American Journal of Civil Engineering and Architecture, 2016, Vol. 4, No. 4, 142-152
Available online at http://pubs.sciepub.com/ajcea/4/4/5
©Science and Education Publishing
DOI:10.12691/ajcea-4-4-5

Assessing Distress Cause and Estimating Evaluation Index for Marine Concrete Structures

Masoud Dehghani Champiri[1,*], Shahin Sajjadi[2], S. Hossein Mousavizadegan[3], Faramarz Moodi[4]

[1]Department of Civil and Environmental engineering, University of Houston, Houston, TX, USA
[2]Department of Construction Management, University of Houston, Houston, TX, USA
[3]Department of maritime technology, Amirkabir University of Technology, Tehran, Iran
[4]Concrete technology and durability research center, Amirkabir University of Technology, Tehran, Iran
*Corresponding author: mdehghanichampiri@uh.edu

Abstract Marine concrete structures may be affected with wide varieties of distresses where they may have different severity and extent. A periodic inspection program should be drawn to assess the structure condition and to specify the maintenance strategies. These inspections are carried out with several destructive and non-destructive tests which are very expensive. This paper tried to classify concrete distresses in the marine environment first and then, provided an evaluation method using an expert system. An extensive literature review, interviews with expert supervisors and a national survey were used to develop this expert system which is capable of determining the health index for concrete structures in marine environment. This marine structure condition index (MSCI) can be applied to assess the structural condition with a visual supervision and elementary measurements. The index is based on expert views with respect to the type, severity and extent of distresses. The specified index provides some appropriate maintenance strategies for the structure. Case studies showed that the proposed method gives better results and removed some deficiencies of some exiting approaches like what US Army Corps of Engineers suggested before.

Keywords: *marine structures, condition index, evaluation of distress, distress value, distress cause*

Cite This Article: Masoud Dehghani Champiri, Shahin Sajjadi, S. Hossein Mousavizadegan, and Faramarz Moodi, "Assessing Distress Cause and Estimating Evaluation Index for Marine Concrete Structures." *American Journal of Civil Engineering and Architecture*, vol. 4, no. 4 (2016): 142-152. doi: 10.12691/ajcea-4-4-5.

1. Introduction

The major types of marine structures are piers, concrete breakwaters and concrete platforms. Piers are common types of concrete structures that are built on posts extending from land out over water, used as a landing place for ships, an entertainment area, a strolling place, etc. Breakwaters are applied for the creation of harbour for a safe space in inshore. Some of them are built to wave refraction. Gravity-Concrete platforms are applied for petroleum extraction in a very rough marine condition. Although these types of platforms are made of high strength concrete, they cannot withstand all type of destruction and distresses may be appeared on them. There are some structures in ice infested waters, in seismic zones and in very harsh marine environments, but also in relatively calm areas. Some are located at large water depth, others in shallow areas. The foundation conditions vary from very stiff sand to very soft clays [1,2] and some of the structures float permanently. Some of the structures have storage facilities, and all have a hydrocarbon processing plant facility of some kind. Such various conditions for the offshore concrete structure require different design procedures. The oil companies are frequently evaluating the extension of operational life and implementing an ongoing inspection program [3].

Marine Structures are very costly and any their damage may have a major destructive effect on the economy. It is also indicated by the specialist that the marine structures needs a considerable attention to control their health. Thus, it is necessary to have a regular schedule to inspect, analyse and evaluate the importance of any distress in marine structures.

The type of distresses is a function of various parameters such as, the type of concrete, the platform location, the functionality of the platform, the environmental conditions such as the wave height, moisture content, ocean depth and so on. Distresses may appear on the structure with various extent and severity.

It is a normal practice to get help from specialists and experts to evaluate the value of distresses. Champiri et al. [4] introduced a decision support system to diagnose the distress cause and later introduced an evaluating method to index the health condition in marine concrete structures with using fuzzy approach, which is quite difficult to follow up the method and evaluate the structure cursory [5].

A performance index (PI) method is developed for fast and cursory evaluation of the physical condition of concrete bridges by Cabrera et al. [6]. This method used for concrete bridges of the zone with numeral evaluating of concrete performance and weighing them founded on distress severity and extent. Visual inspection on concrete damaged surface or near of surface and severity and extent of distress show the condition of occasion correction.

US Army Corps of Engineers [7] established the repair, evaluation, maintenance, and rehabilitation research program to improve maintenance techniques and practices for such concrete structure as coastal structures, gravity dams, and retaining wall which is closer to our case in order to evaluate marine structures. They introduced a condition index which is used for all structures; but engineering judgment and experience are needed to use of this method. They applied an index denoted by X in a condition index CI. Distress in every structure is determined by measuring of the value of X.

$$CI = 100(0.4)^{X/X_{\max}} \quad (1)$$

where X_{max} is defined as a limit for X. Engineer judgments and experiments are necessary for determining of X_{max} and X.

A program related to the concrete bridge rating expert system was developed by Miyamoto et al. [8] enabling the performance of concrete bridge to be evaluated by visual inspection based on knowledge and experience from domain experts. They created a damaged bridge management system with evaluation of expert system output results by genetic algorithm and for suitable maintenance method and minimizing of cost and maximizing of quality.

Moodi [9] proposed a knowledge-based system for repair and maintenance of structures by development of U.S Army Corps of Engineers information. In fact, he removed a deficiency of U.S Army of engineering's method which is about applying different judgments and elegances in determining of X and Xmax with proposing proportionate values of every distress that founded of expert experiments. Also, he offered suitable repair and maintenance solution for distresses.

Yehia et al. [10] prepared a questionnaire forms and ask the specialists to fill them out. However, they take into account only a few types of distress on their work and offered a suitable repair method for them. They considered corrosion of reinforcement, cracking, and delamination, and neglected some other type of distresses.

