Malaysian Journal of Civil Engineering 18(2) 129-138 (2006)

CONDITION ASSESSMENT OF MARINE STRUCTURES USING FUNCTIONAL CONDITION INDEX APPROACH

Sallehuddin Shah Ayop[1], Rosli Mohamad Zin[2,*], Mohammad Ismail [3]

[1]*Faculty of Engineering,Kolej Universiti Tun Hussein Onn, 86400 Parit Raja, Johor*
[2,3]*Faculty of Civil Engineering,Universiti Teknologi Malaysia, 81310 Skudai, Johor*

*Corresponding author: *roslizin123@yahoo.com*

Abstract: Marine structures are subjected to damage and deterioration during their service life because of continuous exposures to aggressive environment. As a result the performance and the intended functions of the structure are affected. This paper presents the development of a condition assessment system for assessing the status of concrete marine structures in Malaysia. The assessment system is based on the Condition Index (*CI*) method developed by the U.S Army Corps of Engineers. The assessment took into account the level of deterioration observed during inspection work. The Functional Condition Index (*FCI*) approach was used to calculate the *CI* of the structure. Field data through visual inspection on concrete wharf structure was collected. Three types of deterioration were considered in the assessment: (1) corrosion of reinforcement, (2) cracking, and (3) spalling of concrete surface. The results show that the calculated *CI* values based on the proposed method is relatively close to the expert opinion values. The condition assessment system based on the *CI* method is found to be reliable and efficient hence can be used to monitor the performance of marine structures in Malaysia.

Keywords: *Condition Assessment System; Condition Index; Concrete Deterioration; Corrosion of Reinforcement; Marine Structures; Expert Opinion.*

Abstrak: Struktur marin akan mengalami kerosakan dan kemerosotan semasa hayatnya akibat terdedah kepada persekitaran agresif yang berterusan. Kerosakan dan kemerosotan boleh mendatangkan kesan ke atas prestasi dan kegunaan struktur tersebut. Kertas kerja ini membentangkan pembangunan satu sistem penilaian status struktur konkrit marin di Malaysia. Pembangunan sistem ini merupakan satu langkah ke arah perlaksanaan penyenggaraan terancang. Sistem penilaian keadaan yang dicadangkan adalah berdasarkan kaedah Indeks Keadaan yang telah dibangunkan oleh U.S Army Corps of Engineers. Penilaian keadaan yang dibuat mengambil kira tahap kemerosotan yang diperhatikan semasa kerja pemeriksaan. Kaedah Indeks Keadaan Berfungsi digunakan untuk menentukan Indeks Keadaan struktur. Data di lapangan melalui pemeriksaan visual ke atas struktur konkrit dermaga telah dikumpulkan. Tiga jenis kemerosotan dipertimbangkan dalam penilaian iaitu: (1) pengaratan tetulang; (2) keretakan dan (3) serpihan pada permukaan konkrit. Keputusan menunjukkan nilai Indeks Keadaan berdasarkan kaedah yang dicadangkan secara relatifnya adalah hampir dengan nilai yang ditentukan oleh penilai pakar. Sistem Penilaian Keadaan bedasarkan Indeks keadaan didapati boleh diterima dan boleh digunakan secara efektif dan berkesan untuk memantau prestasi struktur marin di Malaysia.

Katakunci: *Sistem Penilaian Keadaan; Indeks Keadaan; Kemerosotan Konkrit; Pengaratan Tetulang; Struktur Marin; Penilaian Pakar.*

1.0 Introduction

Maintenance of marine structures is expensive. Many organizations especially port authorities spend more money on maintenance than on capital investment (Lethbridge, 1986).-

The objective of maintenance is to keep concrete structures in full working order and to protect the substantial investment. Adequate and timely maintenance can extend the life of a structure and substantial overall cost saving. The civil infrastructures such as wharves, jetties, quays and building are among the assets that require attention.

In Malaysia, most marine structures especially wharves and jetties are primarily made of reinforced concrete. Concrete is the common choice because it is strong, durable and fire resistant if proper construction practice and design specifications are adhered to. Despite its advantageous, concrete is also subjected to deterioration due to environmental factors such as humidity, moisture, carbon dioxide, and chloride. At Penang Port for example, most of the concrete structures are showing sign of deterioration due to exposure to weather and continuous attack from aggressive agents (Goh and Selvin, 1992). The deterioration is in the form of spalling of concrete cover and corrosion of reinforcement.

