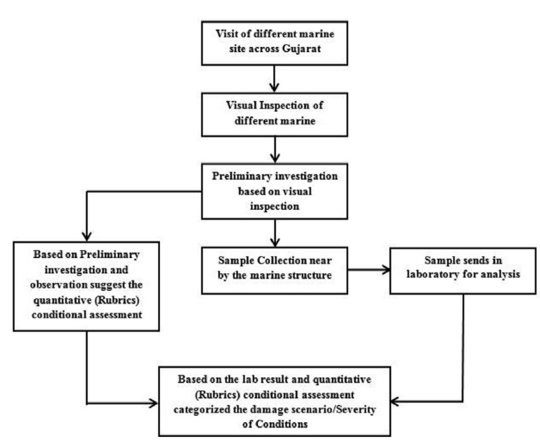

Fig. 1. Flow chart of systematic condition assessment methodology.

Fig. 2. (a) Footings of a transmission tower; (b) Loss of cover and steel corrosion; (c) New foundation; (d) Old deteriorated footing.

Fig. 3. (a) Old concrete tetrapod elements; (b) surface erosion of tetrapod; (c) New concrete tetrapod elements.

Fig. 4. (a) Old office/storage building; (b) Old bridge deck structure; (c) Efflorescence Staining at face of jetty.

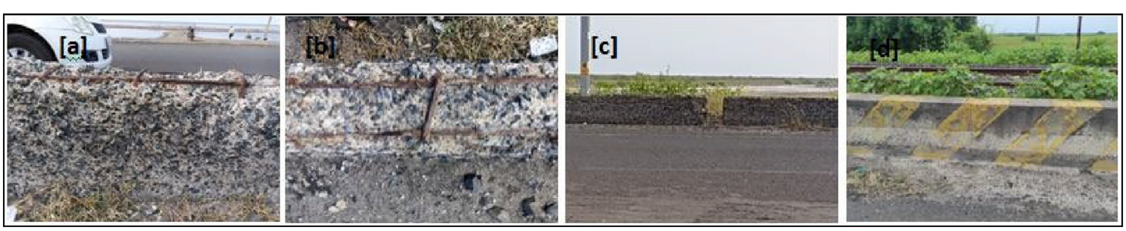

Fig. 5. (a) Concrete wall at coast); (b) Lose of cover at top of wall; (c) Concrete wall 5 km away form coast; (d) Concrete wall 35 km from coast.

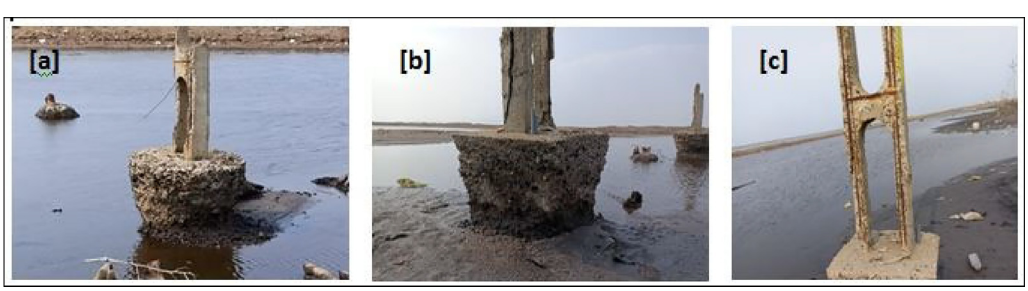

Fig. 6. (a) Circular Foundation of electrical pole; (b) Rectangular Foundation of electrical pole; (c) Corrosion of Electric pole.

forced concrete structures with maximum damage conditions. The building and deck components were not in the direct contact of the marine waters, though the damage was significant. Such conditions may be reduced by timely repairs and necessary concreting as they are primarily developed by the cracks in the concrete. Fig. 5 indicates the influence of marine environment on structures with respect to the distance and Fig. 6 shows the another example of concrete degradation under nearly all three types of impacts of marine surroundings. All the scenarios have been carefully observed, studied and incorporated in the rubric suggesting the qualitative and quantitative conditional assessment of structures.

3. Data collection and interpretation for conditional assessment

3.1. Data collection, assessment rubric and marking scheme

The onsite samples are the most important parameters and should be tactfully collected. The samples of spalling, cracked mass of concrete, broken and corroded lumps and the deposition of the rusting on the steel bars may be collected securely in the air tight containers. The samples of seawaters were also collected for its chemical analysis in laboratory. One of the best possible ways is to obtain the seawaters from different locations namely near the coastal line as well as if possible from the clean distanced a bit deeper areas with precautions if possible. Table 1 shows the list of data required to be collected. The table shows innovative scheme of quantification of the damage scenario. This is a unique feature of the study proposed to reach to a conclusive remark on the damage detection and conditional severity of a structure. The lower marks indicate high and maximum marks indicates low level of damage. It is to be noted that all the parameters are based on the visual inspection and observations, making the assessment more user friendly and less cost intensive as it does not require special instruments or complex methods for the investigations.

