Durability rehabilitation and promotion of reinforced concrete structures in tidal and splash range of deteriorated wharfs in marine environment

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Abstract. Corrosion deterioration of reinforced concrete structures in tidal and splash range has always been an urgent concern of scientific researchers and wharf managers, especially for that serving for more than 20 years in marine environment. Through on-site detection and chemical analysis, it has been found that reinforced structures in tidal and splash range of a passenger terminal in Zhoushan city suffer severe corrosion destructions such as rust expansion of steel bars, concrete cracking and spalling due to technical conditions at the initial stage of construction and insufficient awareness of durability. Meanwhile, chloride content near the surface of steel bars in concrete exceeds the critical corrosion value. In order to rehabilitate and improve the durability of reinforced concrete structures in tidal and splash range of this wharf, a combined programme of partial consolidation and electrochemical desalination is proposed and applied, which shows good performances and ensures the service life of the structure as long as possible.

1. Introduction
Concrete structures in marine environment can be divided into four areas according to the designed water level: atmosphere area, splash area, tidal area and submerged area[1]. Normally, corrosion deterioration of reinforced concrete structures in tidal and splash areas has always been the most severe problem, which attracts much attention in the service process of wharf structures, because of chloride penetrating into concrete from seawater results in steel bars rust that leads to premature structural damage and exposes insufficient durability. In the past 1980s, limited by technical conditions and insufficient awareness of durability, some wharfs appeared a large number of damage problems only in a few years after construction without any protective facilities, resulting in huge economic costs to recover. Until now, it should pay even much more attentions to the service conditions of those wharfs in service or even over-serviced, which has challenged all the decision makers of wharf managements whether to reconstruct or to upgrade.

Usually, there are three corrosion stages of steel bars in concrete induced by chloride[2]: (1) transition stage t0-t1, (2) initial corrosion stage t1-t2, (3) accelerated corrosion stage t2-t3, t0-t1 period depends on the compactness of concrete itself, normally the time when chloride penetrates into
concrete from surface, and the concentration near the surface of steel bars reaches the critical value when they begin to rust; $t_1$-$t_2$ period depends on the corrosion rate of steel bars and the strength of concrete. Those two periods determine the effective service life of concrete structures influenced chloride pollution. Therefore, it is very significant to judge concrete components of wharfs in service or over-serviced in which corrosion stage in marine environment that benefits for evaluating their health condition, and it is also instructive for taking appropriate measures to rehabilitate them.

2. Project background

A passenger terminal in Putuo District of Zhoushan city was built in 1999. This high-piled beam-slab wharf is located in the subtropical monsoon climate zone, where characterizes distinct seasons, abundant rainfall and light. The reinforced concrete structure in tidal and splash range of this wharf includes beams, pile caps, etc., see in Figure 1. After serving for 20 years, it has been found that most of the components without any coatings appear too much deterioration problems of concrete cracking, peeling, steel bars exposed with serious corrosion. Some main steel bars exposed even rust off, see in Figure 2.

Based on all these corrosion problems, chloride in seawater and concrete is measured. Seawater samples adopted at high and low tide level shows that chloride ion content is about 13477 mg/L, and the soluble chloride ion content in different depths of concrete are measured by drilling concrete powder samples as shown in Table 1.

![Figure 1. Section map of this wharf](image1)

![Figure 2. Corrosion appearance of pile cap](image2)

**Table 1. Average free chloride content in different layers of concrete (%)**

| Component   | 0-10mm | 10-20mm | 20-30mm | 30-40mm | 40-50mm |
|-------------|--------|---------|---------|---------|---------|
| Pile caps   | 0.583  | 0.414   | 0.283   | 0.243   | 0.173   |
| Beams       | 0.531  | 0.403   | 0.328   | 0.247   | 0.181   |

From Table 1, it could be found that the average free chloride ion content in concrete around the steel bars has far exceeded the critical corrosion value(0.058%). Meanwhile, most corrosion potentials
of steel bars measured in situ are less than -350mV (vs. SCE) by half-cell potential method, which also indicates that there is obvious corrosion tendency of steel bars.