Deteriorating concrete structures need to be assessed for structural fitness. The assessment effort has to be planned effectively so that repair works can be carried out to ensure its structural integrity. This study proposed an assessment system for evaluating the condition of concrete marine structures under the influence of tropical climate. According to Bevc et al. (1999), condition assessment system can be a numerical system, assigned to each structural component based on the observed material defects and their subsequent effect on the ability of such component to perform its function. Data from both visual inspection and basic tests are commonly used to calculate the condition rating. It can be based on either simple scoring or numerical evaluation (Bevc et al.,1999).

2.0 Methodology

The present system for evaluating the condition of concrete marine structures that are exposed to tropical climate was developed based on the Condition Index (*CI*) method that was earlier introduced by the U.S Army corps of Engineers (McKay, 1998; McKay et al., 1999). The assessment is based primarily on physical deterioration as determined by measurable distress. The *CI* is represented by a quantitative rating between 0 and 100.

The index serves as guidelines for structures that require immediate repairs and further evaluation. There are several methods that can be used to calculate *CI* (e.g. Greimann and Stecker, 1990; Uzarski et al., 1995; Bullock and Foltz, 1995). In this study, the *CI* was calculated based on the Functional Condition Index (*FCI*). The *CI* scales (Table 1) developed by Greimann and Stecker (1990) were used to convert the physical state of the structures into quantitative values.

Table 1: Condition Index scales (Greimann and Stecker, 1990)

Zone	Condition Index	Condition Description	Recommended Action
1	85 to 100	Excellent: No noticeable defects. Some aging or wear may be visible.	Immediate action is not required.
	70 to 84	Very Good: Only minor deterioration or defects are evident.	
2	55 to 69	Good: Some deterioration or defects are evident, but function is not significantly affected.	Economic analysis of repair alternatives is recommended to determine appropriate action.
	40 to 54	Fair: Moderate deterioration. Function is still adequate.	
3	25 to 39	Poor: Serious deterioration in at least some portions of the structure. Function is inadequate.	Detailed evaluation is required to determine the need for repair, rehabilitation or reconstruction. Safety evaluation is recommended.
	10 to 24	Very Poor: Extensive deterioration. Barely functional.	
	0 to 9	Failed: No longer functions. General failure or complete failure of major structural component.	

Among others, the commonly methods for calculating the *CI* are Functional Condition Index (*FCI*) (Greimann et al., 1990), Weight-Deduct Density (Uzarski et al., 1995) and Deduct Value (Bullock and Foltz, 1995). In this study *FCI* was chosen because of its ability to consider the serviceability and subjective safety. *FCI* is developed based upon field measurements of the distress and expert opinion. The expert opinion involves “engineering judgment” and depends upon the experience of the evaluators (Greimann et al., 1990). Factors considered in the evaluation processes are the serviceability of the structure and subjective safety. Subjective safety refers to the experts' opinion on whether the problem can affect the overall safety of the structure or not.

Each structural distress was measured by some geometric or numerical quantity, X. In the case of surface crack, X was determined as crack width. The FCI is given by (Greimann et al., 1990):

$$FCI = 100\,(0.4)^{X/X_{max}} \tag{1}$$

where X_{max} is the limiting value of X. Based on the description in Table 1, the value of X_{max} was at the point when the CI is 40 (dividing point between zones 2 and 3). Figure 1 shows the relationship between X/X_{max} and their CI.