The rubric table also indicates the condition as an important criterion for assigning the quantitative attainment of the given observation. This is the most critical and important parameter for the conditional assessment of the structures. A simple interpretation of the given marking scheme indicates that lower the marks more is the severity of the damage. In other words, the structure indicating extensive amount of loss of the material, the chemical ingress is significant and the deterioration is practically difficult to get repaired or strengthened. Though the upper range is scaled up to 10 points or marks, in some cases there are many conditions to be assigned from marks from 10 to 20 also. About the allocated marks, the concept utilized is the sensitivity of the type of damage to the structure. For example, in point 5, the observation at site to be indicated in eight different conditions wherein it is generally acceptable that the surface distresses namely efflorescence may not be a serious damage to the structures however, the loss of material on the other hand indicates increased level of deterioration and assigned with less marks. About the usage of the rubric for the final evaluation of the given structure for its damage scenario, the marks assigned to an individual criterion can be added together and the total marks of the damage detection may be obtained out of 100 marks. Hence the assessment may be declared as low to extremely sever for maximum and minimum total marks respectively. This has been explained with the help of a case study of one of the structures visited by the authors in the preceding section.

3.2. Root cause analysis for the damage and deterioration of the marine structures

The primary reason of any deterioration of a structure may not be obtained by merely the data collection and marking the damage alone. The damage should be indicated with the primary reason also. This is important because the cause and its root are highly inter- related and must be studied in detail. The fish diagram shown in the Fig. 7 is an example how to study the damage caused by exploring the root cause.(See Fig. 8).

Table 1
Evaluation of the existing structure for damage scenario.

Sr. No.	Observation during Site Visit	Condition	Quantitative Maximum Mark Range	Maximum Marks
1	Distance of the marine structure from sea water	1 to 5 km	9–10	10
		Near shore (>500 m)	6–8	
		Within 500 m of Shore	3–5	
		Directly to sea water	1–2	
2	Type of materials used in building	PCC	8–10	10
		RCC	4–7	
		Steel	1–3	
3	Function of a structure	Based on importance	1–5	5
4	Type of Structure	On Shore	3–5	5
		Off shore	1–2	
5	Apparent damage types	Efflorescence Staining	18–20	20
		Surface Erosion	16–17	
		Creaking of concrete	13–15	
		Surface mortar delamination	11–12	
		Loss of Cover	8–10	
		Corrosion of steel bar	6–7	
		Lump mass Losses	3–5	
		Concrete disintegration	1–2	
6	Scale of the structure	Small	8–10	10
		Medium	4–7	
		Large	1–3	
7	Length, width, depth of cracks	Small	8–10	10
		Medium	4–7	
		Large	1–3	
8	Area of damaged portion	Partial Damage	6–10	10
		Fully Damage	1–5	
9	Causes of Damages based on visual observation(Exposer Condition)	Atmosphere	9–10	10
		Submerged	6–8	
		Splash	3–5	
		Tidal	1–2	
10	Most affected/ damaged area of the structure	Above plinth level/any other level	8–10	10
		at plinth level	4–7	
		sub structures	1–3	

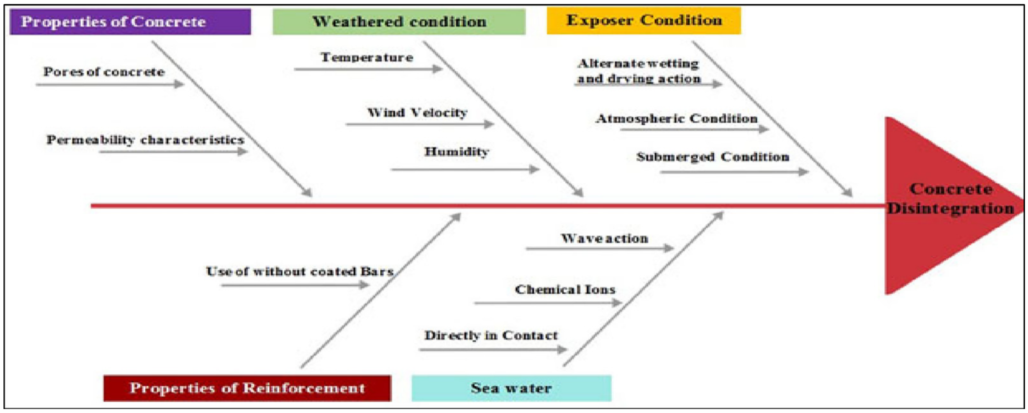

Fig. 7. Root-cause analysis as fish diagram to reach to the grass-root level of the deterioration of structures.

