

# Durability related environmental zonation and design methodology for marine RC structures

Wu Hairong<sup>1,2</sup> Lü Qingfang<sup>3</sup> Jin Weiliang<sup>1</sup>

(<sup>1</sup>Institute of Structural Engineering, Zhejiang University, Hangzhou 310058, China)

(<sup>2</sup>School of Civil and Transportation Engineering, Henan University of Urban Construction, Pingdingshan 467036, China)

(<sup>3</sup>School of Civil Engineering, Southeast University, Nanjing 210096, China)

**Abstract:** A reliability-based quantitative durability design methodology is presented for reinforced concrete (RC) structures in the marine environment on the basis of natural exposure data derived from four berths (1.5, 1.5, 4 and 15 years) of a concrete port. More than 200 chloride profiles are obtained and analyzed. The relationship between nominal surface chloride ion concentration and altitude is discussed. Subsequently, the formula of the apparent chloride diffusion coefficient is proposed with consideration of the surrounding temperature, sodium chloride solution concentration, age factor and altitude. Then, the reliability-based method to predict the durability of RC structures is developed according to Fick's second law. Relationships between the predicted penetration depth of the chloride ion, the ratio of the wetting time per-period and the corresponding altitude are discussed. Subsequently, the environmental zonation methodology is established for concrete structures under a marine chloride environment by considering the ratio of the wetting time per-period of concrete as the zoning index. Finally, the corresponding durability design method for each zone level is established, which contains the durability design regulations of the specimen, and correction coefficients for different water/binder ratios, ages, temperatures and chloride ion concentrations.

**Key words:** reinforced concrete structure; marine; chloride ion; environment; zonation; durability design

**DOI:** 10.3969/j.issn.1003-7985.2018.01.012

**A**mong all of the durability deterioration mechanisms in RC structures, corrosion of the reinforcing steel bar embedded in concrete is one of the most serious deterioration mechanisms. At the initial state of corrosion, the rebar corrosion rate may exhibit at a steady rate<sup>[1]</sup>, and then, the expansion of the iron rust layer will lead to the surface cracking and subsequently spalling over the cover concrete. As a result, the service life of RC structures will be significantly reduced. Environmental fac-

tors, such as the temperature, humidity, precipitation, wind (direction, force and speed), and density of erosion medium on the exposed surface, are all relevant to the durability of reinforced concrete structures<sup>[2-3]</sup>.

Different working environmental classifications have been introduced into some durability design specifications and standards<sup>[4-5]</sup>. These qualitative and experience-based design methods lack quantitative indices and evaluations. As a consequence, the environmental action level chosen for a same target project may be different by different engineers even in a same real case. Thus, it is necessary to establish a quantitative-based durability design method as guidelines for concrete structures.

The basic concept of quantitative-based concrete durability design, durability zonation (DZ), for the design of concrete structures was first proposed in 2005<sup>[6]</sup>. Basic principles for durability zonation standard (DZS) and methodology of the durability environmental zonation standard (DEZS) were further developed and applied in several projects<sup>[6-10]</sup>. Also, other relevant attempts were made on environmental regionalization or classification for concrete structures<sup>[11-13]</sup>. However, the quantification of environmental factors, the effects of material parameters on concrete durability, the performance degradation prediction models, the zonation indices and the design method in accordance with the established zonation need further discussion.

For RC structures exposed to marine environments, chloride penetration is a complex phenomenon, involving various factors such as the diffusion of chloride ions and the movement of chloride ions due to permeation of water into concrete<sup>[14]</sup>. It has been commonly recognized that the working environment can be divided into four regions: atmospheric zone, splash zone, tidal zone and underwater zone. However, only qualitative descriptions for environmental conditions and chloride ions penetration mechanisms are given for each zone<sup>[2,4,15]</sup>, and the quantitative relationship between external environmental actions on the structures and altitudes or other dominant environment indices have not been reported. Many previous investigations have been attempted on the durability of RC structures to predict the service life and give suggestions for the durability design<sup>[11,16-17]</sup>, but these works

**Received** 2017-08-24, **Revised** 2017-12-03.

**Biography:** Wu Hairong (1983—), female, doctor, lecturer, zjuwhr@hncj.edu.cn.

**Foundation item:** The National Natural Science Foundation of China (No. 51508162).

**Citation:** Wu Hairong, Lü Qingfang, Jin Weiliang. Durability related environmental zonation and design methodology for marine RC structures [J]. Journal of Southeast University (English Edition), 2018, 34(1): 78-86. DOI: 10.3969/j.issn.1003-7985.2018.01.012.

have been generally limited to a particular problem, especially focusing on one specific zone (splash, tidal, submerged or atmospheric), and lacking consideration for the environmental spatial continuity. The objective of this paper is to present a quantitative-based durability design methodology associated with environmental zonation considering the spatial continuity. The methodology can be used to guide engineering practice and ease the structural design for structures exposed to marine environments.

## 1 Data and Method

### 1.1 Experimental work

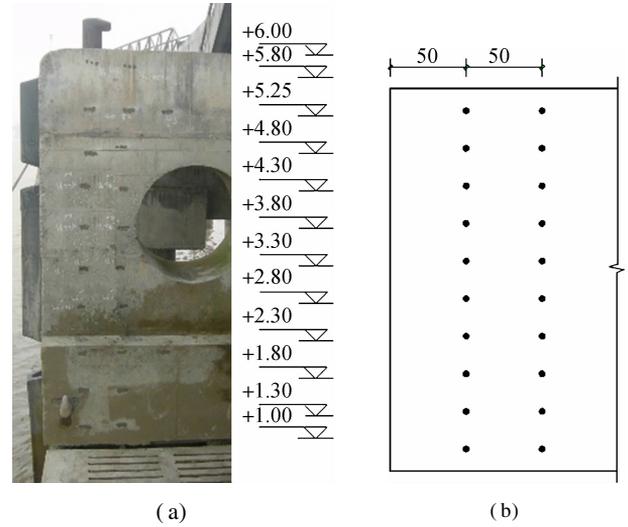
To evaluate the variation of chloride ions penetration into concrete in the marine environment, field detection was performed in Zhapu Port of Jiaying City, which is located in Zhejiang province, the eastern coast of China.

