Table 10. Total Benefits of the Design Exception Project

		Net Present Value of Total Benefit	
Calendar Year	Service Year	Based on INDOT Crash Cost Values	Based on FHWA Crash Cost Values
2011	0	$243,250	$243,250
2012	1	$218,679	$215,813
2013	2	$193,875	$188,254
2014	3	$168,775	$160,494
2015	4	$143,663	$132,835
2016	5	$118,469	$105,191
2017	6	$93,185	$77,547
2018	7	$67,905	$49,998
2019	8	$42,714	$22,629
2020	9	$17,596	-$4,583
2021	10	-$7,462	-$31,657
2022	11	-$32,341	-$58,472
2023	12	-$57,059	-$85,052
2024	13	-$81,670	-$111,460
2025	14	-$105,996	-$137,507
2026	15	-$130,094	-$163,260
2027	16	-$153,945	-$188,702
2028	17	-$177,567	-$213,857
2029	18	-$200,910	-$238,674
2030	19	-$223,928	-$263,107
2031	20	-$246,643	-$287,182

CONCLUSIONS

A thorough evaluation of IHSDM and HSM was conducted to explore the feasibility of using the tools for safety assessment of design exception projects. A case study was performed to illustrate the process of safety evaluation. It was demonstrated that IHSDM can be used to generate quantitative measures of safety impacts of design exception projects. IHSDM is capable of analyzing safety impacts of an individual substandard element as well as combined effects of a number of substandard elements. With IHSDM, the sensitivity of substandard elements can be analyzed by changing the values of design criteria. Using different combinations of substandard elements, such as lane width and shoulder width combinations, designers can choose the best alternative that would minimize the negative safety impacts.

One of the commonly used methods for justifying design exception projects is to use the savings in construction cost. However, this method is not a reasonable one because it does not include the impacts of a substandard highway section to the highway safety and operations. In this study, benefit-cost analysis method was used to evaluate the effectiveness of design exceptions. An Excel based computer program was developed to conduct benefit-cost analysis for design exceptions. This method includes not only the savings in construction cost and other initial costs, but also the user benefits in terms of travel time, vehicle operation, and safety. The computer program provides a useful and convenient tool for highway engineers and planners to evaluate design exception projects.

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Convective Depth of the Chloride Ion in Concrete Surfaces

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ABSTRACT

Based on the hypothesis of chloride ion concentration in concrete surfaces changing linearly, a convective depth model was established in this study. The rationality of the model was verified by experiment. In addition, a novel method for calculating the equivalent chloride ion content in the natural environment is proposed. The results showed that the diffusion of the chloride ion in concrete can be described by Fick's second law, and there was an exact convective depth value in a concrete surface. In general, the value of the convective depth is relative to the wetting-drying ratio of the environment and the permeability coefficient of the concrete. Compared with the water influence depth in concrete, the convective depth was shallow. Moreover, the equivalent chloride ion content in the environment was determined by the characteristics of the environment.

Key Words: Concrete; convective depth; diffusivity; chloride ion

INTRODUCTION

It is well known that the chloride ion is the main factor inducing the deterioration of concrete structures in marine environments. Much research about this has been carried out at home and abroad, and many research results have been obtained. Although the optimal chloride diffusion model is Fick's second law, it still has some shortcomings. For example, the convective depth of the chloride ion is usually obtained by fitting the chloride diffusion profile, which is the indirect method with testing error (Ann 2009; Zhang 1998). How to ensure the chloride convective depth and the concentration in concrete surfaces is obviously significant for forecasting service life and evaluating the durability of reinforced concrete structures in marine environments.

Most existing research on chloride convective depth in concrete surfaces was based on measured data, and the fitting curve of the data was used to obtain the value. Some standards regarded the chloride convective depth value as a constant value, such as 14mm recommended by the Duracrete standard (BE95-1347 2000). But the designated value was so simple that it was not suitable for special conditions. In addition, some researchers set the value as 20mm (Rincon 2004). Vesikari (2003) revealed that the chloride convective depth in concrete approximately accorded with the Beta function by studying the chloride profiles of more than 127 typical engineering situations. Fan et al. (2006) indicated that the chloride convective depth in concrete was about 15mm by discussing the chloride curve of the port in marine environments. Li (2009) regarded the water influence depth as the chloride convective depth in concrete. Generally speaking, the chloride convective depth in concrete depends on the environment, the drying-wetting time ratio, load, and the properties of the concrete (Michael 1999). However, most of time, the research referred to above does not pay attention to these situations, which raises many questions. Furthermore, the test methods also influenced the precision of the convective depth.