Tarighat and Miyamoto [11] were introduced a fuzzy method to deal with the shortcomings from the uncertain and vague data in inspection of structure. The fuzzy bridge deck condition rating method was practically based on both subjective and objective results of existing inspection methods and tools. The parameters of the model were selected as fuzzy inputs with membership functions found from some statistical data and then the fuzziness of the condition rating was calculated by the fuzzy arithmetic rules inherent in the fuzzy expert system.

Ramezanianpour et al. [12] developed a bridge-expert system for diagnosing and evaluation of bridge deck structures. The diagnosis assessment of deck slabs due to structural and environmental effects was developed based on the cracking in concrete, surface distress and structural distress. Fuzzy logic was utilized to handle uncertainties and imprecision involved. The developed expert system would allow the correct diagnosis of concrete decks, realistic prediction of service life, the determination of confidence level, the description of condition and the proposed action for repair.

Also the recent development of digital image correlation (DIC) systems [13,14] can be utilized into this evaluating system in order to calculate the health condition of structures.

The performance and functionality of some structure would be a concern if some types of distresses and their effects are neglected. All types of distresses should be considered. At the same time, we should take into account the harsh environment where the structure is located. There are various evaluation systems for inland structures. The application of them without taking into account the differences with the marine structures may cause some misleading. We should consider the corrosive nature of marine, interaction between structure and different natural causes such as waves. Concrete distresses in marine have more destructive effects than other structures.

As an example, corrosion of reinforcement because of different factor such as chloride attack, sulphate attack, and sea animates effects [15,16,17,18] has different mechanism in comparison with inland structures. Distresses in marine may have different values. We may ignore some types of distresses in inland structures but the ignorance of them in marine structure may cause severe damages on them. Therefore, it is evident that we must use a special method for marine structures taking into account all types of distresses based on specialist experiments in this area.

This paper is trying to investigate all type of distresses in marine environment which are not quite evaluated before, and then has some efforts to evaluate these distresses in a simple manner for a fast and cursory evaluation. Thus, the factors of distresses in marine structures are investigated. An evaluation system is developed to find out the type of distresses, their severity and extension based on the specialist experiments. All types of distresses are taken into account to obtain a complete evaluation routine. The type, severity, and the extent of distresses are considered separately and assign a value to each of them. This makes attention to the fact that a distress with less importance but with intense severity and extent may demonstrate a more destructive effects that a more important distress with a minor extent and severity.

2. Main Causes of Distress in the Marine Structures

The various standards offered many classifications for distresses. The distresses may be divided into three main categories: the physical damages; and the chemical damages and chemical-physical damages. However, the distinction between the chemical and chemical- physical factors is very hard to realize and therefore we may classify them as a single category of chemical-physical.

The classification of the distresses is shown in Figure 1 under two main category of chemical–physical and physical. The chemical-physical includes the damages due to the interaction between the human and nature while the physical are those due to direct action of human and nature.

Casual phenomenon, executive faults, non-structure cause, and design faults are distress causes for physical factors. Detailed information can be obtained from Figure 1. These classifications may be obtained by an extensive literature review.

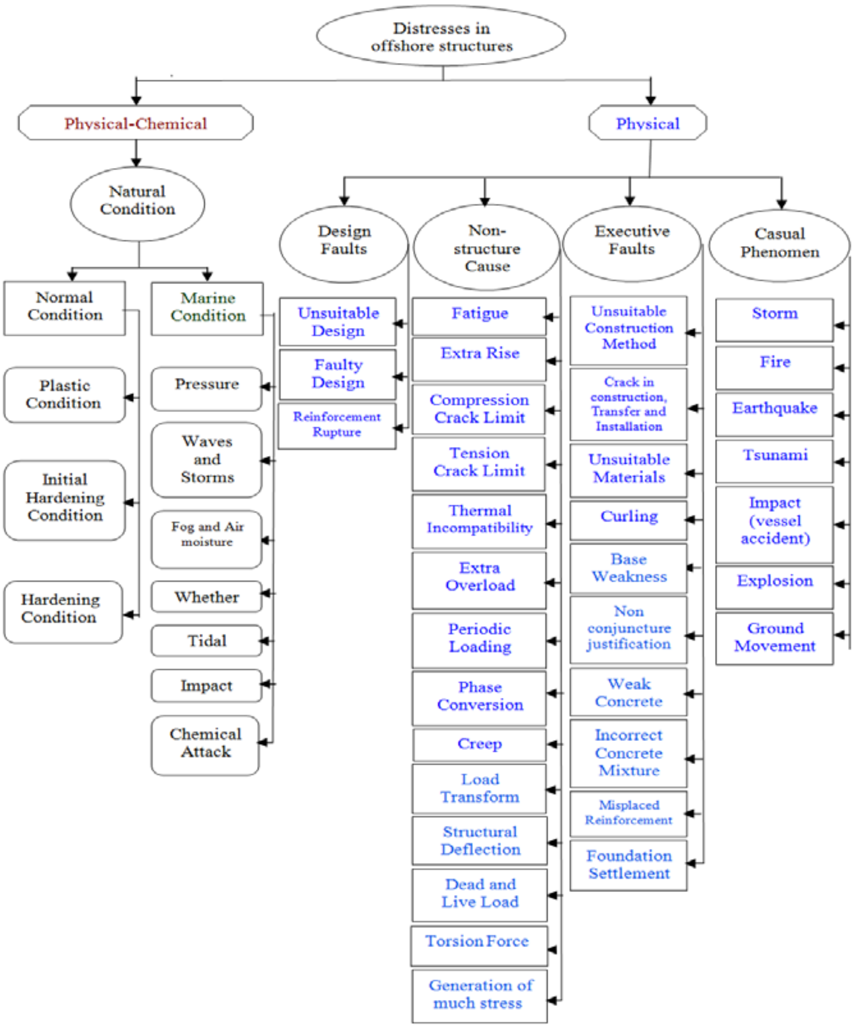

Figure 1. Distresses in marine structures

Natural conditions are divided to two groups. Those factors which are similar in all type of structures are considered as "normal condition". These causes can create some distresses in all structures. In this case, concrete is surveyed in three different conditions:

1) Plastic case (concrete is not thoroughly placed in the specific location).
2) Initial hardening case, concrete is in initial age (3 to 4 weeks).
3) Hardening case (after 28 days).