Zhapu Port belongs to a typical subtropical monsoon climate, with clear distinctions between the four seasons. The environmental characterisation comprises of meteorological and hydrological characteristic data (see Tab. 1). The data was collected by the headquarters of the Hangzhou Bay Cross-Sea Bridge. The temperature shows a large variation with a difference of 24.1 °C between the average temperature of July and January. The relative humidity stays high, ranging from 79% to 85%. The wind direction is remarkably different in summer (SE) from that in winter (NW), and there are obvious seasonal variations in precipitation.

**Tab. 1** Annual average values of environmental factors

Factor	Value	Factor	Value
Temperature/°C	15.9	Relative humidity/%	82
Precipitation/mm	1 250	Salinity/%	1.079
pH	8.1	Mean tidal range/m	4.69
Wind speed/(m · s <sup>-1</sup> )	3.2	Main wind directions	NW, SE

The experimental work of field detection consists of two parts. The first one focused on studying the distribution of chloride penetration in concrete considering the spatial continuity in the vertical direction and the second concentrated on the probability characteristics and the variation of relevant parameters. For the first part, two concrete walls were chosen to be detected with a 0.5 m interval in an altitude from +1.30 to +5.80 m (see Fig. 1), respectively, in Berth 2 of the first phase project (denoted as BN1-2) and Berth 1 of the second phase project (denoted as BN2-1), where the altitude was based on the Wusong Height data. For the second part, specific points were detected and a series of chloride profiles were obtained in different altitudes for +2.3, +5.25 and +7.6 m (roughly located in splash, tidal or atmospheric zones divided by the Industry Standard of China JTJ 275—2000<sup>[15]</sup>) from BN1-2, BN2-1, Berth 4 of the second phase project (denoted as BN2-4) and Berth 1 of the third phase project (denoted as BN3-1).



**Fig. 1** Distribution of sampling site with altitude. (a) On-site sampling location (unit: m); (b) Sampling points arrangement (unit: cm)

### 1.2 Chloride ion concentration in concrete

This paper focused on the methodology of concrete durability design, and therefore only the water/binder ratio of concrete mixtures was discussed, which was a key mix proportion parameter. Five concrete mixes (0.45, 0.40, 0.55, 0.52 and, 0.48) were used in the investigation corresponding to BN1-2, BN2-1, BN2-4, BN3-1 (+7.6 m) and BN3-1 (+2.3 and +5.25 m), respectively.

Concrete powder samples were extracted in situ from the predetermined measuring points of each berth to obtain the chloride profiles through drilling by percussion drill. Considering the exposure location and time, the sampling depths were determined as follows: for BN1-2 and BN2-1, the drilling depth is determined to be 70 mm with an interval of 7 mm; for BN 3-1 and BN2-4, the drilling depth is determined to be 50 mm with an interval of 5 mm. In addition, the samples of measuring points at an altitude of +7.6 m, where the degree of exposure environmental action is relatively low, were all taken up to 50 mm with an interval of 5 mm. For each sample, the amount of the water-soluble chloride ion concentration was determined by a RCT (rapid chloride test) instrument in the laboratory following a procedure similar to that in ASTM C 1218<sup>[18]</sup>.

## 2 Results and Discussion

### 2.1 Chloride profiles

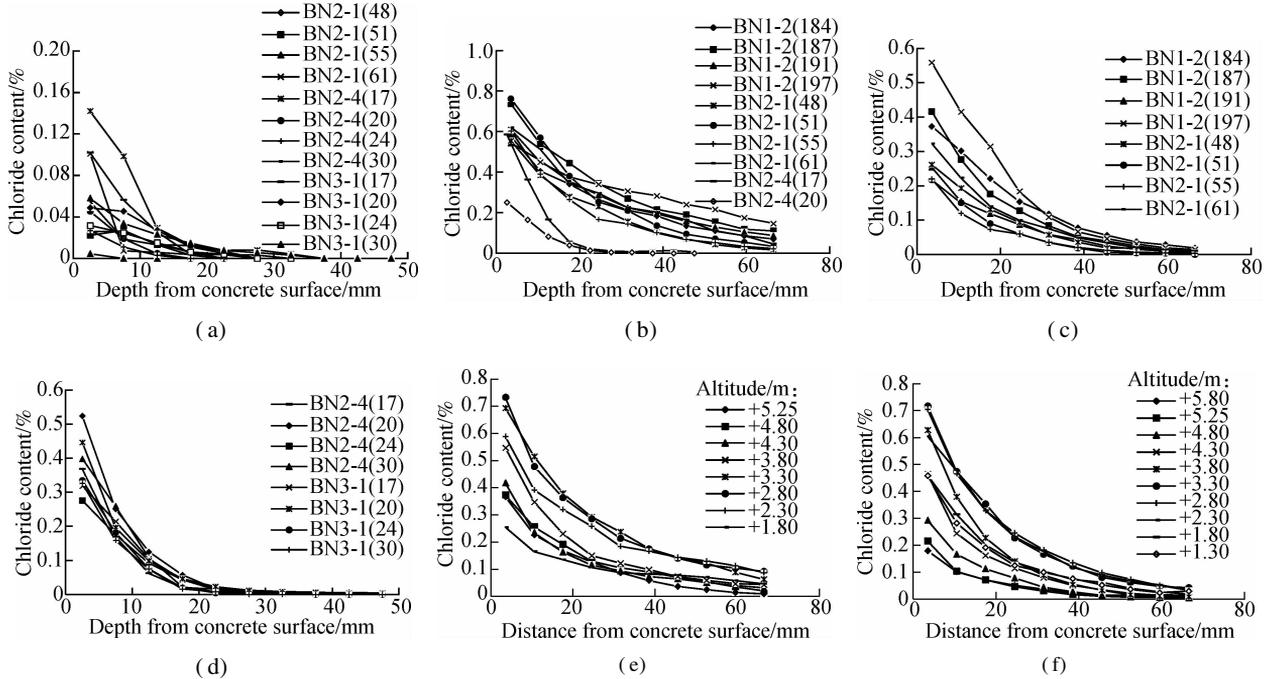
After field detection, more than 200 chloride profiles were obtained and analyzed. The chloride ion concentration profiles are shown in Fig. 2, in which the data of each profile are the corresponding mean values with the same exposure time and altitude of each berth. Therefore, each profile in Fig. 2 is the “mean curve” of 2 to 8 detected profiles. The number in the brackets of the leg-

