CONCRETE IN MARINE TIDAL ENVIRONMENT – MODELLING FOR SERVICE LIFE PREDICTION WITH RESPECT TO CHLORIDE INGRESS

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by

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Certificate

This is to certify that the thesis entitled "**Concrete in Marine Tidal Environment - Modelling for Service Life Prediction with respect to Chloride Ingress**" being submitted by **Mr. Suresh Kumar Padala** to the Indian Institute of Technology Delhi, India, for the award of the degree of **Doctor of Philosophy** in Civil Engineering, is a record of original bona fide research work carried out by him under my guidance and supervision. To the best of my knowledge, the thesis has reached the requisite standard, fulfilling the requirements for the degree of Doctor of Philosophy. The material contained in this thesis, in part or in full, has not been submitted to any other university or institute for the award of any degree or diploma.

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Abstract

Corrosion of steel in reinforced and prestressed concrete members exposed to the marine tidal zone is a severe durability problem. It results in frequent maintenance and repair work leading to high life cycle costs and even premature failure of structural members if left unattended. Thus the design of elements exposed to marine tidal zone for prolonged maintenance-free service life assumes paramount importance. Service life design in exposure environments, including aggressive or extreme ones, can best be done through mathematical modelling of transport processes of aggressive external agents involved in the deterioration of structural elements. All the material degradation processes leading to element deterioration and resulting serviceability failure occur in the solution phase often in the presence of moisture as a necessary condition. The other agents that play a dominant role in the de-passivation of reinforcing or pre-stressing steel are water-soluble chloride salts. Seawater attack on concrete also involves sulfate attack, but the high solubility of calcium sulfates in seawater diminishes their expansive actions and resultant cracking. Hence it is imperative that estimation of service life and design for desired service life demand modelling of moisture and chloride ingress in concrete elements. While numerous physical/empirical mathematical models were developed for the prediction of deterioration of concrete members in the marine environment, modelling the boundary conditions and characterization of moisture and chloride profiles in the tidal zone remains relatively unexplored.

The main aim of this project is to estimate the severity of chloride attack in the tidal zone so as to enable one to estimate the service life with reference to chloride ingress for given concrete material characteristics and section parameters. The above procedure of estimation in turn would enable one to determine the appropriate material characteristics and section parameters as decision variables for desired service life design. This estimation is facilitated by using several penetration indices already reported in the existing literature. To achieve this, finite element (FE) models are developed to solve for the moisture and chloride profiles in concrete members exposed to alternate wetting and drying encountered in the tidal environment. The developed models are validated with published experimental results from existing literature. The validated FE models are then used to evaluate the moisture and chloride profiles for several wet-dry regimes prevalent in the tidal zones. A superimposed tide model having closer proximity to real tides is proposed as a novel alternative to the conventionally used diurnal tide model for simulating the wet-dry regimes in the tidal zone. The simulated moisture and chloride

profiles are characterized using well-defined penetration indices, which are used as metrics for comparing the severity of chloride attacks along the tidal zone. Also, the proposed methodology was implemented for the case of six Indian coastal stations to estimate the safe cover depth for steel reinforcement across tidal zones.

The key findings from the study are: 1) The proposed methodology for evaluating the penetration indices along the tidal zone facilitates locating the critical zone of chloride attack, the attributes of which can be used for the durability design of the rest of the tidal zone. 2) The study presents a systematic methodology for using real-time tidal environmental data in calculating the environmental loads affecting the durability of concrete elements exposed to tidal zone. This methodology helped in estimating the environmental loads and the corresponding responses from concrete elements at different geographical locations. 3) The proposed superimposed tide model is a closer approximation of the real tides compared to the conventionally used diurnal tides. It gives conservative predictions compared to the diurnal tide models, which underestimate the severity of chloride penetration in the tidal zone. 4) The estimated values of safe cover depth to reinforcing steel across 6 Indian coastal stations were found to differ by 20-25 mm, which is significant and indicates a need for classifying the coastline into different severity zones. This zoning would be a significant improvement over the current practice, wherein a distinction is not made between the severities of tidal zones of different coastal stations. 5) The comprehensive parametric study helped in identifying the parameters that cause significant variations in the penetration indices. This preliminary analysis is useful in shortlisting relevant design variables for the development of surrogate/metamodels.

