7. Verification of Durability

The performance verification performed thus far has shown that the structural performance is higher than the performance requirements. That performance must not be lost because of deterioration of materials during the design service life of the structure (performance item 10 defined in Section 2.2). Verification is performed, therefore, to ascertain that the concrete and reinforcing bars used for the floor slabs and the beams meet the durability requirements.

7.1 Carbonation-Induced Corrosion

Verification concerning the corrosion of reinforcing bars due to carbonation of the concrete is made for the lower (bottom) reinforcing bars in the floor slab and in the beam in accordance with Section 2.2 of SSCS/Mate.

7.1.1 Calculation of design value of carbonation depth

The design value of carbonation depth y_d is calculated using the following equation:

$$y_d = \gamma_{cb}\, \alpha_d \sqrt{t} \tag{7.1.1}$$

$$\alpha_d = \alpha_k\, \beta_e\, \gamma_c$$

where γ_{cb} (=1.15) is a safety factor to account for the variation in the design value of carbonation depth y_d, α_d is the design carbonation rate (mm·year$^{-1/2}$), t is the design service life, α_k is the characteristic value of carbonation rate (mm·year$^{-1/2}$), β_e (= 1.0) is a coefficient representing the extent of environmental action, and γ_c (= 1.0) is the material factor for concrete.

For the characteristic value of the carbonation rate coefficient α_k, the following equation proposed in Section 6.4.3 of SSCS/Mate is used:

$$\alpha_k = \gamma_p\, \alpha_p$$

$$\alpha_p = -3.57 + 9.0\, W/C \tag{7.1.2}$$

where γ_p (= 1.1) is a safety factor to account for the accuracy in determining α_p and W/C is the water-to-cement ratio of concrete.

Assuming that the water-to-cement ratio W/C of the concrete is 0.45, $\alpha_k = 1.1\times(-3.57+9.0\times0.45) = 0.53$ mm·year$^{-1/2}$ is obtained. Therefore, the design value of carbonation rate coefficient α_d is calculated as follows: $\alpha_d = 0.53\times 1.0\times1.0 = 0.53$ mm·year$^{-1/2}$. Since the design service life is 50 years, the design value of carbonation depth y_d is calculated from Equation 7.1.1.

$$y_d = \gamma_{cb}\alpha_d \sqrt{t} = 1.15\times 0.53\times\sqrt{50} = 4.3 \text{ mm}$$

7.1.2 Calculation of the critical depth for reinforcement corrosion

The critical depth for reinforcement corrosion y_{lim} is calculated from the following equation:

$$y_{lim} = c - c_k \tag{7.1.3}$$

where c is the concrete cover and c_k is the remaining non-carbonated cover thickness.

Table 7.1.1 Result of verification for carbonation

		Bottom reinforcement in the slab	Bottom reinforcement in the beam
Design value	W/C	0.45	
	α_p (mm·year$^{-1/2}$)	0.48	
	γ_p	1.1	
	α_k (mm·year$^{-1/2}$)	0.53	
	γ_c	1.0	
	β_e	1.0	
	α_d (mm·year$^{-1/2}$)	0.53	
	t (year)	50	
	γ_{cb}	1.15	
	y_d (mm)	4.3	
Limit value	c (mm)	70.0	
	c_k (mm)	25.0	
	y_{lim} (mm)	45.0	
Verification	γ_i	1.0	
	$\gamma_i\, y_d \,/\, y_{lim}$	0.10	
	Judgment	OK	

Since the design concrete cover over the bottom reinforcement in the floor slabs and beams is 70 mm and the remaining non-carbonated cover thickness c_k is 25 mm (because of a salty environment), the critical depth for reinforcement corrosion y_{lim} is obtained as y_{lim} = 70 – 25 = 45 mm. In this calculation, as mentioned in Section 3.7.1 construction error in concrete cover is not taken into account.

7.1.3 Verification results

Table 7.1.1 summarizes the conditions for verification and the verification results. From these results, it can be concluded that the reinforcement in the floor slab and in the beam will not corrode due to the carbonation of concrete.

7.2 Chloride-Induced Corrosion

Verification concerning the corrosion of reinforcement due to ingress of chloride ions is made with respect to the bottom reinforcement in the floor slabs and in the beams in accordance with Section 2.3 of SSC/Mate. This section deals only with the verification process for the bottom reinforcement in the floor slabs. Verification for the bottom reinforcement in the beams can be performed in a similar manner.

7.2.1 Calculation of chloride ion concentration at reinforcement

The design value of chloride ion concentration C_d at a reinforcement location is calculated using Equation 7.2.1. It is assumed here that the chloride ion concentration of concrete during mixing is zero.

$$C_d = \gamma_{cl} C_o \left(1 - erf\left(\frac{0.1c}{2\sqrt{D_d t}} \right) \right) \tag{7.2.1}$$

where γ_{cl} (= 1.3) is a safety factor to account for the scatter in C_d, C_o is the chloride ion concentration at the concrete surface, c is the concrete cover, D_d is the design value of diffusion coefficient of chloride ions in concrete , t is the design service life, and *erf* is an error function.

Because the amount of measurement data obtained in the environment in which this open-type wharf is located is not sufficient, the chloride ion concentration at the surface C_o is defined according to Table 2.3.1 of SSC/Mate. For the bottom reinforcement in the floor slabs, 9.0 kg/m^3 is used in view of the fact that the height from the mean monthly-highest water level (H.W.L) is about 2 m, and for the bottom reinforcement in the beams, 13.0 kg/m^3 is used because the beams is located in the splash zone.