In this study, the change law of the chloride ion in concrete under natural and artificial environments was investigated. Based on the hypothesis of the chloride ion concentration in concrete cover changing in linearly, the convective depth model was obtained. In addition, the rationality of the model was verified by testing.

THEORETICAL MODEL

Based on the distribution law of the chloride ion in concrete under drying-wetting environments, concrete can be divided into two parts—convective zone and internal diffusion zone (Castro 1997). The author considered the distribution of the chloride associated with the drying-wetting action and pore structure of the concrete, and the chloride transmission mode within convective zone was still by diffusion. Based on the hypothesis of chloride diffusion in semi-infinite concrete processing along the direction of one dimension and the concentration gradient changing along the convective zone to the steel surface, Fick's second law, which was a function of time and space, was used to describe the diffusion, as shown in Equation (1).

$$C(x,t) = C_0 + (C_s - C_0)\left[1 - erf\left(\frac{x - \Delta x}{2\sqrt{D_{app} t}}\right)\right] \tag{1}$$

Where $C(x,t)$ is the chloride content in concrete at depth x and exposure time t, %; C_s is the chloride content at the concrete surface,%; C_0 is the chloride content at the initial period,%; t is the exposure time, s; x is the distance from the concrete surface, m; D_{app} is the diffusion coefficient, $m^2/$ s; Δx is the convective depth in concrete, m; and erf(z) is the error function.

From Equation (1), it can be seen that ensuring the value of convective depth Δx and concrete surface chloride content C_s was very significant for forecasting service life and evaluating the durability of reinforced concrete structures. The accumulation of chloride in alternating wetting-drying convective zones was very complex and, most of time, was the coupling effect of multiple factors, including convection and diffusion. Some researchers revealed that the concentration of chloride in a convective zone was a constant value, and the corresponding depth was regarded as the convective depth in concrete. Most of existing studies about the value of Δx were based on measured data and deduced by Equation (1), which still faced some controversy, such as the subjective evaluation had poor transparency and reappearance, the objective method lacks a theoretical foundation, and the subjective and objective weights tended to pay no attention to theory. If the diffusion coefficient D_{app}, initial chloride concentration C_0, and concrete surface chloride content C_s were all regarded as constant values, then the convective depth Δx can be indirectly obtained by Equation (1) and as shown in Equation (2).

$$\frac{C(x,t_1)-C(x,t_2)}{C_s-C_0}=erf\left(\frac{x-\Delta x}{2\sqrt{D_{app}t_2}}\right)-erf\left(\frac{x-\Delta x}{2\sqrt{D_{app}t_1}}\right) \tag{2}$$

Although the method above can obtain the convective depth value Δx, there are some shortcomings, including being time-consuming and achieving low accuracy. Moreover, it cannot directly obtain the convective depth value Δx in the absence of the concrete's physical characteristics and environment. In other words, it cannot overcome long-time field testing.

Li (2009) recommended water influence depth as the convective depth of chloride in concrete, which did not match with the facts. At present, accurately obtaining the convective depth is rarely of concern at home and abroad.

Based on the hypothesis of chloride concentration with linearity in the convective zone and referencing Li (2009), the model of the convective depth in concrete cover was inferred. This study was conducted as follows: the chloride salt solution was a chloride ion-containing solution that was absorbed by capillary suction of unsaturated concrete under continuous wetting-drying cycles. In the early drying process, the chlorine salt solution was transferred bi-directionally into the concrete inner and surface. In the early drying stages, the water transferred from concrete inner in the form of vapor under the condition of pore water without sustaining continuous status, and the chloride salt concentrated and crystallized in the concrete. Generally speaking, the chloride concentration in the convective zone maximized and maintained balance with time. Due to hysteresis and the blocking effects of the concrete, the evaporation and condensation effects occur only on the concrete surface. Therefore, the chloride convective depth was less than the water influence depth. When the concrete was wet again, the chloride salt solution was absorbed by capillary suction of the unsaturated concrete, and the chloride ion was absorbed into the concrete and supplemented the consumption. Concentration of the chloride at a certain depth in the concrete reached a new equilibrium state with the drying-wetting test, and the corresponding convective depth and limited chloride concentration were generated, which was related to the drying-wetting time ratio. In this study, the convective depth in concrete was established, as shown in Figure1. The corresponding water influence curve is shown in the upper portion of Figure 1, and the corresponding convective depth model profile is described below.