When concrete is fresh, plastic condition occurs. Shrinkage and settlement can be placed in this category. Settlement and contraction are the most important cause of distresses in initial hardening case. Concrete can earn its strength after 28 days. Drying shrinkage, weathering, and some chemical causes such as corrosion, sulphate attack and alkali reaction can create in this stage.

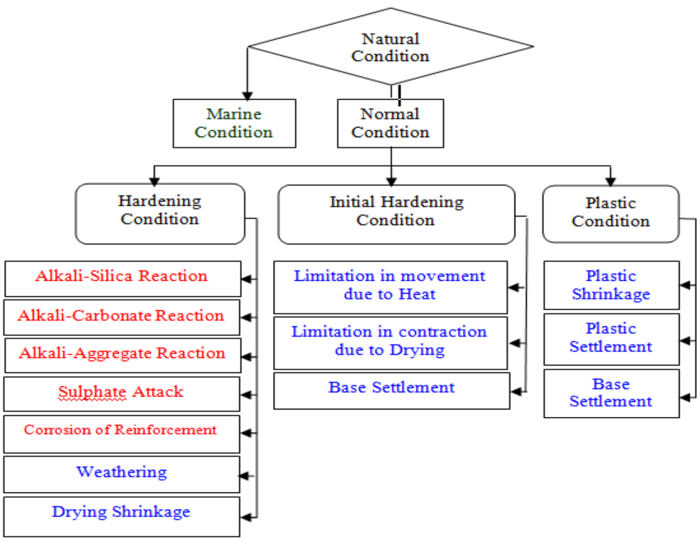

Figure 2. Destroyer normal condition in structures

Common causes of distresses in structures are listed in Figure 2. Some of distresses are happen due to the marine factors. These are pressure, wave, storm, air moisture, weather condition, tide, impact due to ices and vessels and chemical attacks. Pressure factors can be categorized into hydrostatic pressure and salt crystallization. Tide and wave can cause freezing and thawing, cold/hot cycles and wet/dry cycles.

Figure 3. Destroyer marine condition in structures

These can create some concrete destruction. Air moisture can transfer chemical material and create some distresses. Chemical attack is the most important factor in happening of distress. Some distresses due to the chemical attacks have severe effect on structures. These distresses are propagated and may cause the most destructive distress over the time. Weather normally can cause severe effect on distress. This factor can help the distresses to expand. Some factors due to weathering in different conditions are shown in Figure 3.

3. Types of Distresses

The main causes of propagating a distress for marine concrete structure were discussed in the previous section. Between the current evaluating systems, most researches considered the effect of cracking in concrete [19,20,21]. Kim et al. [19,20] proposed an index for maintenance of concrete structures based on the fuzzy method. Marzouk et al. [21] suggested a system for repair of concrete structures. The effects of surface distresses can be seen in fewer papers [22,23]. Chan [22] developed a prototype knowledge based expert system for civil engineering applications in the knowledge domain of diagnosis of deterioration and other problems in reinforced concrete structures. PCA [23] introduced some type of surface distresses. The effect of miscellaneous distresses has been neglected mostly and a small section of researchers considered them [24,25]. Woodson [24] proposed maintenance and evaluating approach for concrete structures and considered the 3 main types of distresses and developed an expert system for concrete airport pavement. The largest types of distresses are presented in this paper including cracks and surface and miscellaneous distresses.

Table 1 briefly shows the results of the literature review. As shown in this table, the distresses can be divided into three major classes according to the literature [26,27,28].

(1) Cracking in concrete: That is a type of distress that causes a groove with distinct depth and width in concrete. Base on its shape, cracks are divided to 8 types: longitudinal, diagonal, crazing, pattern, joint related, random, and D cracking. Some information about this group of distress is presented in Table 2.

(2) Surface Distresses: This Type of distress impairs concrete surface and its appearance. spalling, joint related spalling, spalling caused by corrosion, popouts, scaling, delamination, blistering, efflorescence, discoloration, dusting, honeycombing, encrustation, exudation, wear and erosion (abrasion and cavitation), defect due to frost attack, and freezing and thawing are in this group. Table 3 gives detailed information about distresses in surface distress group.

(3) Miscellaneous Distresses: This kind causes to look unsuitable appearance with different essence, so that don't impair appearance of concrete. Rust staining, leakage and deposit, curling, scouring, temperature changes, phase conversion, extra rise and creep are in this group. Table 4 shows classification of miscellaneous distress.

Table 1. Results of literature review

	Researcher	Yehia [10]	Woodson [24]	Moodi [21,26]	Ismail [25]	Chan [22]	Marzouk [21]	Waller [29]	PCA [23]	USACE [7,27]	Ramezan. [12]	Kim [19,20]
1	Cracking in concrete	*	*	*	*	*	*	*	*	*	*	*
2	Surface distresses	*	*	*	*	*		*	*	*	*	
3	Miscellaneous distresses		*	*	*						*	

Table 2. Classification of cracks in concrete

Crack types	Definition
D-cracking	Progressive structural deterioration of the concrete beginning in certain types of susceptible coarse aggregate, caused by repeated freezing and thawing after absorbing moisture.
Random and Multiple or irregulars over the surface	It shows several cracks in a reinforced concrete slab without any regular pattern.
Diagonal	It is caused by loss of foundation support, base erosion and shear stresses, at about 45 degrees to the natural axis of a concrete member.
Pattern or Map	It is fine openings on concrete surfaces in the form of a pattern.
Crazing	It is fine and random cracking extending only through the surface.
Longitudinal and generally straight	It develop parallel to the long direction of the member.
Transverse	It develop at right angles to the long direction of the member.
Cracks at joint, edge and opening	They are Cracks either at or in the vicinity of transverse and longitudinal joints e.g. within the length of dowel or tie bars or immediately adjacent to them.