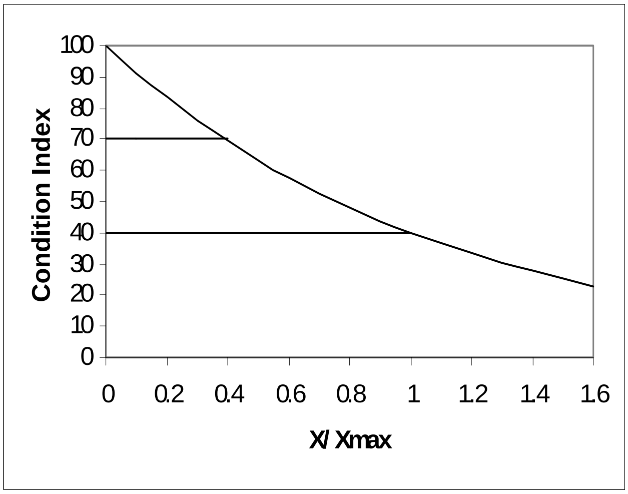

Figure 1: Subjective Condition Index related to X/X_{max} (After Greimann et al., 1990)

Once the value of X is identified, experts were asked to select X_{max} for each distress. X_{max} is the level of distress that needs immediate repair or at least require a detailed inspection.

2.1 Multiple Distresses

When several types of distresses occurred, the CI values were combined and converted to a single value. This was achieved by assigning a weighting factor w_i, to reflect the importance of various distresses (Greimann and Stecker, 1990; McKay, 1999). The weightage is assigned according to the severity of each distress relative to other distresses. The combined Condition Index, $CI_{combined}$ for a structural component is taken to be a linear weighted combination of the individual distress using the following equation (Greimann and Stecker, 1990):

$$CI_{combined} = \sum_{Distresses} (W_i)(FCI_i) \qquad 0 < CI_{combined} < 100 \qquad (2)$$

where,

$$W_i = (w_i / \Sigma w_i)\ (100) \qquad (3)$$

2.2 Data Collection

Data was collected in two stages. In the first stage, experts in the field of concrete maintenance and repair were identified. They were senior engineers from Kuantan Port, Penang Port, Klang Port, and lecturers from Universiti Teknologi Malaysia. These experts were requested to classify different levels of distress on concrete structures based on their knowledge and experience. Three types of major distresses were considered in this study, i.e. spalling of concrete, corrosion of reinforcement and surface crack. Design deficiencies or current inadequacies such as poor workmanship were not considered in the distresses assessment. The information collected were analysed in order to establish the severity levels for each type of distress. At the same time the values of X_{max} (level of distress where immediate repair is required) for corrosion, spalling and cracks were determined.

In the second stage, a case study was conducted on a wharf structure at Penang Port. The case study was to test the condition assessment method that has been developed. The focus was on assessing the conditions of concrete structural elements consisting of piles, pile caps, and beams.

3.0 Results and Discussion

3.1 Expert Opinion on Levels of Distress for Corrrosion, Spalling and Cracks

The information collected from experts has enabled the establishment of severity levels of concrete spalling, corrosion of reinforcement and surface cracks. The followings are brief descriptions of each distress and its associated levels of severity.

Corrosion of Reinforcement

The effect of corrosion in atmospheric, splash and tidal zone was used to evaluate the functional condition index because it can be detected during visual inspection. Based on the expert opinions, the level of concrete corrosion is divided into five classes as shown in Table 2. The limiting value of corrosion of reinforcement is selected as X_{max} = Fair.

Table 2: Severity levels of corrosion of reinforcement

Severity level	Description
1	- Dotted stains on the concrete surface
2	- Light rust stains on the concrete surface - Corrosion of wires - No exposed rebar
3	- Minor corrosion of exposed rebar - Rust stain along rebar on concrete surface. - Reinforcing steel ties, exposed
4	- Major rust stain along rebar - Exposed rebar with heavy rusting and localized pitting - Loss of bar section, 10% to 20%
5	- Loss of section > 20%

1= Excellent, 2= Very Good, 3= Good, 4= Fair, 5=Poor

Spalling

For compressive members, spalling of concrete can reduce the effective cross section of the concrete, thereby reducing the ultimate compressive load. The severity classes are presented in Table 3. The limit level (X_{max}) of spalling is selected as fair condition. At this condition, it can reduce the effective cross-section and also expose the reinforcement thus increase the risk to corrosion.