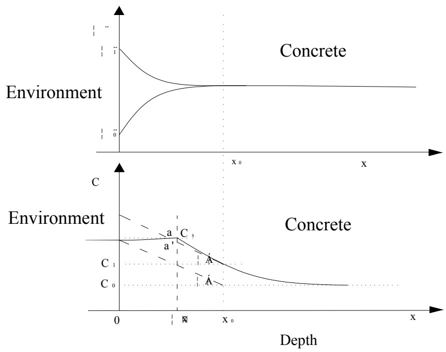


Figure 1. Convective depth model of chloride ion in concrete surface.

In this study, the hypothesis of chloride concentration in water influence depth zone x_0 was regarded as fitting to a linear function. The equivalent chloride concentration of environment C_e was perceived as a constant, and Fick's second law was used to describe the distribution of the chloride within the convective depth zone. Concentrations of the chloride at the water influence depth x_0 and convective depth Δx were expressed as C_1 and C_s, respectively. From Figure 1, it can be seen that the chloride ingress profile can be represented as Equation (3) based on the hypothesis of the linear function, shown as dotted line in Figure 1, and the corresponding model of the convective depth Δx can be shown as Equation (4).

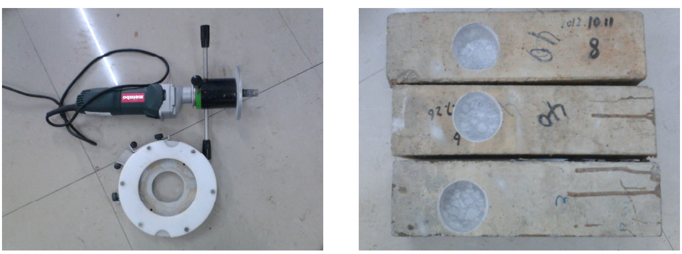
$$\mathrm{tg}\alpha = \frac{C_e - C_0}{x_0} = \frac{C_s - C_1}{x_0 - \Delta x} \tag{3}$$

$$\Delta x = \left(1 - \frac{C_s - C_1}{C_e - C_0}\right) x_0 \tag{4}$$

As far as is known, the initial chloride concentration C_0, the equivalent chloride concentration of the environment C_e, and the water influence depth C_1 can be directly measured in concrete. Moreover, the concrete surface chloride concentration C_s can also be calculated, which is discussed below. The corresponding depth x_0 based on the model of the water influence depth by Li (2009) can be obtained, and the convective depth Δx can be calculated by Equation (4). From Equation (4), it is seen that the convective depth Δx is the function of the water influence depth, which overcame the shortcomings of the traditional methods.

EXPERIMENT PROCESS

Grade 42.5 Portland cement, polycarboxylic type high performance water reducer, class I fly ash, grade S95 slag, water, sand, and limestone the size of 5–20 mm were used as the main raw materials to produce concrete. The mass ratio of the limestone, sand, cement, water, slag, fly ash, and water reducer was 1060:710:355:155:70:45:4.5, and the sizes of the samples were 150 mm×150 mm×150 mm and 150 mm×150 mm×400 mm. Only one side of the samples was left for testing; the other sides were sealed with epoxy. There were three stages for an experiment cycle, and the cycling time was about 72 hours. A spray stage was set for 50 minutes, and the last period was for drying. Temperature and duration time were set as 40℃/30 h, 50℃/12 h, and 60℃/30 h. The concentration of the salt solution was 5%, and the wind speed was set as 3m/s. A profile grinding machine (Model PF1100 produced in Denmark) was used to prepare the powder; its fineness passed the sieve with the size of 75 μm. Then, the chloride content in the concrete was tested according to China standard JTJ 270-1998. The profile grinding machine and samples are shown in Figure 2.



(a) (b)

Figure 2. Profile grinding machine and sample.