Table 3. Classification of surface distresses

Distress name	Definition
Blister	Blister is hollow; low profile bumps on the concrete surface.
Dusting	Dusting is formation of powder or chalk at the surface of a concrete slab.
Bug holes and Honeycombing	Bug holes are voids formed during placement. Honeycombing is the formation of pockets of coarse aggregate during placement.
Exudation or Stalactite	It forms on concrete, and on plumbing where there is a slow leak and limestone (or other minerals) in the water supply.
Efflorescence	Efflorescence is a deposit of salts, usually white in color that occasionally develops on the surface of concrete.
Delamination	Delamination is similar to blisters in that delaminated areas of surface mortar result from bleed water and bleed air being trapped below the prematurely closed (densified) mortar surface.
Discoloration	Gross color changes in large areas of concrete, spotted or mottled light or dark blotches on the surface, or early light patches of efflorescence.
Popout	It is conical fragment that breaks out of the surface of the concrete leaving a hole.
Spalling	Spalling is a process of detachment of a concrete fragment, usually in the shape of a flake, from concrete by the action of weather, by pressure or by expansion within the larger mass.
Joint related spalling or faulting	Faulting is a spall adjacent to a joint.
Encrustation	Encrustation occurs when mineral salts are deposited on the surface of the catheter, both internally and externally.
Abrasion	Abrasion is an external condition only, which is caused by movement of an object or medium across the surface of the concrete, e.g. constant exposure to sea action
Cavitation	Cavitation occurs when high velocity waterflows encounter discontinuities on the flow surface. Discontinuities in the flow path cause the water to lift off the flow surface, creating negative pressure zones and resulting bubbles of water vapor.
Scaling, Disintegration and removal of materials	Scaling is local flaking or peeling away of the surface layers of hardened concrete.
Pothole	Pothole is bowl-shape holes of various sizes in concrete pavement surfaces, which when fully developed, are larger than popouts.

Table 4. Classification of miscellaneous distress

Distress name	Definition
Stain	Stain is an early sign of reinforcement corrosion.
Scouring and leaching	Scouring is excess water rising in the forms can produce stream-like patterns in the surface of the concrete.
Dampness and leakage	Water and dissolved salts attack reinforcing steel, post tensioning tendons, and anchorages; thus they are greatly affecting the capacity of the structure.
Pitting	It is the development of relatively small cavities in a concrete surface.
Segregation, Bleeding, and Stratification	Segregation is the differential concentration of the components of mixed concrete, aggregate, or the like, resulting in non-uniform proportions in the mass. Bleeding channel is the autogenous flow of mixing water within, or its emergence from, newly placed concrete or mortar caused by the settlement of the solid materials within the mass which is also called water gain. Stratification is also the separation of overwet or overvibrated concrete into horizontal layers with increasingly lighter material toward the top.
Temperature changes and Phase conversions	Phase changes which involved volume changes can cause disruption of concrete. Temperature rises particularly those that occur early, may be responsible for a great deal of early cracking in structures.
Strucutral Related Distresses	Crack locations and directions are indicative of the nature of the structural deficiencies which are caused by overloading, poor construction, deterioration owing to environmental factors, inadequate design detailing, differential settlement of foundations and creep.
Collapsed Member	Careless overloading can occur during construction or use, but the direct evidence may have been removed.

4. Questionnaire from Technology Specialists

When a distress takes place on surface of structure, it has a severity and an extant. Also, type of distress is very important. For example, cracking in concrete is more important than blistering because of its shape and its discontinuity. Therefore, these 3 factors were considered to build questionnaire forms. These evaluation Forms were sent to the several specialists that have practical experience in field of concrete and marine environment and offshore industries. These specialists are working in universities or marine industries. Our aim is to find out their view point about:

(1) The importance of each distress;

(2) The effect of each distress on the functionality of the structure.

The cracking may be distinguished in two dimensions, the depth and width. These two factors are considered in these sample forms for each distress. This method is providing a number for comparison of different types of distresses. As an example, the value of longitudinal crack from cracking in concrete subclass can be compared with designated value of scaling from surface distress subclass.

The total number for the distress is divided into a number for the type and a number for the extent and severity. The main purposes in designing the questionnaire forms are as follow:

- Finding the most destructive distress types without consideration of their extent and severity. The most experts distinguish that cracking in concrete is the most important destroyer factor than other distresses in concrete offshore structures.
- Efficacy of extent and severity. In this stage delineate that how much the severity case of specific distress in comparison to slightly case, can affect on the structure.

5. Determining of Deduct Value (DV)

First, total of the questionnaire forms be gathered, forty seven surveys were returned, resulting in a 42% response rate. Since, some of data did not place in suitable range or in comparison with other data didn't have appropriate accuracy, be omitted of range data. Then total acceptable data be averaged and finally, for every distress designate the deduct value (DV). In result, the deduct values are presented in Table 5, Table 6 and Table 7. This method is totally heuristic and will be seen that have acceptable verity for marine structures in following subject. Target of this evaluation is entering the calculation mathematics in science of damage detection and showing the best time for repairing of deteriorated concrete and removing hasty actions and decreasing the project costs.

We adopt a same procedure as given in ACI and BSI standard and U.S Army Corps of Engineers reports to classify the width and depth of cracks [27-32].The width is classified into 4 groups:

- Wide (wider than 2 mm),
- Medium (between 1 to 2 mm),
- Fine (between 0.25 to 1 mm),
- Very fine (finer than 0.25 mm).

For the depth, the crack is also classified into 3 groups:

- Through (>20mm);
- Deep (10-20 mm); and
- Shallow and surface (up to 10 mm).

This classification for longitudinal crack is shown in Table 5 along with the deducted value. It can be seen that longitudinal crack has the value of 8000 in maximum case.