Based on average free chloride ion content in Table 1, the corrosion period can be calculated as follows [3] by optimal fitting method:

1. The time when steel bar starts to rust (Fick’s second diffusion law) could be calculated by Equation (1)(2):

$$ t_i = \left( \frac{c}{k_{cl}} \right)^2 $$

$$ k_{cl} = 2\sqrt{D} \text{erf}^{-1} \left( 1 - \frac{C_r}{C_T \gamma} \right) $$

Whereas: $t_i$-the time from concrete cast to steel bar begins to rust (a); $c$-concrete cover (mm); $k_{cl}$-chloride corrosion coefficient (mm/a²); erf-error function; $C_r$-chloride critical value where the steel bars begins to rust; $C_T$-chloride content of surface concrete; $D$-effective coefficient (mm/a²); $\gamma$-bidirectional permeability coefficient of chloride ion, that is 1.0.

2. The time when concrete cover begins to crack could be calculated by Equation (3)(4)(5):

$$ t_c = \frac{\delta_{cr}}{\lambda_1} $$

$$ \delta_{cr} = 0.012 \frac{c}{d} + 0.00084 f_{cuk} + 0.018 $$

$$ \lambda_1 = 0.0116 \delta $$

Whereas: $t_c$-the time from steel corrosion to the cracking of concrete cover (a); $\delta_{cr}$-critical corrosion depth of steel bar when concrete cover cracks (mm); $\lambda_1$-average corrosion rate before concrete cover cracks (mm/a); $c$-concrete cover (mm); $d$-steel bar diameter (mm); $f_{cuk}$-concrete compressive strength (MPa); $i$-corrosion current density (μm/cm²), that is 1.0.

3. The time suffering obvious functional deterioration could be calculated by Equation (6):

$$ t_d = \left( 1 - \frac{3}{\sqrt{10}} \right) \frac{d}{2 \lambda_2} $$

Whereas: $t_d$-the time from cracking of concrete cover to section area reduction of steel bar to 90% of original diameter (a); $d$-steel bar diameter (mm); $\lambda_2$-average corrosion rate after concrete cover cracks (mm/a), that is 0.2 mm/a.

| Components | $D$ | $C_i$ | $C_t$ | $c$ | $f_{cuk}$ | $i$ | $\lambda_1$ | $\lambda_2$ | $t_i$ | $t_c$ | $t_d$ |
|------------|-----|-------|-------|-----|----------|----|-----------|-----------|-----|-----|-----|
| Pile caps  | 0.408 | 0.058 | 0.624 | 50  | 30       | 1.0| 0.0116    | 0.2       | 10  | 6   | 2   |
| Beams      | 0.543 | 0.058 | 0.572 | 50  | 30       | 1.0| 0.0116    | 0.2       | 9   | 6   | 2   |

Finally, all the time are calculated in Table 2, $t_i$ of pile caps and beams is about 9 years, $t_c$ of pile caps and beams is 6 years, and $t_d$ of pile caps and beams is only 2 years, therefore calculated service life of pile caps and beams is only 18 years, comparing to real service time, the remaining service life of pile caps and beams is 0, whereas the real service period hasn’t reached to the designed value yet, considering all the cost and output at this stage, we envisage how to redesign and recover all the deteriorated pile caps and beams of this wharf in order to rehabilitate and improve their durability.
3. Durability redesign and recovery

According to all the detective data, all the caps and beams of this wharf suffer severe deterioration and they need to be recovered at once.

3.1 Surface rehabilitation

| Specification | Strength/MPa | Concrete cover/mm |
|---------------|--------------|------------------|
| Outdated      | 30           | 50               |
| Current       | 40           | 65               |

According to severe environment of structures in tidal and splash range and requirements in current specifications, designed strength and concrete cover of wharf structures should be reasonably optimized, just consider strength as 40MPa and concrete cover as 65mm, seen in Table 3. While concrete strength and concrete cover were designed as 30Ma and 50mm in the beginning of construction, the concrete chiselled should be recovered by the material with 40MPa, while surface would be recovered as before while supplemented by auxiliary strengthened coatings.

3.2 Electrochemical desalination

Chloride ion in reinforced concrete structures is such a harmful substance which induces the corrosion of steel bars. To prevent secondary corrosion of steel bars, electrochemical desalination technology should be applied as well as corrosion inhibitors\(^5\). Corrosion inhibitors are popular and won’t be explained too much in this paper. Such an electrochemical desalination patent technology is designed to move chloride ion out, proposed by our group, authorized as ZL201410280899.7.

Normally, current density in desalination process of the whole circuit should be designed about \(1.0 \sim 2.0\text{A/m}^2\) so as to sustain for a certain period to migrate chloride content below 0.1% around steel bar relative to cement mortar, meanwhile steel bars are depolarized to keep passive with half-cell potential positive to -200 mV(vs. SCE)\(^6\).