RESULTS AND DISCUSSION

To verify the rationality of the chloride convective depth model in concrete surfaces, an artificial simulation environment test was carried out. The initial water saturation in the concrete was 0.8, and the environment water saturation applied to the concrete was set as 0.4. The initial chloride concentration of the concrete was 0.016%, which was the mass of the concrete. Figure 3 shows the curve of the water saturation distribution of the concrete in the simulation environment, and the chloride ion content profile in concrete for eight months under artificial simulation environment is shown in Figure 4.

From Figure 3, it can be seen that the water saturation on the concrete surface changed only in a certain depth zone x_0, and its value did not change when the value was more than a certain depth. The water influence depth x_0 was about 14mm, which was calculated based on Li (2009). The following sections investigate the simulation test results used to calculate the chloride convective depth Δx in concrete.

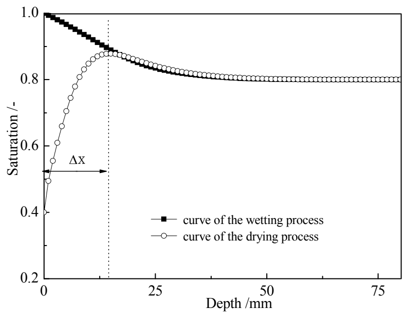


Figure 3. Water saturation distribution curve of concrete in simulation environment.

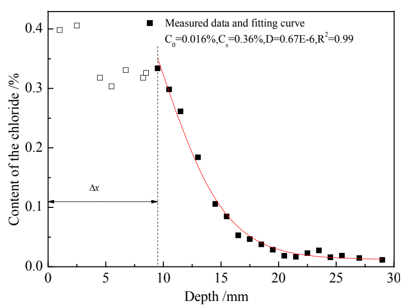


Figure 4. Chloride ion content curve of concrete in artificial simulation environment.

It can be seen from Figure 4 that the chloride concentration can be described by Fick's second law when the chloride convective depth Δx was more than a certain value and the measured data perfectly fit the fitted curve. The chloride convective depth Δx calculated by the Equation (1) was about 10 mm. Although the method above could be used to calculate the chloride convective depth, it also had some shortcomings, including lengthy time consumption, measured data, and low precision. To overcome these difficulties, a chloride convective depth model in the concrete based on the special environment and property of the concrete was established in this study. Among the influences of the theoretical simulation factors, the water influence depth x_0 was estimated by numerical simulation. In view of the results above, the corresponding chloride convective depth of the concrete in the artificial simulation environment was about 11mm, and the value was very close to the measured value. In addition, the chloride convective depth of a trestle bridge built for 12 years in a marine environment was also calculated. The tidal range infiltrated time ratio was about 0.776, and the sea water salt concentration of the test point was about 2.9%, regarded as the chloride salt value. The water influence depth of the concrete structure was about 6mm, which was calculated by theoretical simulation. Figure 5 shows the curve of the chloride ion content (mass of concrete) of the trestle bridge.

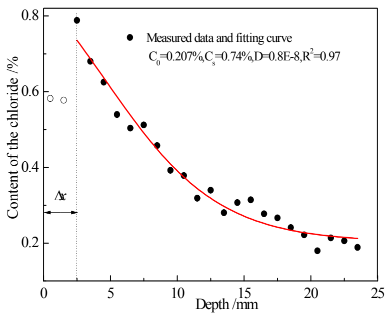


Figure 5. Chloride ion content curve of trestle bridge.

Figure 5 reveals that the chloride concentration in concrete can also be described by Fick's second law, when the depth was more than a certain value. The measured data perfectly accorded with the fitting curve, and the chloride concentration in a certain depth of the concrete was a constant value. From the results discussed above, it can be seen that the convective depth also existed in field concrete structures in a marine environment. The chloride convective depth of the concrete structure was about 3.5mm, and the measured data was about 2.5mm, which was in accordance with the calculation. It also indicated that the model used to calculate the chloride convective depth of the structure in marine environments was feasible.

CONCLUSIONS

From the discussion above, conclusions can be made as follows:

(1) Distribution of chloride ion content in concrete in drying-wetting environments indicated that the concrete can be divided into two parts - a convective zone and an internal diffusion zone, and the distribution of chloride ion within the convective zone can be described by Fick's second law.

(2) Based on the linear function hypothesis of the chloride content change in the convective zone, a chloride convective depth model was established. By analyzing the measured data of the concrete in an artificial simulation environment and a marine environment, the rationality of the model was proved.

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