Table 3: Severity levels of spalling of concrete

Severity level	Description
1	- Good original surface, hard material
2	- Small chip or popouts - Surface spalling that exposed coarse aggregate
3	- Spalling of concrete with 1/3d to 1/2d in depth
4	- Spalling of concrete result in 10% to 15% area of component affected - Large spall 150mm or more in width and depth ½d to 1d
5	- Spalling more than 15% area of beam or 30% area of slab - Spalling depth > 1d

1= Excellent, 2= Very Good, 3= Good, 4= Fair, 5=Poor; d = concrete cover

Surface Crack

Cracks in reinforced concrete are normally acceptable if their width, length and distribution are not enough to cause further deterioration on the structure. Wide cracks could facilitate water penetration deep into the concrete matrix, thus enhance corrosion process. Based on the expert opinions, surface crack is critical when the actual crack width (X) exceeds X_{max} which is 0.3 mm for beam, haunch and slab or 0.25 mm for pile and pile cap.

3.2 Case Study – Penang Port

The structural elements investigated in the case study are piles, pile caps, and beams. These components contribute significant impact to the performance of overall wharf structure. The nature of the structural spalling and corrosion are summarized in Table 4. The *FCI* values, calculated using equation (1) are presented in Table 5 together with the experts' ratings on the structural components. Since multiple distresses existed in each structural component, equations (2) and (3) were used to calculate the $CI_{combined}$ (Table 6).

The results show that the values given by the field engineers are comparable with the calculated values using the *FCI* equation. These differences range from 10% to 25% for spalling, 0% to 14% for corrosion of reinforcement and 15% for surface cracks. When the $CI_{combined}$ is used, the differences range from 15% to 42%.

Table 4: Description of distress on wharf structural components at Penang Port

Structural Component	Description of Distress
Pile Cap 1	Spalling – 150mm x 300mm x 100mm depth Corrosion – exposed rebar and heavily corroded
Pile 1	Spalling – 900mm x 250mm x 50 mm depth Corrosion - exposed rebar and heavily corroded Cracks – width 0.15mm and 0.2mm
Beam 1	Spalling – 900mm x 530mm x 75mm depth Corrosion – exposed rebar with minor corrosion
Pile 2	Spalling – 880mm x 500mm x 40mm depth Corrosion – exposed rebar with minor corrosion
Beam 2	Spalling – 1300mm x 300mm x 50mm depth Corrosion – loss of cross-section area > 10%

Table 5: Functional Condition Index of wharf structural components at Penang Port

Structural Component	Type of Distress	X	X_{max}	FCI	Expert Ratings
Pile Cap 1	Spalling	4	4	40	48
	Corrosion	5	4	32	37
	Surface Cracks	No crack	No crack	100	100
Pile 1	Spalling	4	4	40	32
	Corrosion	5	4	32	29
	Surface Cracks	0.2	0.5	69	60
Beam 1	Spalling	4	4	40	44
	Corrosion	3	4	50	50
	Surface Cracks	No crack	No crack	100	100
Pile 2	Spalling	4	4	40	50
	Corrosion	3	4	50	56
	Surface Cracks	No crack	No crack	100	100
Beam 2	Spalling	5	4	32	38
	Corrosion	5	4	32	32
	Surface Cracks	No crack	No crack	100	100

Table 6: Combined Condition Index of wharf structural components at Penang Port

Structural Component	Type of Distress	FCI *Eqn. 1*	W_i *Eqn. 3*	$CI_{combined}$ *Eqn. 2*	Expert Ratings
Pile Cap 1	Spalling	40	0.40	54	43
	Corrosion	32	0.33		
	Surface Cracks	100	0.27		
Pile 1	Spalling	40	0.40	45	32
	Corrosion	32	0.33		
	Surface Cracks	69	0.27		
Beam 1	Spalling	40	0.40	60	48
	Corrosion	50	0.33		
	Surface Cracks	100	0.27		
Pile 2	Spalling	40	0.40	60	52
	Corrosion	50	0.33		
	Surface Cracks	100	0.27		
Beam 2	Spalling	32	0.40	50	35
	Corrosion	32	0.33		
	Surface Cracks	100	0.27		

Two cases (Pile 1 and Beam 2) produced lower values than the calculated one. This is because one or more severe distresses in the structural components could significantly affect the overall condition of the structural component. For example in Beam 2 the corrosion of reinforcement is so severe, thus significantly reduces the overall condition rating of the component. To take into account such situation, Greimann et al., (1990) had introduced an adjustment factor as follows:

$$AF = 8\text{-}7\ [(CI - 40)/30],\ 40 < CI < 69 \tag{4}$$

where, AF is the Adjustment Factor and CI is the Condition Index.