ends in Figs. 2(a) to (d) represents the exposure time (in month) till the detection.

A clear variation of chloride penetration into concrete over altitude is observed. The surface chloride ion concentration of concrete and chloride ion concentration in the same depth from the concrete surface increase with the increase of the altitude and reach the maximum value when the altitude is located between +2.8 and +3.8 m, and then decrease (see Figs. 2(e) and (f)).

The influence of exposure time can be clearly seen between different berths. Chloride penetration depth and

content in concrete of BN1-2 (about 70-80 mm) are larger than that of BN2-1 (about 40-60 mm) under a shorter exposure time, and are much larger than that of BN2-4 (less than 20 mm) with a higher water/binder ratio but a relatively short time of exposure (see Fig. 2(b)). Similar phenomena can be seen in Fig. 2(c). As a validation, the chloride penetration depths and contents in concrete of BN2-4 and BN3-1, which have the same exposure and similar water/binder ratio, show very little difference between each other (see Fig. 2(d)).



**Fig. 2** Chloride profiles of concrete. (a) +7.6 m; (b) +2.3 m; (c) +5.25 m I; (d) +5.25 m II; (e) BNI-2; (f) BN2-1

Figs. 2(a), (c) to (f) show that the water/binder ratio plays an important role in concrete surface chloride ion concentration when the altitude is above +4.8 m. The accumulation rate of surface chloride ion concentration in concrete increases with the increase in the water/binder ratio (see Fig. 2(a) and (c)), and is proportional to the water/binder ratio when the surface chloride ion concentration comes up to a stable value (exposure for a relatively long time, see Fig. 2(c)).

Generally, diffusion due to a concentration gradient, which is usually described by Fick's second law, is considered to be the primary mechanism. A typical error function solution of Fick's second law<sup>[19]</sup> is commonly introduced to analyze the chloride profiles in order to obtain the surface chloride ion concentration and the diffusion coefficient, which are regarded as constants with time and independent variables. Considering the differences between real conditions in engineering and theoretical hypothesis in the solution of Fick's second law for chloride ingress into concrete<sup>[11]</sup>, ignoring the initial chloride ion concentration in concrete as it is usually very low, an ex-

pression used in this paper is defined as

$$C(x, t) = C_{sn} \left[ 1 - \operatorname{erf} \left( \frac{x}{2\sqrt{D_a t}} \right) \right] \quad (1)$$

where  $C(x, t)$  is the chloride ion concentration at the depth  $x$  from the concrete surface with exposure time  $t$ ;  $C_{sn}$  is the nominal surface chloride ion concentration;  $D_a$  is the apparent diffusion coefficient; and  $\operatorname{erf}(\cdot)$  is the error function.

In Eq. (1),  $C_{sn}$  and  $D_a$  are obtained by performing a nonlinear regression of Eq. (1) according to the experimental data, which are not the real values at the time  $t$  but the equivalent average values during the time interval of  $t$ . Consequently, the obtained  $C_{sn}$  and  $D_a$  can be directly substituted into Eq. (1) to calculate the chloride ion concentration at a certain depth  $x$  at the corresponding exposure time  $t$  which can avoid complex calculations such as integral when considering the time dependence of diffusion coefficient.

The values of  $C_{sn}$  and  $D_a$  involved in the following parameter analysis are obtained by fitting about 200 chloride

profiles using Eq. (1).

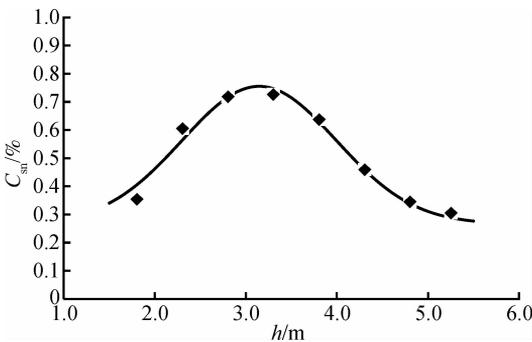
## 2.2 Nominal surface chloride ion concentration $C_{sn}$

The influence of factors (exposure time, water/binder ratio, environment, etc.) on the surface chloride ion concentration of concrete at different locations is very complicated. The water/binder ratios of the berths are between 0.40 and 0.55, and the amount of detected data of BN1-2 with the longest exposure time (about 15 years) and a water/binder ratio of 0.45 is the largest. The maximum values of regulations for the requirements of the water/binder ratio in the durability design codes<sup>[20-21]</sup> are generally between 0.40 and 0.45. The surface chloride ion concentration of concrete accumulating up to a stable value has a linear relationship with the water/binder ratio of concrete<sup>[4,22]</sup>. Taking the above mentioned into account, differences of mix proportion and exposure time in detection points are not considered in the analysis of concrete surface chloride ion concentration, which is assumed to be stable and constant in the following analysis.