The design diffusion coefficient for chloride ions in concrete D_d is calculated from the following equation:

$$D_d = \gamma_c D_k + \left(\frac{w}{l}\right)\left(\frac{w}{w_a}\right)^2 D_o \tag{7.2.2}$$

$$w/l = 3\ (\sigma_{se} / E_s + \varepsilon'_{csd})$$

where γ_c (= 1.0) is the material factor for concrete, D_k is the characteristic value of diffusion coefficient of chloride ions in concrete, D_o (= 200 cm^2/year) is a constant to represent the effect of cracks on transport of chloride ions in concrete, w is the crack width, w_a is the crack width limit specified in Table 3.6.1, l is the crack spacing, σ_{se} is the increment in stress of reinforcement from the state in which concrete stress at the portion of reinforcement is zero, E_s is Young's modulus of reinforcement, and ε'_{csd} is compressive strain for evaluation of increment of crack width due to shrinkage and creep of concrete.

The characteristic value of the diffusion coefficient of chloride ions in concrete D_k is calculated by using the estimation formula for ordinary Portland cement-based concrete shown in Section 6.4.4 of SSC/Mate.

$$D_k = \gamma_p D_p$$
$$\log D_p = -3.9\ (W/C)^2 + 7.2\ (W/C) - 2.5 \tag{7.2.3}$$

where γ_p (= 1.2) is the safety factor for the accuracy of D_p.
Since the water-to-cement ratio W/C of the concrete is 0.45, D_k = 1.2×0.89 = 1.07 cm^2/year is obtained.

The values needed for the calculation of the crack width w and the ratio of crack width to crack spacing w/l are those calculated in Table 4.7.1 for the bottom reinforcement parallel to the face line of the wharf at the midspan of the floor slabs, and those calculated in Table 5.7.2 for the bottom reinforcement in the beams.

From these values, the design diffusion coefficient of chloride ions D_d can be obtained as D_d = 1.0×1.07 + 0.00158 × (0.245 / 0.245)^2 × 200 = 1.39 cm^2/year. Therefore, since the design concrete cover for the bottom reinforcement in the floor slabs is 70 mm and its design service life is 50 years, the design value of chloride ion concentration C_d at the reinforcement location can be calculated as follows:

$$C_d = \gamma_{cl}\, C_o \left(1 - erf\left(\frac{0.1c}{2\sqrt{D_d t}}\right)\right) = 1.3 \times 9.0 \times \left(1 - erf\left(\frac{0.1 \times 70}{2\sqrt{1.39 \times 50}}\right)\right) = 6.5 \text{ kg/m}^3$$

7.2.2 Threshold chloride ion concentration for reinforcement corrosion

For the threshold chloride ion concentration C_{lim} at the onset of reinforcement corrosion, a typical value of 1.2 kg/m^3, which is given in Section 7.4.5 of SSC/Struc, is used. According to the results of studies on the relationship between the chloride ion concentration in the superstructure of open-type wharves and reinforcement corrosion and chloride-induced deterioration, it may be possible to use a value greater than 1.2 kg/m^3 as the threshold value, although the value of 1.2 kg/m^3 is used as a standard one for this verification.

7.2.3 Verification results

Table 7.2.1 summarizes the conditions for verification and verification results for the bottom reinforcement in the floor slabs and the bottom reinforcement in the beams. The verification results indicate a high possibility of having corrosion and performance loss of the reinforcement in these members caused by chloride ions during the design service life. It is, therefore, essential to consider a measure to ensure the required level of durability during the design service life. This is described in Chapter 9.

Table 7.2.1 Result of verification for chloride-induced corrosion

		Bottom reinforcement in the floor slab	Bottom reinforcement in the beam
Design value	Type of cement	OPC	OPC
	W/C	0.45	0.45
	D_p (cm^2/year)	0.89	0.89
	γ_p	1.2	1.2
	D_k (cm^2/year)	1.07	1.07
	γ_c	1.0	1.0
	D_o (cm^2/year)	200	200
	w/l	0.00158	0.00197
	w_a (mm)	0.245	0.245
	w (mm)	0.245	0.245
	D_d (cm^2/year)	1.39	1.46
	c (mm)	70	70
	C_o (kg/m^3)	9.0	13.0
	t (year)	50	50
	γ_{cl}	1.3	1.3
	C_d (kg/m^3)	6.5	9.5
Limit value	C_{lim} (kg/m^3)	1.2	1.2
Verification	γ_i	1.0	1.0
	$\gamma_i\ C_d\ /\ C_{lim}$	5.42	7.92
	Judgment	NG	NG

7.3 Freezing and Thawing

Verification concerning freezing and thawing may be omitted because the site of the open-type wharf is free from freezing and thawing (Section 2.4 of SSC/Mate).

7.4 Chemical Attack

Verification concerning chemical attack may be omitted because the superstructure of the open-type wharf is free from chemical attack [Section 2.6 of SSC/Mate].

7.5 Alkali-Aggregate Reaction

Verification concerning alkali-aggregate reaction may be omitted by ensuring deterioration resistance to alkali-aggregate reaction through testing of concrete materials and so on [Section 2.6 of SSC/Mate].

7.6 Water Tightness

Verification of water tightness may be omitted because water tightness is not required for the superstructure of the open-type wharf [Section 2.7 of SSC/Mate].