Table 5. Deduct value for longitudinal crack

Type of Crack	Depth of Crack	Deduct Value			
		Width of Crack			
		Very Fine <0.25 mm	Fine 0.25-1mm	Medium 1-2 mm	Wide >2 mm
Longitudinal Crack	Through	2000	4000	6000	8000
	Deep	1200	2400	3600	4800
	Surface and Shallow	400	800	1200	1600

Table 6. Deduct value for spalling and chemical attack

Type of Surface Distress	Rating	Description	Deduct value
Caused by Chemical attack (Sulphate, …)	Very Severe	Loss of coarse aggregate particles as well as surface mortar surrounding aggregate, generally to a depth greater than 20 mm along with wide map cracks	5500
	Severe	Loss of surface mortar 5 to 10 mm in depth with some loss of mortar surrounding aggregate particles 10 to 20 mm in depth along with medium map cracks	4400
	Moderate	Loss of surface mortar up to 5 to 10 mm in depth with fine map cracks, exposure of coarse aggregate	2200
	Slightly	Loss of surface mortar up to 5 to 10 mm in with very fine cracks, no exposure of coarse aggregate	825
	Very Slightly	Noticeable	275
Spalling	Very Severe	Deeper than 20 mm and greater than 150 mm in any dimension	5000
	Severe	Not greater than 20 mm in depth nor greater than 150 mm in any dimension	4000
	Moderate	Holes larger than popouts	2000
	Slightly	Clearly noticeable	750
	Very Slightly	Barely noticeable	250

Table 7. Deduct value for two types of miscellaneous distresses

Type of Miscellaneous Distress	Rating	Description	Deduct value
Rust Stain	Very Severe	Over than 75 percent of area along with wide crack	4000
	Severe	Between 50 and 75 percent of area along with medium crack	3200
	Moderate	Between 25 and 50 percent of area along with fine crack	1600
	Slightly	Between 5 and 25 percent of area	600
	Very Slightly	Less than 5 percent of area	200
Dampness and Leakage	Very Severe	Surface material along with stalactite	2500
	Severe	Surface material more than 10 mm thick	2000
	Moderate	Surface material more than 10 mm thick	1000
	Slightly	Noticeable surface efflorescence	375
	Very Slightly	Barely noticeable surface discoloration	125

The results of the surveys are shown in bar diagrams. These diagrams show the deduct values of all distresses. The deduct values for all crack types, extension and severities are shown in Figure 4, Figure 5, and Figure 6. The Figure 4 is shown DVs for through cracks while Figure 5 shows the DVs for deep cracks and Figure 6 gives DVs for surface cracks. These values represent type, severity and extent of cracking in concrete. They can present the importance of cracking. If we move to right side, deduct values of distresses will decrease. It can be determined that longitudinal cracks have more value in comparison with crazing.

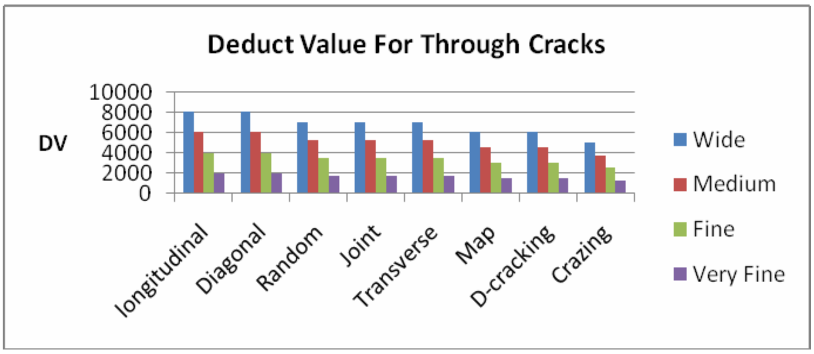

Figure 4. The deduct value for through cracks

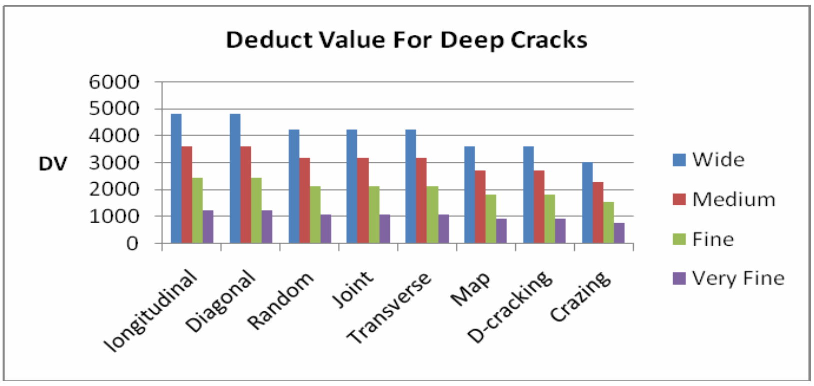

Figure 5. The deduct value for deep cracks

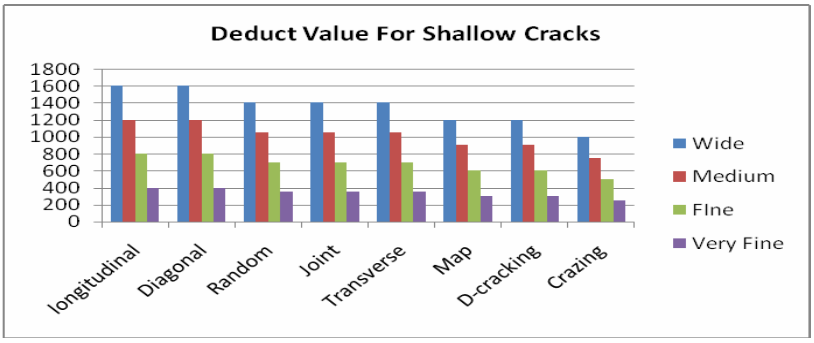

Figure 6. The deduct value for shallow cracks

Table 6 shows the deduct value for two types of surface distresses (chemical attack and spalling). For all of surface distresses, there is a classification for placing in the specific zones.

This specific criterion is based on codes and standards for every distress, but could not express them because of compendium observation.

Figure 7 shows DVs for surface distresses. For all types of surface distresses, DV is given in a bar diagram. We can realize the importance of every surface distress. DV decreases as we move to right side. The spalling is the most important surface distresses while the dusting is the minor one. This Figure illustrates severity and extent of the surface distresses at the same.