### 2.2.1 Relationship between $C_{sn}$ and altitude

Fig. 3 presents the relationship between  $C_{sn}$  and the corresponding detection altitude  $h$ , where each data point represents the mean value of the corresponding results in the same altitude of BN1-2 and BN2-1. A single peak Gaussian distribution with a tendency of “decrease-increase-decrease” can be observed in Fig. 3, which can be expressed as

$$C_{sn} = 0.266 + 0.489 \cdot 1 \times \exp\left[-\left(\frac{h-3.146}{1.198}\right)^2\right] \quad (2)$$



**Fig. 3** Relationship between nominal surface chloride concentration  $C_{sn}$  and the corresponding detection altitude  $h$

### 2.2.2 Probability characteristic of $C_{sn}$

A statistical analysis is conducted on data of  $C_{sn}$  related to the second part of the experimental work. A large scatter of the analyzed data is observed at the altitude +7.6 m which should be located at the atmospheric zone and has a small amount of data. The range of variation coefficient is from 0.28 to 0.41 (Only data at altitude +2.3 m and +5.25 m is considered). The result shows that  $C_{sn}$  can be considered to obey a log-normal distribution. The statistical distribution of  $C_{sn}$  is thus defined as follows: Log-

normal distribution with a variation coefficient  $\delta = 0.40$ .

## 2.3 Apparent diffusion coefficient $D_a$

$D_a$  represents the equivalent mean value of the chloride diffusion coefficient during the time period from initial exposure to detection. It has been generally recognized that  $D_a$  is a time-dependent variable and decreases with time due to the development of cement hydration, the reduction of pore distribution, the swelling of cement paste, the pore blocking effect due to chloride ingress, and the reaction of hydration products with chloride ions. The relationship between  $D_a$  and exposure time can be described as<sup>[11,16,23]</sup>

$$D_a = D_0 \left(\frac{t_0}{t}\right)^n \quad (3)$$

where  $D_a$  and  $D_0$  are the corresponding apparent diffusion coefficients at exposure time  $t$  and  $t_0$ , respectively;  $n$  is the age exponent related to concrete mixes and environmental conditions. Regarding  $t_0$  as a standard reference time,  $D_a$  can be obtained by Eq. (3) when  $D_0$  is known. In practice, the reference time  $t_0$  is commonly regarded as 28 d or 1 year.

### 2.3.1 Influence of environmental factors on $D_a$

Focusing on the reaction between concrete materials and environmental conditions, many standardization studies on test methods for corroded concrete have been accomplished<sup>[22,24]</sup> to establish the influence law and correlation equations corresponding to different materials and environments. Based on the study results<sup>[22]</sup>, the coefficients of environmental temperature  $k_T$  and chloride ion concentration  $k_{Cl}$  can be expressed as

$$k_{Cl} = 3.48 - 1.20 C_{Cl}^{1/3} \quad (4)$$

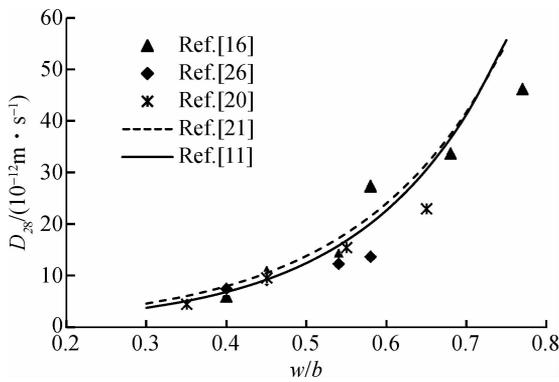
$$k_T = \exp\left(3.593 \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right) \quad (5)$$

where  $C_{Cl}$  is the chloride ion concentration of the environmental solution, %;  $T$  is the environmental temperature, K.

### 2.3.2 Determination of $D_0$ at reference time $t_0$

The reference apparent diffusion coefficient  $D_0$  is generally determined by the analysis of original detection data or by experience. In this paper, the reference time  $t_0$  is regarded as 28 d.  $D_{28}$  was determined referring to only experimental data tested following the procedure similar to the regulations in NT Build 443 (Concrete, hardened: Accelerated chloride penetration)<sup>[25]</sup> of North Europe. Published data on the relationship between apparent diffusion coefficient and water/cement ratio were collected for OPC based concrete. Fig. 4 shows the relationship between  $D_{28}$  and the water/binder ratio  $w/b$ , which is converted into equivalent values under a standard reference environmental condition at 20 °C and a concentration of  $(165 \pm 1)$  g/dm<sup>3</sup> NaCl solution using Eq. (4) and Eq.

(5). As a comparison, the relationship between the chloride migration coefficient  $D_{RCM,28}$  and  $w/b$ , suggested by LIFECON<sup>[11]</sup>, is also presented in Fig. 4. It can be seen that the converted results of different environmental conditions at laboratory and natural environment have a good agreement with each other, which indicates that  $k_T$  and  $k_{Cl}$  are reasonably determined. The suggested relationship between  $D_{RCM,28}$  and  $w/b$  in Life-365<sup>[23]</sup> is basically larger than the other data sets and can be regarded as the conservative values. Also, a good correlation is shown between  $D_{28}$  and  $D_{RCM,28}$ , which indicates that the value of the migration coefficient can be used as a substitute when the apparent coefficient is not available and the reference time  $t_0$  is relatively short, e. g. 28 d.



**Fig. 4** Relationship between  $D_{28}$  and water/binder ratio  $w/b$

For security and conservative concerns, the suggested curve of  $D_{28}$  and  $w/b$  in Life-365<sup>[23]</sup> is introduced as

$$D_{28} = 10^{-12.06 + 2.4w/b} \quad (6)$$

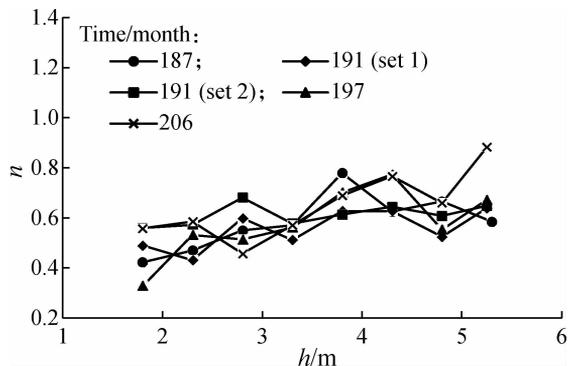
### 2.3.3 Age exponent $n$

Age exponent  $n$  is an empirical coefficient related to concrete mixes and environmental conditions. It is an important factor of the decay rate of the concrete diffusion coefficient. Under the same environmental condition, the resistance of concrete to chloride ingress decreases largely with the decrease of  $n$ .