Chloride content detected in pile caps and beams of this wharf exceeds the critical value, electrochemical desalination method could be adopted for intact structures, and then while suffering peeling and rust expansion, it needs to be rehabilitated and consolidated, seen in Figure 3.

![Figure 3. Methods adopted at different corrosion period](image)

No matter the structures in tidal and splash zone of wharfs is in service or even over-serviced according to calculated service life, facilities should be to taken to recover and promote their durability:

*while service condition is in \(t_1-t_2\) period, concrete is uncracked and swelled, desalination method could be applied, and coatings are necessary to promote the durability.
※while service condition is in t2-t3 period, concrete is cracked and spalling, local consolidation and surface rehabilitation method should be applied to recover.

4. Applications in field

![Diagram of applications in field](image)

All the facilities carried out in situ are illustrated in Figure 4. For the designed service life of this wharf unsatisfied, rehabilitation and promotion methods are applied together.

4.1 Electrochemical desalination

When loosen concrete and dust is removed, steel bars are cleared up to metallic luster, then monitoring wire and connecting line between anode and steel bar are welded. Anode chambers are fixed on surface of concrete structures at a proper position, desalination effective area should be taken in account in about 2.0m² around the device in case of rising tide[8]. Finally, the original design structure surface is restored by polymer modified cement mortar, seen in Figure 5. The potential of anodes and steel bars are monitored consecutively, while anode is exhausted, chloride content is measured of cement paste near steel bars by drilling concrete core. Finally, all the devices are dismantled.

![Illustration of electrochemical desalination process](image)

4.2 Coatings

After repair, all the surface of components without carbon fiber cloth is polished, the putty is scraped, and then the coating is completely sealed for three layers.
4.3 Surface rehabilitation
The concrete where steel bars rust with expansion is chiselled out, and the scope of chiselled is expanded as possible in width to expose more than 5 cm of no rusty steel bar at both ends, and the concrete behind steel bars is chiselled in depth for 1-3 cm until the hard part is exposed. After chiselled, the corroded steel bars are rusted, and finally the rust is removed to St2 grade. Rinse the floating ash, loose matter and other attachments on the surface of steel bar and concrete with high-pressure fresh water.

Steel bars are strengthened when they are rusted to the loss of steel bar section more than 10%. For strengthened main bars, overlap welding of the same diameter steel bars is used to control overlap length of double-sided welding (≥5d) and single-sided welding (≥10 d). For treated steel bars, the surface is coated by cement mortar with corrosion inhibitors. Polymer modified cement mortar to recover original surface artificially. After repaired, the surface of components is kept as compact, uniform and smooth. Compressive strength is detected more than 40MPa without any hollow defects and adhesive strength between mortar and original concrete is more than 2.5MPa.

4.4 Local consolidation
Original concrete surface is polished. While in a humid environment, the surface would be dried. Then clear the surface of floating ash and grind the corner into a circular arc (R equals about 20mm). Then, coat carbon fiber primer, use carbon fiber leveling adhesive for repairing defects on concrete surface, brush epoxy glue, stick carbon fiber cloth repeatedly for two layers.

4.5 Monitoring in situ
All the methods are carried out on pile caps and beams of this wharf in situ. To evaluate the recovery effect, current density and potential are measured sustainably in the process of desalination as well as the adhesive strength between carbon fiber cloth and mortar, coatings with concrete, seen in Figure 6, Figure 7. During the process desalination, anode potential is controlled about -550mV~650mV, current density is about 1.36A/m², after 65 days, chloride content in cement paste around steel bars is about 0.084%, finally, potential of steel bars is above -200mV. Meanwhile, adhesive strength between carbon fiber cloth and modified mortar is above 2.5MPa, and the value of coating is above 1.5MPa.

Figure 6. Electrochemical desalination Patent ZL 201410280899.7 application in situ (a) (b)
5. Conclusions
The phenomenon of corrosion deterioration of reinforced concrete structures in tidal and splash range can’t be neglected. Through regular inspection of wharfs, we could make diagnosis of their healthy conditions. For the wharf in service period while the calculated remaining service life is 0, durability of structures in tidal and splash range could be recovered and promoted by electrochemical desalination and partial consolidation methods, meanwhile all the monitoring data should be detected sustainably to ensure good performances in the applications in situ.

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