Miscellaneous distresses cannot be put together with the cracks and the surface distresses. It is due to the performance and different nature of them. Table7 shows some of them for rusting and scouring. The all of these distresses are depicted in Figure 8.

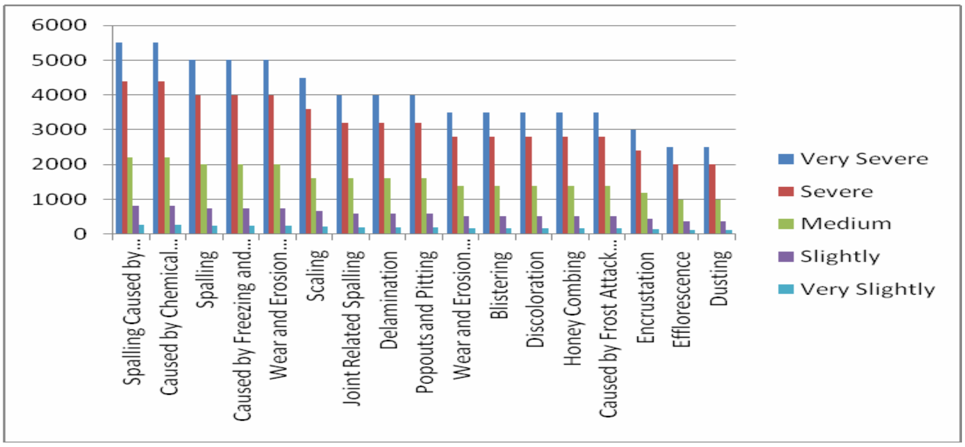

Figure 7. Deduct value for surface distress

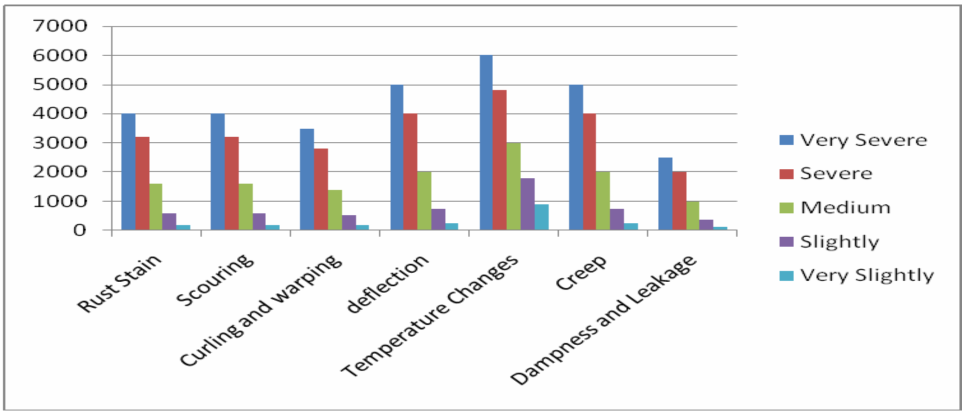

Figure 8. Deduct values for miscellaneous distresses

6. Determining of Marine Structural Condition Index (MSCI)

We should put all of DVs together in some way to find the condition of the structure. The total condition of a structure can be obtained by using the weight - division method.

$$W = \frac{\sum DV_i}{\sum DV_{\max}} \tag{2}$$

where Dv_i is deducting value for distress iand $DV_{\max}$ is the maximum deduct value of distress i that may be occurred in an element of the structure. Using W, a condition index (MSCI) is defined in the following form.

$$MSCI = 100 - (W * 100) \quad (3)$$

To prevent the influence of individual distress or slight distress, a confidence level is taken in denominator. If the denominator is less than 1.5-2 (depend on importance of structure) times of maximum distress (8000), the total dominator in (2) is replaced by:

$$\sum DV_{\max} = (1.5 - 2) \times 8000. \quad (4)$$

7. Determining the Health Structural Limitation

Various standards give different limitation for health structure limitation. Overall, four health zones can be defined for a marine structure. The Table 8 shows this limitation.

In slightly distress condition can say that maintenance of structure must do periodic and continuum. In this case, immediate action is not recommended for repair of structure. In medium distress, structure must be repaired and this is immediate action for every expert. In medium to severe distress, economic analysis is the most important action. If economic condition of constructor is appropriate, repair can be the best action, if it is not appropriate, destruction will be the right action. In severe distress, repair of structure does not have economic justification and this cannot be an ideal method.

Now, with having standard limitation and modern condition index of structure we can find that structure condition is in what confines, and with considering it, the best action is assumed.

Table 8. standard limitation for health structure [9,29]

Zone	CI	Description	Recommended Action
Slightly Distress	85-100	Barely noticeable and minimum distress	Condition of structure is suitable. Maintenance of structure is done.
Slightly to medium Distress	50-85	Distress is noticeable	Repair action is done.
Medium to Severe Distress	30-50	Severe faulty is observable in members	Economic analysis and elaborative Inspection are necessary for repair of structure.
Severe Distress	0-30	Maximum case of distress	Structure Condition is not suitable. Destruction of structure and construction a new structure can be best recommendation.

8. Case Study

The developed method is applied to Eskeleh pier in Bandar Abbas in Iran. The deck of the bridge is reinforced concrete slab. The total length of the bridge is 208.4 m with a width of 6.40 m. The thickness of the slab is 20 cm. Based on technical reports, slab concrete is in medium condition but it is damaged in some areas. Surface of Concrete has crack and efflorescence in major points.

The developed method is compared with the method of U.S Army engineering research. The U.S Army engineering research applied the following equation to obtain the condition index (CI) for the structure.

$$CI = 100 - \begin{bmatrix} 1.0(DV_1) + 0.4(DV_2) + 0.2(DV_3) \\ +0.15(DV_4) + 0.1(DV_5) \end{bmatrix} \quad (5)$$

where: Dv_i was the value of distress for any type which was proposed by Moodi [9]. The notation DV_1 is the maximum value of distress that happens in the structure and DV_5 is 5th maximum value.