Fig. 8. (a) Damaged footings;(b) Closer look;(c) Adversely influenced footing.

The Figure indicates that between the result of disintegration of concrete and responsible parameter there are sub parameters to be mentioned. For example, concrete deteriorated due to the weathered conditions should be assessed in the line of the sub parameters namely temperature, wind velocity and humidity of the surrounding of the structures under study or observation. Further, to quantify the damage of the concrete due to the weather related parameters a standalone rubric may be developed and severity may be assigned with the range of the marks according to the actual conditions recorded as all the parameters are measurable namely wind velocity, temperature and humidity are all recordable quantities and may be utilized to assess their impacts on the deterioration. The ways of utilization of the assessment rubric and root cause analysis have been explained in the case study presented in the ascending section.

3.3. Importance of sample collection and laboratory investigations

The damage of a marine structure or the structures within the marine environments should be analysed on the basis of the laboratory investigations also as mentioned in the literature. The possible laboratory tests on the samples are chemical analysis of sea water, strength tests of concrete and durability assessment of the concrete samples for evaluating the damage due to chemical ingress.The chemical analysis of sea water supports the information and data collection on the types of chemical ingress with their influences on the concrete structures. It is well known that the chloride like ions and the salinity of the land, water and air some of the dominating chemicals generating the disintegration of concrete as well as steel reinforcements. The other chemicals of the sea water tend to create secondary effects on the surface namely erosion and loss of outer concrete layers combined by the chemical and physical impacts. The distresses in concrete due to water increase with the water and wind velocity and more importantly in the condition of the alternate wet and dry conditions or the structures those are partially submerged in the sea water permanently as observed at the real sites shown in the Fig. 2 (a), (b), (c) and (d).

The systematic assessment of the marine structures may be carried out effectively and uniquely with the proposed three major aspects mentioned in this section. The assessment rubric, the root cause analysis and the laboratory as well as field investigations and tests are the primary attributes of process of assessment. To support thesuggested system of assessment of marine structures, a case study carried out by the authors at the real site near "Charakla Salt Work" located at the coast lines of the Arabian sea near Dwarkahas been presented. The structure was the foundations of the transmission tower located at the coast line in partially submerged condition. The details are discussed on the assessment process in the ascending section.

4. Case study: Conditional assessment of a reinforced concrete foundation located in the marine environment

4.1. Methodology

The isolated reinforced concrete foundations were selected for conditional assessment, supporting the steel transmission tower at the coastal area of Arabian Sea near Dwarka-Jamnagar, west coastal line of Gujarat. The structure was selected as it represented all the three conditions of possible impacts of marine environments namely air, water and soil. Moreover, it was noticed that the location of the foundation was such that the structure is subjected to the alternate wet-dry conditions by the sea waters. This further increased the interest of observations also. It is to be noted that the pre-assessment stage indicates the initial survey and information details of the structures. In second stage the sea water and concrete as well sand was sent to the laboratory for chemical analysis and availability of the chemical compounds generated within the damaged concrete.

Table 2
Composition of seawater from around the Gujarat.

Major Ions (gm/l)	Charkla Salt Work, Dwarka	Dwarka	GMB- Port, Jamnagar	Navlakhi Port, Morbi
Na^+	12.3	15.7	37.76	25.4
K^+	0.31	0.81	1.72	1.1
Cl^-	24.44	40.19	69.49	27.81
Mg^{+2}	1.33	2.55	4.86	1.28
Ca^{2+}	1.6	2.8	6.1	1.4
SO_3^-	2.3	2.8	4.1	2.7
PH	8.14	8.08	7.93	7.78
TDS	31.4	24.9	72.7	32.6

Table 3
Conditional assessment rubric for damaged concrete foundation of transmission tower.