सार

समुद्री ज्वारीय क्षेत्र में रीन्फोर्स्ड और प्रीस्ट्रेस्ड कंक्रीट बनावटों में स्टील का क्षरण एक गंभीर स्थायित्व समस्या है। इसके वजह से लगातार रखरखाव और मरम्मत का काम होता है जो उच्च जीवन चक्र लागत और यहां तक कि बनावटों की समयपूर्व विफलता कर सकता है, अगर उपेक्षित छोड़ दिया जाए। इसीलिए लंबे समय तक रखरखाव से मुक्त सेवा जीवन पाने के लिए समुद्री ज्वारीय क्षेत्र के संपर्क में आने वाले बनावटों का डिज़ाइन बहुत महत्वपूर्ण है। आक्रामक या अतिवादी सहित वातावरणों में बनावटों की सेवा जीवन डिजाइन उनकी ह्रास में शामिल आक्रामक बाहरी पदार्थों की परिवहन प्रक्रियायों की गणितीय मॉडलिंग के माध्यम से सबसे अच्छा किया जा सकता है। बनावटों के ह्रास और परिणामस्वरूप सेवाक्षमता विफलता की ओर ले जाने वाली सभी भौतिक अवक्रमण प्रक्रियायो में नमी की उपस्थिति आवश्यक है । अन्य पदार्थ जो रीन्फोर्स्ड या प्रीस्ट्रेसिंग स्टील के डीपासिवेशन में प्रमुख भूमिका निभाते हैं वह पानी में घुलनशील क्लोराइड लवण हैं। कंक्रीट पर समुद्री जल का प्रतिकूल प्रभाव के साथ साथ सल्फेट का असर भी शामिल है, लेकिन समुद्री जल में कैल्शियम सल्फेट की उच्च घुलनशीलता उनके विस्तारी गतिविधि और परिणामी दरार को कम कर देती है। इसीलिए यह अनिवार्य है कि सेवा जीवन का आकलन और वांछित सेवा जीवन की डिजाइन के लिए कंक्रीट में नमी और क्लोराइड प्रवेश की मॉडलिंग का प्रयोग करें। जबकि समुद्री पर्यावरण में बनावटों की ह्रास की भविष्यवाणी के लिए कई भौतिक/अनुभवजन्य गणितीय मॉडल विकसित किए गए थे, ज्वारीय क्षेत्र में सीमा स्थितियाँ, और नमी और क्लोराइड प्रोफाइल्स का लक्षणवर्णन अपेक्षाकृत निराधार रहता है।

इस काम का मुख्य उद्देश्य ज्वारीय क्षेत्र में क्लोराइड के प्रतिकूल प्रभाव की गंभीरता का अनुमान लगाना है ताकि दिए गए कंक्रीट सामग्री विशेषताओं और खंड पैरामीटरों के लिए क्लोराइड अन्तःक्षेपण के संदर्भ में सेवा जीवन का अनुमान लगाने में सक्षम बनाये। उपरोक्त अनुमान की प्रक्रिया बदले में वांछित सेवा जीवन डिजाइन के लिए निर्णय चर के रूप में उपयुक्त सामग्री विशेषताओं और खंड मापदंडों को निर्धारित करने में सक्षम होगा। पहले से ही मौजूदा साहित्य में बताए गए कई अन्तःक्षेपण सूचकांक इस अनुमान में सुविधा देते है। इसे प्राप्त करने के लिए, ज्वारीय वातावरण में वैकल्पिक गीलापन और सुखाने का सामना करने वाली कंक्रीट के फाइनाइट एलिमेंट (एफ ई) मॉडल्स विकसित किए गए हैं जिससे नमी और क्लोराइड प्रोफाइल्स का समाधान किया गया है। विकसित मॉडल्स मौजूदा साहित्य से प्रकाशित प्रयोगात्मक परिणामों के साथ मान्य हैं। मान्य एफ ई मॉडल्स फिर ज्वारीय क्षेत्रों में प्रचलित कई गीले-सूखे शासनों के लिए नमी और क्लोराइड प्रोफाइल्स का मूल्यांकन करने के लिए उपयोग किये गए है। ज्वारीय क्षेत्र में वास्तविक गीला-शुष्क शासनों के सिमुलेशन के लिए पारंपरिक रूप से इस्तेमाल किए