8.1. Slab

The distresses on slab surface are:

- Deep pattern crack with 2 mm wide;
- Slight efflorescence;
- Slight dusting;
- Severe rust staining;
- Medium popouts; and
- Through transverse crack with 2 mm wide.

Table 9 shows a comparison between these two. The CI is obtained as follows:

$$CI = 100 - \begin{bmatrix} 1.0(30) + 0.4(25) + 0.2(20) \\ +0.15(15) + 0.1(10) \end{bmatrix} = 52.75$$

while:

$$MSCI = 100 - \left[\frac{\begin{pmatrix} 2700 + 375 + 375 \\ +3200 + 5250 + 1600 \end{pmatrix}}{\begin{pmatrix} 6000 + 2500 + 2500 \\ +4000 + 7000 + 4000 \end{pmatrix}} \right] * 100 = 48$$

As shown, the proposed method can describe the condition of the structure properly.

Table 9. Condition index of slab in the Eskeleh pier

Example	MSCI	Maximum of MSCI	Before method	Rank
deep pattern crack with 2 mm wide	2700	6000	30	1
slightly efflorescence	375	2500	10	5
slightly dusting	375	2500	5	-
severe rust staining	3200	4000	15	4
through transverse crack with 2 mm wide	5250	7000	25	2
medium popouts	1600	4000	20	3

8.2. Column A

There are some types of distresses on one of the columns in front of pier that interacts with tide and wave. They are:

- Through longitudinal crack with 2.5 mm wide.
- Spalling more than 200 mm in diameter.
- Severe cavitation
- Medium honeycombing

This column is in the critical condition. Table 10 shows a comparison between these two. The CI is obtained as follows:

$$CI = 100 - \begin{bmatrix} 1.0(70) + 0.4(50) \\ +0.2(40) + 0.15(20) \end{bmatrix} = -1$$

This is not a real number for condition of column, while:

$$MSCI = 100 - [\frac{8000 + 5500 + 4000 + 2800}{8000 + 5500 + 5000 + 3500}]*100 = 8$$

As shown here, US Army corps of engineer's method cannot express the condition of the structure properly with assigning a negative number where this number doesn't make sense with looking at the standard limitation as described in Table 8.

Table 10. Condition index of column A in the Eskeleh pier

Distress	MSCI	Maximum of MSCI	Before method	Rank
Through longitudinal crack with 2.5 mm wide	8000	8000	70	1
Very severe spalling	5500	5500	50	2
severe cavitation	4000	5000	40	3
medium honeycombing	2800	3500	20	4

8.3. Column B

There are some types of distresses on one of the columns in back of pier in the safe zone. They are:

- Severe dusting,
- Surface transverse crack with fine wide,
- Slightly abrasion,
- Very slightly efflorescence.

This column is in the good condition. Table 11 shows a comparison between these two. The CI is obtained as follows:

$$CI = 100 - [1.0(10) + 0.4(5) + 0.2(5) + 0.15(2)] = 86.7$$

while:

$$MSCI = 100 - [\frac{700 + 525 + 2000 + 125}{7000 + 3500 + 2500 + 2500}]*100 = 79$$

Here again, the described methodology works compatible with the US Army method. In the most cases, our method gives a fewer amount than CI method. In other word it shows that the structure is in a worse condition as they are located in a harsh environment. It may draw the attention of the people to survey more accurately.

Table 11. Condition index of column B in Eskeleh pier

Distress	MSCI	Maximum of MSCI	Before method	Rank
Surface transverse crack with fine wide	700	7000	5	3
Slightly abrasion	525	3500	5	2
Severe dusting	2000	2500	10	1
Very slightly efflorescence	125	2500	2	4

9. Conclusion

An evaluation system is developed for distress evaluation in marine structures. Some questionnaire forms were prepared and some experts in the area marine industries were asked to fill them up in order to provide their judgments about the value of each distress in the structure with a clear distinction between the type, extent and severity. Based on the expert comments, an health index was developed to evaluate the condition of the structure. The index may vary between 0 and 100. The number zero shows that the structure is in the worst condition while the number 100 shows that the structure is in a complete health condition. The method took into account all distresses may happen to a concrete structure in sea environment and accounted them in computation of MSCI. In order to obtain MSCI, first, we classified the distresses into two main group of chemical–physical and physical to obtained the factors may cause any distress on a marine structure. Then, all of distresses were sorted and numbered including the types, extent and severity of the distress. This number called as the deduct value (DV). This DVs are normalized based on the maximum anticipated DVs. Based on the normalized DVs, MSCI index has obtained.

Case studies showed that the method is more reliable than any other similar method that is originally designed for inland and offshore structures. The health index can help us to see whenever the structure is in the unsuitable condition, some actions should be considered in order to make the structure safe for operation.

Acknowledgement

The authors would like to thank all offshore engineers and faculty who participated in the survey. Their input was valuable and vital in this work.

References

[1] Joshaghani, M. S., Raheem, A. M., and Mousavi M.M. R., "Analytical Modeling of Large-Scale Testing of Axial Pipe-Soil

Interaction in Ultra-Soft Soil,"*American Journal of Civil Engineering and Architecture*, 4(3): 98-105, 2016.

[2] Raheem, A. M., and Joshaghani, M. S., "Modeling of Shear Strength-Water Content Relationship of Ultra-Soft Clayey soil," *International Journal of Advanced Research*, Volume 4, Issue 4, pp. 537-545, 2016.

[3] Sandvik, K., Eie, R., &Advocaat, J.D., "A new challenge," in *XIV National Conference on Structural Engineering*, Acapulco Offshore Structures, Norway, 2004.

[4] Champiri, M. D., Mousavizadegan, S. H., & Moodi, F., "A decision support system for diagnosis of distress cause and repair in marine concrete structures," *Computers and Concrete,* Vol. 9, Issue 2, Pages 99-118, 2012.