Based on the obtained chloride profiles and the related environmental conditions of BN1-2 (longest exposure duration, OPC-based concrete with water/binder ratio 0.45), age exponent  $n$  can be obtained by Eq. (3) with the values of  $D_a$  (obtained by fitting the standard numerical solutions of Fick's second Law) and  $D_0$  (calculated by Eqs. (4) to (6)). Fig. 5 shows five curves to represent the relationship between  $n$  and altitude  $h$ , in which each curve is the "average curve" of the corresponding detected data at the same detection conditions (altitude and exposure time). An increasing trend of  $n$  can be seen with the increase of altitude. By taking the value at +2.3 m as reference (denoted as  $n_{ref}$ ), the relationship between  $n$  and the altitude  $h$ , which is the mean value of the corresponding results in Fig. 5, can be found:

$$n = n_{ref} k_{nh} = 0.46 (0.8e^{0.1h}) = 0.368e^{0.1h} \quad h > 2.3 \text{ m} \quad (7)$$

where  $k_{nh}$  is the influence coefficient of altitude  $h$  to the age exponent  $n$ .



**Fig. 5** Relationship between age exponent  $n$  and altitude  $h$

In Fig. 5, it can be seen that the values of  $n$  at +1.8 m and +2.3 m are similar except the curve at 197 months. Therefore,  $n$  decays with the decrease of  $h$  according to Eq. (7) until  $h$  reaches +2.3 m, and then  $n$  is assumed to be a constant with the decrease of  $h$ .

Statistical analysis of  $n$  is done with the data of the second part of the experimental work.  $n$  at different altitudes can all be considered to obey a log-normal distribution, with a range of variation coefficient from 0.12 to 0.34. The statistical distribution of  $n$  is thus defined as follows: Log-normal distribution with variation coefficient  $\delta = 0.30$ .

The relationships between  $n$  and the water/binder ratio of concrete have been reported in some literature. The value of  $n$  is regarded as a constant in Duracrete<sup>[4]</sup> and Life-365<sup>[23]</sup>, but considered to increase with the increase of the water/binder ratio by Jin<sup>[27]</sup> and Mangat et al<sup>[16]</sup>. Also, the value of  $n$  decreasing with the increase of the water/binder ratio is reported in Ref. [28]. The influence of other parameters of concrete mixes, such as content of cementitious material and type of cementitious material, on the value of  $n$  is involved in Refs. [4, 23, 27]. Therefore, there is no agreement on the relationship between  $n$  and concrete mixes. Thus, the influence of concrete mixes is not considered in this paper. However, a conservative approach is to consider  $n$  as a constant.

## 2.4 Probability-based prediction method

Safety, serviceability and durability of concrete structures are the key issues in the reliability analysis and design. How to identify the relevant limit states and reliability index for the durability of RC structures are the prerequisites for the probabilistic method based durability prediction.

Considering that the limit state relevant to structural design generally does not account for the crack stage of

components, the durability limit state for concrete structures under chloride ingress is identified as chloride ion concentration in concrete at the surface of the rebar reaching the critical chloride ion concentration  $C_{cr}$ <sup>[29]</sup>:

$$p_f = p(C(x = d_{cover}) - C_{cr} \geq 0) \leq \Phi(-\beta) \quad (8)$$

where  $p_f$  is the failure probability;  $C(x = d_{cover})$  is the chloride ion concentration at the depth  $x$  and  $d_{cover}$  is the reinforcement protection layer thickness of concrete;  $\beta$  is the reliability index.

The durability limit state is usually identified according to the requirements for serviceability and reparability of structures. It is similar to the method for determining the limit state of serviceability, but the two limit states are essentially different<sup>[30]</sup>. According to Lay et al.<sup>[11]</sup>, for the durability design, the value of  $\beta = 1.5$  is accepted. Durable life with 95% confidence is predicted in actual conditions.

The critical chloride ion concentration  $C_{cr}$  refers to the chloride ion concentration in concrete at the surface of reinforcing steel required to initiate corrosion. There is no identifiable concentration of chloride ion to initiate corrosion. According to the relevant results presented in Refs. [11, 23, 31–32], the  $C_{cr}$  value selected is 0.15% chloride ions by weight of concrete, which is a conservative estimate. The probability characteristic of  $C_{cr}$  is defined as: Log-normal distribution with variation coefficient  $\delta = 0.20$ .

With the associated parameter analysis, based on Eqs. (1) and (8), the calculated results of chloride penetration depth at different altitudes and the corresponding detected values of BN 1-2 and BN 2-1 are shown in Fig. 6. The

reference demarcation point of chloride ion concentration is considered to be 0.1% by the weight of concrete for convenience of the determination of detected chloride penetration depth. The changing trend of chloride ion concentration with the altitude can be well reflected by the predicted curve which is on the safe side.

### 3 Durability Design Methodology

The design methodology for chloride penetration induced durability under the marine environment is developed based on the research work of DEZ by Jin et al.<sup>[6-7]</sup>. Focusing on the interaction between the external environmental action and the resistance of concrete structures, research on DEZ of concrete structures can be divided into two parts: 1) The environmental zonation according to the effects of environments on the durability of concrete structures, and 2) Suggested regulations of materials and constructions for each zone meeting the durability limit states and the corresponding reliability index. By combining the two parts, the durability design zonation standard can be established, which can be used as guidelines for the durability design in the lifecycle.