जाने वाले डायरनल टाइड मॉडल के नव विकल्प के रूप में ज्वार के निकट एक आरोपित ज्वार मॉडल प्रस्तावित किया गया है। सिम्युलेटेड नमी और क्लोराइड प्रोफाइल्स को अच्छी तरह से परिभाषित अन्तःक्षेपण सूचकांकों का उपयोग करके चित्रित किया जाता है, जो ज्वारीय क्षेत्र में क्लोराइड के प्रतिकूल प्रभावों की गंभीरता की तुलना करने के लिए मेट्रिक्स के रूप में उपयोग किये जाते है। इसके अलावा, प्रस्तावित कार्यप्रणाली स्टील रीन्फोर्स्मेंट के लिए सुरक्षित कवर गहराई का अनुमान लगाने के लिए छह भारतीय तटीय स्टेशनों के मामले में लागू किया गया है।

अध्ययन के प्रमुख निष्कर्ष हैं: 1) ज्वारीय क्षेत्र में अन्तःक्षेपण सूचकांकों का मूल्यांकन के लिए प्रस्तावित पद्धति क्लोराइड के प्रतिकूल प्रभाव की संकटमय क्षेत्र का पता लगाने की सुविधा प्रदान करता है, जिसकी विशेषताओं का उपयोग शेष ज्वारीय क्षेत्र के स्थायित्व डिजाइन के लिए किया जा सकता है। 2) इस अध्ययन ज्वारीय क्षेत्र में उजागर कंक्रीट तत्वों पर पर्यावरणीय भार की गणना करने के लिए वास्तविक समय के ज्वारीय पर्यावरण आधार-सामग्री का उपयोग करने का एक व्यवस्थित पद्धति प्रस्तुत करता है। इस पद्धति ने पर्यावरणीय भार और विभिन्न भौगोलिक स्थानों पर कंक्रीट बनावटों से संबंधित प्रतिक्रियायों का आकलन करने में मदद की। 3) प्रस्तावित अध्यारोपित ज्वार मॉडल पारंपरिक रूप से उपयोग किया गया दैनिक ज्वार मॉडल की तुलना में वास्तविक ज्वार का एक निकट सन्निकटन है । यह ज्वार मॉडल दैनंदिन ज्वार मॉडल की तुलना में अनुदार भविष्यवाणियां देता है जो ज्वारीय क्षेत्र में क्लोराइड के अन्तःक्षेपण की गंभीरता को कम आंकते हैं। 4) 6 भारतीय तटीय स्टेशनों में प्रबलित स्टील की सुरक्षा आवरण गहराई के अनुमानित मूल्य 20-25 मिलीमीटर से भिन्न पाए गए है, जो अभिप्रायपूर्ण और तटरेखा कों विभिन्न गंभीरता क्षेत्रों में वर्गीकृत करने की आवश्यकता को इंगित करता है। यह क्षेत्रीकरण वर्तमान प्रथाओं पर एक महत्वपूर्ण सुधार होगा, जिनमे विभिन्न तटीय स्टेशनों के ज्वारीय क्षेत्रों की गंभीरता के बीच अंतर नहीं किया जाता है। 5) विस्तृत पैरामीट्रिक विश्लेषण ने अन्तःक्षेपण सूचकांकों में महत्वपूर्ण बदलाव का कारण बनने वाले पैरामीटर को पहचान करने में मदद की। यह प्रारंभिक विश्लेषण सरोगेट/मेटामॉडल्स के विकास के लिए प्रासंगिक डिजाइन चरों को चुनने में उपयोगी है।

