



Thermo–hydro–ionic transport in sea immersed tube tunnel



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ABSTRACT

This paper investigates the multi-species and multi-fields transport processes in the concrete wall of sea immersed tube tunnel, exposed externally to sea water and internally to road traffic. A thermo–hydro–ionic (THI) model is established for the transport processes, taking into account the heat, mass and electrical charge conservations, the electrical neutrality and solid–solution equilibria in the representative elementary volume (REV) of material. Then, the characteristic lengths for drying and wetting are proposed for the tunnel wall through simplified model of moisture transport to define different durability patterns for tunnel wall, and the associated durability risks are identified. The THI model is applied to the immersed tube tunnel of Hong Kong–Zhuhai–Macau (HZM) sea link project, and the transport processes are simulated for a service life of 120 years and different working cases. The analysis shows that: (1) the thermal gradient has more important impact on transport processes than the external sea water pressure on tunnel wall; (2) the drying and wetting extents are overlapped through the wall thickness at 120 years, and the internal drying and external leaching condition the multi-species transport; and (3) the corrosion initiation range attains 65 cm at 120 years but the corrosion current is below the depassivation value ($0.1 \mu\text{A}/\text{cm}^2$).

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1. Introduction

The immersed tube tunnel is one of the most challenging civil engineering works. Compared to buried type tunnels, the immersed tunnel has the advantage of faster construction procedure, better quality control as well as better adaption to sea bed geology (Rasmussen, 1997). Since the first immersed tube tunnel construction in US in 1910, this type of tunnel had been adopted in more than 150 projects according to the statistics (Rasmussen and Grantz, 1997). One engineering concern for concrete immersed tube tunnel is the durability issues associated with the exposure of structural concrete to sea water. One design option is to protect the structural concrete by external membrane (Glerum, 1995) while alternative design concept consists in exposing the structural concrete of immersed tube tunnel directly to sea water during its service life (Jassen and Lykke, 1997). Accordingly, the deterioration processes of structural concrete are crucial to the durability performance of tunnel during its service life (Gokce et al., 2009).

The durability performance of concrete immersed tube tunnel is closely related to the transport processes of the aggressive agents

in sea water into the structural concrete. The aggressive agents include the ion species such as H^+ , SO_4^{2-} , Cl^- and Mg^{2+} , and the free CO_2 in sea water (Mehta, 1980). These agents can deteriorate the structural concrete through different mechanisms: the Cl^- ions can transport into concrete pores and induce the electrochemical reactions of corrosion of the embedded reinforcement steel (Tuutti, 1982; Melchers and Li, 2009); the SO_4^{2-} ions can migrate into concrete, induce the internal sulfate reaction and deteriorate concrete materials by the expansive products (Atkinson and Heame, 1990; Chen et al., 2008); Mg^{2+} alone can react with the cement hydrates and dissolve the material matrix (Vedalakshmi et al., 2011). Concrete leaching is another important phenomenon for structural concrete directly exposed to water: as the external wall keeps in contact with the surrounding sea water, the ion species in concrete pore solution, especially Ca^{2+} and OH^- , can migrate out and trigger the dissolution of cement hydrates of Portlandite (CH) and calcium silicate hydrates (C–S–H)¹; with time this process can enlarge the material porosity, decrease the mechanical strength and destruct the solid matrix in extreme cases (Ulm et al., 1999; Haga et al., 2005). So far, the chloride migration process has been

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¹ According to the notations of Cement Chemistry: C = CaO, S = SiO₂, H = H₂O, M = MgO. These notations are used throughout this paper.

investigated in literature (Song et al., 2009) but comprehensive study on the multi-species transport of aggressive agents is not yet reported.

The durability of the tunnel wall is controlled by these processes related to multi-species transport. Normally the concrete permeability is regarded as the foremost parameter of tunnel to resist the sea water penetration as well as the migration of aggressive agents. External wrapping, internal lining and cathodic protection of reinforcement steel in tunnel are available as additional protection measures against the deterioration processes. However, the specification for concrete permeability and the use of protection measures are so far prescribed on empirical basis, and a scientific approach is not yet available to support the quantitative durability design of tunnel wall. To this purpose, this paper proposes a thermo–hydro-ionic model to describe the multi-species transport of marine ions, the multi-fields couplings during the transport, and the leaching process of concrete. Meanwhile, some dimensional analysis is carried out for the tunnel wall exposed externally to sea water and internally to dry air. The established model and results from dimensional analysis are applied to an ongoing project of immersed sea tube tunnel designed for a service life of 120 years. Recommendations for durability design of this tunnel are provided on the basis of the analysis results. Following this logic line, the paper is organized as such: the thermo–hydro-ionic model is given in Section 2; the dimensional analysis for length scales is provided in Section 3; the application to the immersed tube tunnel is presented in Section 4; and the recommendations and conclusions are given in Section 5.