Sr. No.	Observation during Site Visit	Condition	Quantitative Maximum Mark	Total Marks
1	Distance of the marine structure from sea water	Directly to sea water	2	19 Marks(Extremely Severe)
2	Type of materials used in building	RCC	4	
3	Function of a structure	Based on importance	2	
4	Type of Structure	Off shore	2	
5	Apparent damage types	Concrete disintegration	1	
6	Scale of the structure	Medium	4	
7	Length, width, depth of cracks	Large	1	
8	Area of damaged portion	Fully damage	1	
9	Causes of Damages based on visual observation(Exposer Condition)	Tidal	1	
10	Most affected/ damaged area of the structure	Sub structures	1	

Table 4
Severity grading of the concrete structure in marine environments.

Grade	Quantification of damages	Severity of Conditions
A	81–100	Low
B	61–80	Medium
C	41–60	Exposed
D	21–40	Severe
E	1–20	Extremely Severe

4.2. Images of the structure considered for case study

As mentioned, the reinforced concrete members were found suitable for study and assessment case study as it represented varying conditions and effects of marine environments on the concrete.

4.3. Sample collection and laboratory investigations to support the assessment

The structure showed apparently sever damage though, it was necessary to systematically carry out the assessment for supporting the final remarks on the condition. As the samples are important attributes of such assessment the sea water sample, damaged concrete lumps, sea sand at the site and stone having weathering effects were obtained from the structure and attached surroundings. Fig. 9 shows the samples collected for investigations.

Since the structure was not of the large scale, obtaining the core of concrete was not practiced. The water samples were tested for the presence of chemical constituents present in the sea water.

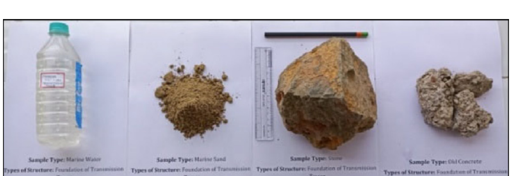

Fig. 9. Samples of materials collected at the site of the structure.

The sea water samples were also collected from the other place as shown in Table 2 those were remotely located from the site. This was necessary to establish that the local marine conditions tend to vary with the chemical attributes and therefore sea water should be analysed specifically for each site and structure under consideration. As the analysis indicated, the sodium, potassium, magnesium, calcium and chloride contents vary noticeably within the sites located far away from each other's from the assessment site. Regarding the usage of the analysis, it may be interpreted that the corrosive effect may have primarily occurred to the concrete due to the alkalinity and chloride ingress inside the mass of the concrete. Presence of sodium increases the volumetric expansion and the chloride increases the corrosive effect in the concrete and steel reinforcement. There can be similar test possible for soil and air samples as well for further ensure such causes. This process of analysis may be get well mapped to the damage during the root cause analysis also. Therefore, while assessment of the marine structures, maximum types of samples should be collected and analysed with the support of the laboratory investigations. Such leads may help in the protective remedies of the structure in future or for the new structure planned to be erected with advance protection provisions.

4.4. Conditional assessment rubric, special remarks and concluding summary for case study

From the visual inspection, all the necessary details were collected as per the rubric proposed for the assessment (Table 1). All the influential parameters have been closely monitored and observed as given in Table 3 and utilized in the present case study as shown below;

Based on the survey details, measurements, and laboratory investigations together, the assessment rubric was prepared to finally declare the damage condition and category of the structure supported by the systematic assessment carried out on the marine structure.

5. Conclusion

From the case study and the proposed systematic assessment methodology, the authors have observed that the conditional assessment of a marine structure requires a panoramic perspective on the investigations. The site survey remains the key factor for obtaining the exact details of the structural conditions, however the pre-assessment survey and related inquiries supports the process significantly. The laboratory tests and results contributed to a significant extent in ascertaining the scientific reasons for the damage. The study encouraged the authors to propose an overall severity rubric based on the systematic assessment process suggested in the present study. Table 4 indicates the overall rating to be utilized for declaring the damage scenario of the structures impacted by the marine environment.

The marks for qualifying the structure for damage severity by the influence of the marine environmental conditions may be obtained from the Table 4.The table represents that lower the marks higher is the damage scenario for the structures. In other words, the structure that cannot score higher values of marks are taken as to be in the worst scenario of the state. To obtain the grades or marks for a damaged structure, appropriate data collection, survey and site visit along with the laboratory tests may be collectively observed and by referring the assessment rubric, the marking may be finalized. In addition, the utilization of a root cause analysis is a useful tool to understand the main and sub factors affecting a specific damage of the structures in marine environment and may help the assessment process.

Data availability

Data will be made available on request.

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.

Acknowledgements

The authors are thankful to the management and authorities of Marwadi University for a continuous support, facilitating the travelling and necessary permissions at the marine site for access and providing the laboratory support for the investigations required in the case study. The authors are thankful to the colleagues and students supported the work unconditionally throughout the study.

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