#### 3.1 Environmental zonation

##### 3.1.1 Choose of zonation index

The index for environmental zonation related to concrete structural durability should not only represent the characteristics of the environments but also the changing law of concrete structural durability with the change of exposure environments.

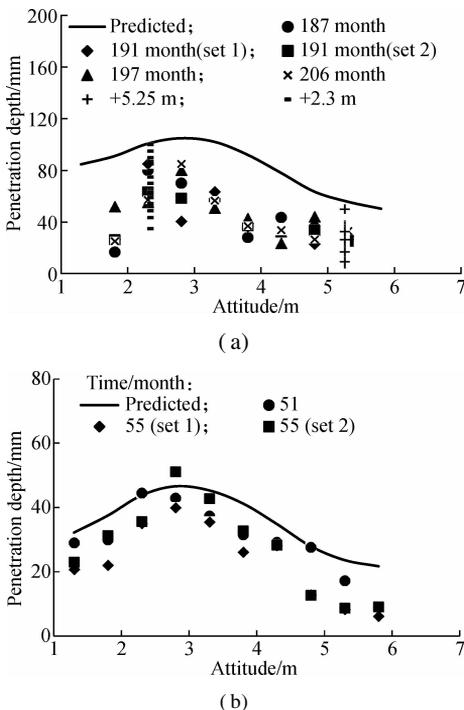
The distribution of chloride penetration into concrete along altitude is determined by the law of environmental factors changing along the altitude. The ratio of the wetting time per-period  $k_{JR}$  is proposed and defined as the time proportion of concrete in wet conditions for the whole time period, and it can be used to describe the dry-wet conditions in concrete. Analysis on the in-situ detected results of Zhapu Port shows that the penetration of chloride, the accumulation of surface chloride concentration, and the decay of the chloride diffusion coefficient are all related to  $k_{JR}$ <sup>[33]</sup>.

Therefore, the ratio of the wetting time per-period  $k_{JR}$  in concrete is the essential reflection of the environmental characteristics. It is a dominant environmental factor influencing the chloride penetration and is determined as a common index in different coastal areas.

The calculation of  $k_{JR}$  at each altitude should refer to the tide level records within a relatively long period by statistical tests. The detailed method can be referred to in Ref. [33].

##### 3.1.2 Index-based environmental zonation

According to the achieved models Eq. (1), Eq. (8) and the corresponding parameter analysis, chloride penetration depth (or concrete cover depth)  $X_{50}$  meeting the



**Fig. 6** Comparison of predicted and tested values of BN1-2 and BN2-1. (a) BN1-2; (b) BN2-1

given limit state and target reliability index are calculated for the virtual specimen (defined as OPC-based concrete with a water/cement ratio of 0.45) exposed for 50 years under natural environments in Zhapu Port (see Tab. 1) by means of the Monte-Carlo simulation. The statistical distribution of the thickness of concrete cover is assumed to obey a normal distribution with the variation coefficient  $\delta = 0.11$ . The relationships between the predicted penetration depth  $X_{50}$ , the ratio of the wetting time per-period  $k_{JR}$  and the corresponding altitude  $h$  are shown in Fig. 7. Taking  $k_{JR}$  as the environmental zonation index, determination of the boundary lines of delineation is shown in Fig. 7 based on the principle that the gap of the damage in each zone is relatively equal. It can be concluded as follows: 1) Divide the value range of the lower half curve of  $X_{50}$  vs.  $h$  which is gradually stabilized into five equal parts; 2) Divide the curve of  $X_{50}$  vs.  $h$  into five zones according to the obtained cut-off values of  $X_{50}$ ; 3) Determine the cut-off values of  $k_{JR}$  at each zone according to the corresponding cut-off values of  $h$  at each zone of the curve of  $X_{50}$  vs.  $h$ . Thus, the environmental zonation for concrete structures in marine environments is achieved and shown in Fig. 7 by taking  $k_{JR}$  as the environmental zonation index. Five zones can be obtained and expressed as [1, 2, 3, 4, 5], in which 1 represents the least severe degree of erosion and 5 the most. Environmental zonation levels and characteristics for each zone are introduced in Tab. 2.

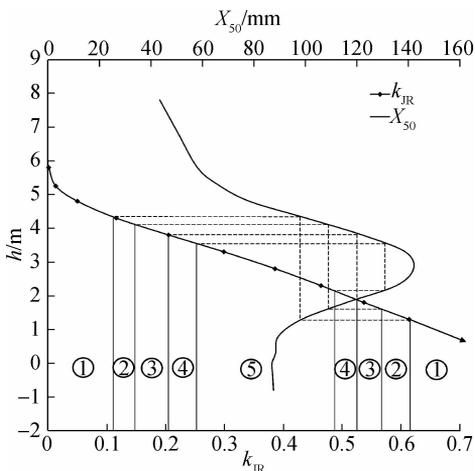


Fig. 7 Relationships between  $X_{50}$ ,  $k_{JR}$  and  $h$

Tab. 2 Environmental characteristics and values of  $X_{50}$  for each zone

Zonation level	$k_{JR}$	$X_{50}/\text{mm}$
1	$>0.61$ or $<0.11$	$<98$
2	$0.11$ to $0.148$ or $0.567$ to $0.616$	$98$ to $109$
3	$0.148$ to $0.204$ or $0.525$ to $0.567$	$109$ to $120$
4	$0.204$ to $0.253$ or $0.488$ to $0.525$	$120$ to $131$
5	$0.253$ to $0.488$	$131$ to $142$

### 3.2 Regulations of materials and constructions

The material and environmental conditions involved in the establishment and analysis of the chloride penetration prediction model and environmental zonation are the reference conditions when a different environment or concrete mix needs to be considered. Subsequently, the reference conditions are referred to as a standard condition, and it includes two aspects: standard material conditions (OPC-based concrete with a water/binder ratio of 0.45) and standard environmental conditions. Relevant parameters are listed in Tab. 1.