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$[\boldsymbol{B^e}]$ = element level matrix added to account for boundary conditions that are functions of the degrees of freedom

$\mathrm{B_h}$ = surface mass transfer coefficient $(1/\mathrm{m}^2/\mathrm{s})$

C_0 = initial chloride concentration (kg of chloride/m^3 of concrete)

C_b = bound chloride content (kg of chloride/m^3 of concrete)

C_{en} = environmental chloride concentration (kg of chloride/m^3 of solution)

C_f = free chloride concentration (kg of chloride/m^3 of solution)

$C_{f,0}$ = initial free chloride concentration (kg of chloride/m^3 of solution)

C_{fr} = relative free chloride concentration $(-)$

C_i = free ion concentration (kg of chloride/m^3 of solution)

C_s = surface chloride concentration (kg of chloride/m^3 of solution)

C_{sw} = chloride concentration of surrounding seawater (gm/L)

C_{swr} = relative chloride concentration of surrounding seawater (-)

C_{sol} = solubility limit of chloride in the pore solution (gm/L)

$[\boldsymbol{C^e}]$ = element level damping matrix

D_{agg} = humidity diffusion coefficient of the aggregate $(\mathrm{m}^2/\mathrm{s})$

D_{Cl} = chloride diffusion coefficient $(\mathrm{m}^2/\mathrm{s})$

$D_{Cl,a}$ = apparent diffusion coefficient $(\mathrm{m}^2/\mathrm{s})$

D_{cp} = humidity diffusion coefficient of the cement paste $(\mathrm{m}^2/\mathrm{s})$

$D_{d,wet}$ = wetting diffusivity of an initially dry medium $(\mathrm{m}^2/\mathrm{s})$

D_{eff} = effective chloride diffusion coefficient $(\mathrm{m}^2/\mathrm{s})$

D_i = ionic diffusion coefficient $(\mathrm{m}^2/\mathrm{s})$

D_i^{ref} = ionic diffusivity measured at the temperature T^{ref} $(\mathrm{m}^2/\mathrm{s})$

D_m = moisture diffusion coefficient/moisture diffusivity (m^2/s)

D_r = reference diffusivity at age t_{ref} $(\mathrm{m}^2/\mathrm{s})$

$D_{w,dry}$	=	drying diffusivity of an initially wet medium ($\mathrm{m^2/s}$)
E_1	=	total heat of adsorption per mole of vapor (J)
E_b	=	breakdown voltage (V)
E_b^0	=	standard breakdown voltage (V)
E_{CP}	=	corrosion potential (V)
E_l	=	latent heat of condensation per mole of vapor (J)
F	=	Faraday's constant (C)
$f(\theta_r)$	=	dimensionless moisture diffusivity functions (-)
g_i	=	aggregate volume fraction
h	=	relative humidity (-)
h_c	=	critical relative humidity (-)
h_{en}	=	relative humidity of the surrounding environment (-)
I	=	ionic strength of pore solution (kg/m^3 of pore solution)
J_h	=	the humidity flux ($1/\mathrm{m^2/s}$)
J_w	=	the mass flux of water at the surface ($\mathrm{kg/m^2/s}$)
$[\boldsymbol{K^e}]$	=	element level stiffness matrix
k_r	=	relative permeability of water (-)
k_w	=	permeability of water (m^2)
L	=	spatial extent of the domain (m)
l	=	length of the finite element (m)
$[\boldsymbol{M^e}]$	=	element level mass matrix
M_{Cl}	=	surface mass transfer coefficient of chloride ($\mathrm{m/s}$)
M_w	=	molecular mass of water (kg/mole)
m	=	age factor (-)
N_i, N_j	=	shape functions
n	=	empirical constant ranging from 6-8 for building materials (-)