The application of adjustment factor was able to narrow down the difference between the calculated *CI* values and the expert assigned values (Table 7). This is due to the fact that the adjustment factor takes into account the effect of dominant distress on the overall condition of the structural components.

Table 7: Adjusted Combined Condition Index of wharf structural components at Penang Port

Structural Component	Type of Distress	FCI *Eqn. 1*	W_i *Eqn. 3*	AF Eqn. 4	Adjusted $CI_{combined}$
	Spalling	40	0.40	8	
Pile Cap 1	Corrosion	32	0.33	8	39
	Surface Cracks	100	0.27	1	
	Spalling	40	0.40	8	
Pile 1	Corrosion	32	0.33	8	38
	Surface Cracks	69	0.27	1.23	
	Spalling	40	0.40	8	
Beam 1	Corrosion	50	0.33	5.7	46
	Surface Cracks	100	0.27	1	
	Spalling	40	0.40	8	
Pile 2	Corrosion	50	0.33	5.7	46
	Surface Cracks	100	0.27	1	
	Spalling	32	0.40	8	
Beam 2	Corrosion	32	0.33	8	35
	Surface Cracks	100	0.27	1	

4.0 Conclusions

Condition rating is a suitable method for assessing the overall condition of concrete structures because the condition of each component can be monitored continuously. This study proposed a systematic method for assessing the condition of marine structures. The condition rating system is developed based on a method introduced by the U.S Army Corps of Engineers. This model has been tested through a field study involving a concrete wharf structure comprising of beam, pile and pilecap structural components. The condition ratings based on the developed *FCI* method is capable of producing reliable assessment on concrete structural components.

Acknowledgement

The authors would like to thank RMC and UTM for the financial support of this study, and the management of Kuantan Port, Penang Port and Klang Port for their cooperation and encouragement.

References

Bevc, L., Mahut, B. and Grefstad, K. (1999) Review of Current Practice for Assessment of Structural Condition and Classification of Defects. BRIME Project (Bridge Management in Europe), Deliverable D2.

Bullock, R.E. and Flotz, S.D. (1995) Navigation and Reservoir Structures Condition Rating Procedures for Concrete in Grvity Dam, Retaining Walls and Spillways. Technical Report REMR-OM-16. Champaign, Illinois: U.S. Army Construction Engineering Research Laboratory.

Goh, B.H. and Selvin, J. (1992) Methdodolgy of inspection and structural repair of reinforced concrete beam of a coastal structure – The Penang Port Commission's Experience. *PPC Internal Report*.

Greimann, L.F and Stecker, J.H (1990) Maintenance and repair of steel sheet pile structure. *Tech. Report REMR-OM- 9.* U.S. Army Constr. Engrg. Res. Lab., Champaign, Illinois.

Greimann, L.F., Stecker, J.H. and Kao, A.M. (1990) Inspection and Rating of Steel Sheet Pile. *Journal of Performance of Constructed Facilities,* ASCE, 4(3): 186-201.

Lethbridge, J. (1986) The challengers of port maintenance in developing countries. *Maritime and Offshore Structure Maintenance.* Thomas Telford Ltd., London.

McKay, D.T. (1998) REMR Management System - Navigation Strustures: A Simple Condition and Performance Rating Procedure for Reverine Stone Training Dike and Revetment. Tech. Report REMR-OM- 21. U.S. Army Const. Engrg. Res. Lab., Champaign, Illinois.

McKay, D.T, Rens, K.L, Greimann, L.F, and Stecker, J.H (1999) Condition index assessment for U.S. Army Corps of Engineers Civil Work. *Journal of Infrastructure System,* ASCE, 5(2): 52-60.

Uzarski, D.R., Weightman, P.A., Hunter, S.L. and Brotherson, D.E. (1995) Development of Condition Indexes for Building Wxteriors. USACERL Technical Report 95/30. Champaign, Illinois: U.S. Army Construction Research Laboratory.