Based on the available results of environmental zonation under marine chloride environments (see Fig. 7 and Tab. 2), the construction regulations of concrete cover depth  $X_{50}$ , which meets the durability limit states and the corresponding reliability index for concrete structures in the standard condition (standard material conditions and standard environmental conditions mentioned above) with 50 years' exposure, are presented in Tab. 3.

Tab. 3 Suggested values of  $X_{50}$  for standard specimen

Zonation level	1	2	3	4	5
$X_{50}/\text{mm}$	100	110	120	130	145

In engineering practice, numerous material and environmental conditions, different from the standard condition, need to be considered in the durability design. In this case, the corresponding durability design regulations for each zone level are given. The correction coefficients for different water/binder ratios  $\zeta_i$  are shown in Tab. 4. The correction coefficients for different age  $\zeta_t$  are shown in Tab. 5. The correction coefficients for different temperature  $\zeta_T$  are shown in Tab. 6. The correction coefficients for different chloride ion concentrations  $\zeta_{Cl}$  are shown in Tab. 7.

When the material and environmental conditions are determined, the design values of cover depth  $X$  can be determinate as  $X_{50}\zeta_i\zeta_t\zeta_T\zeta_{Cl}$ .

Tab. 4 Correction coefficients for different water binder ratios

$w/b$	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
$\zeta_i$	0.51	0.58	0.66	0.76	0.88	1.00	0.89	0.80	0.73	0.69

Tab. 5 Correction coefficients for strength

$t/a$	10	30	50	75	100
$\zeta_t$	0.53	0.78	1.00	1.23	1.42

Tab. 6 Correction coefficients for temperature

$T/^\circ\text{C}$	0	5	10	15	20	25	30	35	40
$\zeta_T$	0.696	0.784	0.876	0.984	1.096	1.207	1.337	1.469	1.620

Tab. 7 Correction coefficients for chloride ion concentration

$C_{Cl}/\%$	0	0.5	1.0	1.5	2.0	2.5
$\zeta_{Cl}$	1.194	1.031	0.963	0.925	0.897	0.865

## 4 Conclusions

1) The nominal surface chloride ion concentration  $C_{sn}$

and the penetration depth of chloride into concrete have a similar change law to the altitude or the ratio of the wetting time per-period  $k_{JR}$ . The relationship between  $C_{sn}$  and the altitude is expressed in a single peak curve with the peak appearing when the value of  $k_{JR}$  ranges from 0.253 to 0.488.

2) Focusing on the interaction between the external environments and the structures, the quantitative durability design methodology is presented particularly for the RC structures exposed to marine environments. The ratio of the wetting time per-period is identified as the environmental zonation index, and it can characterize the environments in different coastal areas and has a crucial influence on the ingress of chloride into concrete.

3) The environmental zonation methodology and the corresponding durability design method for each zone level are established. The durability design regulations contain the zoning design regulations  $X_{50}$  of the specimen in the standard condition, correction coefficients for different water/binder ratios  $\zeta_i$ , correction coefficients for different ages  $\zeta_j$ , correction coefficients for different temperatures  $\zeta_T$ , and correction coefficients for different chloride ion concentrations  $\zeta_{Cl}$ . The durability design regulations associated with environmental zonation can be used as guidelines for durability design of concrete structures.

## References

- [1] Ahmad S. Reinforcement corrosion in concrete structures, its monitoring and service life prediction—A review[J]. *Cement and Concrete Composites*, 2003, **25**(4/5): 459 – 471. DOI: 10.1016/s0958-9465(02)00086-0.
- [2] Conciatori D, Grégoire É, Samson É, et al. Sensitivity of chloride ingress modelling in concrete to input parameter variability[J]. *Materials and Structures*, 2015, **48**(9): 3023 – 3036.
- [3] Angst U M, Polder R. Spatial variability of chloride in concrete within homogeneously exposed areas[J]. *Cement and Concrete Research*, 2014, **56**: 40 – 51. DOI: 10.1016/j.cemconres.2013.10.010.
- [4] Ministry of Housing and Urban-Rural Development of the People's Republic of China. GB/T 50476—2008 Code for durability design of concrete structures[S]. Beijing: China Building Industry Press, 2008. (in Chinese)
- [5] Crete D. General guidelines for durability design and re-design [R]. Brussels: The European Union-Brite EuRam III, 2000.
- [6] Jin W L, Lü Q F. Study on durability zonation standard of concrete structural design[C]//*Proceedings of Durability of Reinforced Concrete on the Combined Mechanical Climatic Loads*. Qingdao, China, 2005: 35 – 42.
- [7] Jin W L, Lü Q F. Durability zonation standard of concrete structure design[J]. *Journal of Southeast University (English Edition)*, 2007, **23**(1): 98 – 104.
- [8] Jin W L, Yuan Y S, Wei J. *Theories and design for durability of concrete structures exposed to chloride environment* [M]. Beijing: Science Press, 2011. (in Chinese)
- [9] Wu H R, Jin W L, Lv Q F, et al. Reliability-based zonation of environmental area according to its effect on durability of concrete structures[J]. *Journal of Zhejiang University (Engineering Science)*, 2012, **46**(3): 416 – 423. (in Chinese)
- [10] Wu H R, Jin W L, Yan Y D, et al. Environmental zonation and life prediction of concrete in frost environments [J]. *Journal of Zhejiang University (Engineering Science)*, 2012, **46**(4): 650 – 657. (in Chinese)
- [11] Lay S, Schissel P, Cairns J. Probabilistic service life models for reinforced concrete structures [D]. Munich, Germany: School of Architectural Technology, Technical University of Munich, 2003.
- [12] Luo D M, Wang Y, Niu D T. Durability environmental regionalization for concrete structures [J]. *Mathematical Problems in Engineering*, 2013, **2013**: 1 – 11. DOI: 10.1155/2013/482641.
- [13] Huang Q H, Xu N, Gu X L. Environmental zonation for durability assessment and design of reinforced concrete structures in China[C]//*Proceedings of the First International Conference on Microstructure Related Durability of Cementitious Composites*. Nanjing, China, 2008: 735 – 743.
- [14] Otieno M, Beushausen H, Alexander M. Chloride-induced corrosion of steel in cracked concrete—Part II: Corrosion rate prediction models[J]. *Cement and Concrete Research*, 2016, **79**: 386 – 394. DOI: 10.1016/j.cemconres.2015.08.008.
- [15] Ministry of Transport of the People's Republic of China. JTJ 275—2000 Corrosion prevention technical specifications for concrete structures of marine harbour engineering [S]. Beijing: China Communications Press, 2001. (in Chinese)
- [16] Mangat P S, Molloy B T. Prediction of long term chloride concentration in concrete [J]. *Materials and Structures*, 1994, **27** (6): 338 – 346. DOI: 10.1007/bf02473426.
- [17] Kassir M K, Ghosn M. Chloride-induced corrosion of reinforced concrete bridge decks[J]. *Cement and Concrete Research*, 2002, **32**(1): 139 – 143.
- [18] ASTM International. ASTM C 1218/C 1218M—99 Standard test method for water-soluble chloride in mortar and concrete [S]. West Conshohocken, PA, USA: ASTM International, 2008.
- [19] Crank J. *The mathematic of diffusion* [M]. 2nd ed. Oxford: Clarendon Press, 1979: 1 – 18.
- [20] American Concrete Institute. ACI 318—05 Building code requirements for structural concrete and Commentary (ACI 318R-05) [S]. Farmington Hills, USA: American Concrete Institute, 2005.
- [21] CEBFIP. The fib model code for concrete structures 2010 [S]. Lausanne, Switzerland: Comité Euro-International du Béton (CEB)-Fédération Internationale de la Précontrainte (FIP), 2010.
- [22] Wang C K. Standardization study on test of chloride ion penetration and carbonation of concrete[D]. Hangzhou: School of Architectural Engineering, Zhejiang University, 2010. (in Chinese)
- [23] Bentz E C, Thomas M D A. Life-365 user manual: Computer program for predicting the service life and life-cycle cost of reinforced concrete exposed to chlorides [R].