P_c	=	capillary pressure (Pa)
Q^e	=	moisture flux variable (kg/m^2/s)
$\{\boldsymbol{Q^e}\}$	=	vector of moisture flux
q_{wet}	=	wetting flux (m/s)
q_{dry}	=	drying flux (m/s)
R	=	universal gas constant (J/kg/K)
$\mathrm{r}_{\mathbf{cp}}^{\mathbf{peak}}$	=	peak radius of a capillary pore (nm)
T	=	temperature (K)
T_0	=	reference temperature (K)
t	=	time coordinate/age (s)
t_0	=	curing time of concrete (s)
t_a	=	age of concrete (day)
t_{a0}	=	age of concrete at the start of exposure (d)
t_e	=	equivalent maturation age (d)
t_{ex}	=	exposure duration (d)
t_{ISL}	=	intended service life (y)
t_r	=	relative time coordinate (–)
t_{ref}	=	reference age (s)
U	=	activation energy (J)
V_m	=	monolayer capacity of cement (m^3 of water/m^3 of cement)
x	=	space coordinate (m)
x_c	=	carbonation depth (m)
x_r	=	relative space coordinate (–)
w	=	water content (kg/m^3)
w/c	=	water to cement ratio (–)
z_i	=	valence ion ‘i’ (–)

α = chloride binding parameter ($\mathrm{m^3}$ of solution/$\mathrm{m^3}$ of concrete)

α_0 = ratio of minimum drying diffusivity to maximum drying diffusivity ($-$)

β = empirical constant ranging from 6-8 for cementitious materials ($-$)

Γ = temporal extent of the domain (s)

γ_i = activity coefficient of ion 'i'(-)

δ = tortuosity (-)

ζ = ratio of diffusion coefficient $t_e \to \infty$ and $t_e = 28$ days (-)

η = empirical coefficient ranging from 6 to 16 for cementitious materials ($-$)

κ = thermal conductivity (W/m/K)

κ^{ref} = reference thermal conductivity at the temperature T^{ref} (W/m/K)

θ = volumetric moisture content ($\mathrm{m^3}$ of moisture/$\mathrm{m^3}$ of concrete)

θ_0 = initial moisture content ($\mathrm{m^3/m^3}$)

θ_{eq} = equilibrium moisture content ($\mathrm{m^3/m^3}$)

θ_m = mass basis moisture content (kg of moisture/kg of concrete)

θ_r = relative moisture content ($-$)

$\theta_{r,0}$ = initial relative moisture content ($-$)

$\theta_{r,c}$ = critical relative moisture content at which the drying diffusivity dips ($-$)

$\theta_{r,eq}$ = equilibrium relative moisture content ($-$)

$\theta_{r,j}^{e}$ = nodal relative moisture content ($-$)

$\theta_{r,c}$ = critical relative moisture content ($-$)

θ_{sat} = saturated moisture content ($\mathrm{m^3/m^3}$)

ρ = density ($\mathrm{kg/m^3}$)

ρ_c = density of concrete ($\mathrm{kg/m^3}$)

ρ_w = density of water ($\mathrm{kg/m^3}$)

τ = temporal extent of the relative domain ($-$)

ϕ_0 = initial porosity of concrete ($\mathrm{m^3/m^3}$)

ϕ	=	total porosity of concrete (m^3/m^3)
$\phi_{\mathbf{paste}}$	=	porosity of cement paste (m^3/m^3)
ψ	=	electric potential (V)
Ω	=	constrictivity (−)

List of Abbreviations

CTD	=	Chloride threshold depth
CWAA	=	Cyclic water absorption amount
DPCC	=	Depth of occurrence of peak chloride concentration
DWTR	=	Drying to wetting time ratio
EMPD	=	Effective moisture penetration depth
FEM	=	Finite Element Method
HTL	=	High tide level
IDMT	=	Influential depth of moisture transport
LCTD	=	Lower chloride threshold depth
LTL	=	Low tide level
MCTD	=	Median chloride threshold depth
MPD	=	Moisture penetration depth
MSL	=	Mean sea level
PCC	=	Peak chloride concentration
RH	=	Relative humidity
StMC	=	Stable moisture content
UCTD	=	Upper chloride threshold depth