[5] Champiri, M. D., Mousavizadegan, S. H., & Moodi, F., "A fuzzy classification system for evaluating the health condition of marine concrete structures," *Journal of Advanced Concrete Technology,* Vol. 10, Issue 3, Pages 95-109, 2012.

[6] Cabrera, J.G., Kim, K.S., & Dixon, R., "COBDA: An Expert System for the Assessment of Deterioration of Concrete Bridges," in *Developments in Artificial Intelligence for Civil and Structural Engineering,* Edited by B. H. V. Topping, Civil Comp Press, 151-157, 1995.

[7] USACE, *REMR Management Systems for Civil Works Structures*, U.S Army Corps of Engineers, REMR Technical Note OM-MS-1.1, USA, 1996.

[8] Miyamoto, A., Kawamura, K. and Nakamura, H., "Bridge Management System and Maintenance Optimization for Existing Bridge," in *International Conference on Computer Aided Design and Machine Learning*, Oxford, England, 1999.

[9] Moodi, F., "Integration of Knowledge Management and Information Technology into the Repair of Concrete Structures: An Innovative Approach," *The International Journal of Information Technology in Architecture, Engineering and Construction (IT-AEC)*, 2(3), CICE, UK, 2004.

[10] Yehia, S., Abudayyeh, O., Fazal, I., & Randolph, D., "A decision support system for concrete bridge deck maintenance," *Advances in Engineering Software,* 202-210, 2008.

[11] Tarighat, A., & Miyamoto, A., "Fuzzy concrete bridge deck condition rating method for practical bridge management system," *Expert Systems with Applications*, Elsevier, 36(10), 12077-12085, 2009.

[12] Ramezanianpour, A.A., Shahhosseini, V., & Moodi, F., "A fuzzy expert system for diagnosis assessment of reinforced concrete bridge decks," *International journal of Computers and Concrete,* 281-303, 2009.

[13] Beizaee, S., Willam, K., Xotta, G., Mousavi R., "Error Analysis of Displacement Gradients via Finite Element Approximation of Digital Image Correlation System,"in *9th International Conference on Fracture Mechanics of Concrete and Concrete Structures (FraMCoS-9),* 2016.

[14] Willam, K., Mohammadipour, A., Mousavi, R., and Ayoub, A. S., "Failure of unreinforced masonry under compression," in *Proceedings of the Structures Congress*, pages 2949-2961, 2013.

[15] Sajedi, S., & Huang, Q., "Probabilistic prediction model for average bond strength at steel–concrete interface considering corrosion effect," *Engineering Structures*, 99, 120-131, 2015.

[16] Sajedi, S., & Huang, Q., "Time-dependent reliability analysis on the flexural behavior of corroded RC beams before and after repairing," *Structures Congress, ASCE*, 1470-1481, 2015.

[17] Sajedi, S., Huang, Q., and Miran, S.A., "Reliability-Based Life-Cycle-Cost-Analysis of Corroded Reinforced Concrete Substructures Considering Patch Repair", in *NACE Corrosion Risk Management Conference,* Houston, TX, Paper No. RISK16-8732, 2016.

[18] Sajedi, S. and Huang, Q., "Load-Deflection Behavior Prediction of Intact and Corroded RC Bridge Beams with or without Lap Splices Considering Bond Stress-Slip Effect", *Journal of Bridge Engineering, ASCE*. 2016.

[19] Kim, Y.M., Kim, C.K., & Hong, S.G., "Fuzzy set based crack diagnosis system for reinforced concrete structures," *Computers & Structures*, Elsevier, 85(23-24), 1828-1844, 2007.

[20] Kim, Y.M., Kim, C.K., & Hong, S.G., "Fuzzy based state assessment for reinforced concrete building structures," *Engineering Structures*, 28(9), 1286-1297, 2006.

[21] Marzouk, M.M., Abdel Hamid, S.N., & Ibrahim, M.E., "An automated system for repairing defects in reinforced concrete elements," in *12th international colloquium on structural and geotechnical engineering (ICSGE)*, Cairo, Egypt, 2007.

[22] Chan, P.P.F., *An expert system for diagnosis of problems in reinforced concrete structures* (M.Sc. Thesis). Royal Melbourne Institute of Technology, Australia, 1996.

[23] PCA (Portland Cement Association), *Concrete Slab Surface Defects: Causes, Prevention, Repair*. Item Code: IS177, 2001.

[24] Woodson, R. D., "Evaluating concrete in concrete structures," *Concrete Structures*, 3-18, 2009.

[25] Ismail, N., Ismail, A.,& Rahmat, R. A. "Development of expert system for airport pavement maintenance and rehabilitation," *European Journal of Scientific Research*, ISSN 1450-216X, 35(1), 121-129, 2009.

[26] Moodi, F., "Investigation of a Management Framework for Condition Assessment of Concrete Structures Based on Reusable Knowledge and Inspection," *International Journal of Computers and Concrete*, 7(3), 249-269, 2010.

[27] USACE, *Engineering and Design: Evaluation and Repair Concrete Structures*, U.S Army Corps of Engineers, Engineer Manual 1110-2-2002, USA, 1995.

[28] ACI, *Causes, Evaluation, and Repair of Cracks in Concrete Structures*. American Concrete Institute, ACI committee 224, ACI 224-1R-07, USA, 2010.

[29] BSI., *Concrete*. British Standard Institution, BS 1810 and BS 5328, UK, 2008.

[30] Yang, G., Zomorodian, M., Belarbi, A., and Ayoub, A., "Uniaxial Tensile Stress-Strain Relationships of RC Elements Strengthened with FRP Sheets." *J. Compos. Constr.*, 2015.

[31] Yang, G., Zomorodian, M., Belarbi, A., and Ayoub, A., "Behavior of FRP-Reinforced Concrete Element under Shear: Experimental and Analytical Investigations", in *Proceedings of the Structures Congress*, 1879-1890, 2013.

[32] Mohammadipour, A., and Willam, K., "Lattice Approach in Continuum and Fracture Mechanics", *J. Appl. Mech*, 83(7), 071003, 2016.