- Washington, DC, USA: The Silica Fume Association, 2013.
- [24] Xu X W. Standardizing study on concrete freeze-thaw tests under different environments[D]. Hangzhou: School of Architectural Engineering, Zhejiang University, 2010. (in Chinese)
- [25] NordTest. NT BUILD 443 Accelerated chloride penetration into hardened concrete[S]. Nordtest, Espoo, Finland: NordTest, 1995.
- [26] Zhao S C. The impact of non-bearing elements on reliability of flexural component under chloride environment[J]. *Highway*, 2003, **9**: 12 - 17. (in Chinese)
- [27] Jin L B. Multi-environmental time similarity (METS) theory and its application in coastal concrete structural durability[D]. Hangzhou: School of Architectural Engineering, Zhejiang University, 2010. (in Chinese)
- [28] Wu J, Cheng J X. Durability assessment of reinforced concrete structures under marine environment[J]. *Journal of Hydroelectric Engineering*, 2005, **24**(1): 69 - 73. (in Chinese)
- [29] Söderqvist M K, Vesikari E. Generic technical handbook for a predictive life cycle management system of concrete structures (LMS) [R]. Finland: The Finnish Road Administration, 2003.
- [30] Chen Z Y. Durability design of concrete structures[J]. *Architecture Technology*, 2003, **34**(5): 328 - 333. (in Chinese)
- [31] Glass G K, Buenfeld N R. The presentation of the chloride threshold level for corrosion of steel in concrete[J]. *Corrosion Science*, 1997 (5): 1001 - 1013. DOI: 10.1016/s0010-938x(97)00009-7.
- [32] Alonso C, Andrade C, Castellote M, et al. Chloride threshold values to depassivate reinforcing bars embedded in a standardized OPC mortar[J]. *Cement and Concrete Research*, 2000, **30**(7): 1047 - 1055. DOI: 10.1016/s0008-8846(00)00265-9.
- [33] Yao C J. Penetration laws of chloride ions in concrete infrastructures at coastal ports[D]. Hangzhou: School of Architectural Engineering, Zhejiang University, 2007. (in Chinese)

## 海洋钢筋混凝土结构耐久性环境区划与设计方法

武海荣<sup>1,2</sup> 吕清芳<sup>3</sup> 金伟良<sup>1</sup>

(<sup>1</sup> 浙江大学工程研究所, 杭州 310058)

(<sup>2</sup> 河南城建学院土木与交通工程学院, 平顶山 467036)

(<sup>3</sup> 东南大学土木工程学院, 南京 210096)

**摘要:** 针对海洋环境中的钢筋混凝土结构, 基于某混凝土港口 4 个泊位的自然暴露检测数据(暴露时间分别为 1.5, 1.5, 4, 15 年), 提出了一个基于可靠性的混凝土结构耐久性量化设计方法. 基于检测得到的 200 多条混凝土中氯离子含量随侵蚀深度的分布曲线, 对表面氯离子浓度与高程的关系进行了讨论, 进一步提出了考虑环境温度、氯离子浓度、龄期系数和高程等因素的表观氯离子扩散系数的计算公式. 然后, 依据 Fick 第二定律, 建立了基于可靠度的钢筋混凝土结构耐久性概率预测方法. 讨论了混凝土氯离子侵蚀深度预测值、浸润时间比和高程的关系, 建立了以海水浸润时间比为指标的海洋环境区划体系. 最后, 建立针对环境区划体系的分区设计方法, 包括了标准试件的分区设计规定和不同水胶比、设计年限、温度、氯离子含量修正系数的分区设计规定体系.

**关键词:** 钢筋混凝土结构; 海洋; 氯离子; 环境; 区划; 耐久性设计

**中图分类号:** TU528.01