2. Thermo–hydro-ionic modeling

The structural concrete is considered as a porous medium and the transport processes are investigated on a representative elementary volume (REV) of material. The pore space is assumed to be connected and partially saturated by pore solution. The connected porosity, ϕ , includes liquid-occupied porosity ϕ_l and gas-occupied porosity ϕ_g , and the liquid saturation degree s_l is defined as,

$$s_l = \phi_l / \phi, \quad \phi = \phi_l + \phi_g \quad (1)$$

The gas phase is assumed to be composed of dry air and water vapor. The gas pressure P_g is the addition of the partial pressure of dry air P_a and partial pressure of vapor P_v , i.e. $P_g = P_a + P_v$. Both dry air and vapor are considered as ideal gas, obeying

$$P_i M_i = \rho_i R T \quad \text{with } i = a, v \quad (2)$$

where M_i is the molar mass of gas i (mol/kg), ρ_i is the density of gas i (kg/m³), R is the ideal gas constant (J/mol/K) and T the absolute temperature (K). At a certain temperature T , the equilibrium between liquid water and vapor can be expressed through,

$$\ln \left[\frac{P_v}{P_{vs}(T)} \right] = \frac{M_v}{RT \rho_w} (P_l - P_{atm}) \quad (3)$$

with $P_{l,vs,atm}$ standing for liquid pressure, saturated vapor pressure and atmospheric pressure (Pa) respectively, and ρ_w for water density (kg/m³). In the following the THI modeling is deduced on the basis of these assumptions.

2.1. Heat conservation

The heat conservation of partially saturated porous media states that the entropy change rate of REV is equal to the convection heat by fluid flow and the conduction heat by temperature gradient. The change rate of total entropy of the REV, S_{tot} (J/m³/K), writes,

$$\dot{S}_{tot} = \frac{\partial S_{tot}}{\partial t} = -[\nabla \cdot (w_a S_a + w_v S_v + w_w S_w)] - \frac{1}{T} \nabla \cdot (-\lambda \nabla T) \quad (4)$$

with

$$\frac{\partial S_{tot}}{\partial T} = \rho_{sk}(1 - \phi) \frac{C_{sk}}{T} + \rho_w \phi s_l \frac{C_w}{T} + \sum_{i=a,v} \rho_i \phi (1 - s_l) \frac{C_i}{T} \quad (5)$$

where $S_{w,a,v}$ stand for the entropies of water, dry air and vapor (J/kg/K), λ stands for the thermal conductivity (W/m/K), $\rho_{sk,w,a,v}$ for the densities of solid skeleton, water, dry air and vapor (kg/m³) and $C_{sk,w,a,v}$ for the heat capacities of solid skeleton, water, dry air and vapor (J/kg/K) respectively.

The two terms at the right of Eq. (4) are respectively convection and conduction terms for heat transfer. The flux of pore water and gas phases in the convection term write,

$$w_w = -\rho_w \frac{k_{int} k_{rl}}{\mu_l} \nabla P_l \quad (6)$$

$$w_{a,v} = -\rho_{a,v} \frac{k_{int} k_{rg}}{\mu_g} \nabla P_g - f(\phi, s_l) D_g^0 \left[\frac{E_a E_v (M_{v,a} - M_{a,v})}{RT} \nabla P_g + \rho_g \nabla E_{a,v} \right] \quad (7)$$

where k_{int} is the intrinsic permeability of porous medium (m²), $k_{rg,rl}$ stand for the relative permeabilities to gas and liquid of porous medium (–), $\mu_{g,l}$ are the viscosities of gas and liquid (kg/m/s), and $E_{a,v}$ are the mass fractions of dry air and vapor in gas mixture (–) with $E_{a,v} = \rho_{a,v} / (\rho_a + \rho_v)$. Note that the density $\rho_{a,v}$ can be expressed in terms of $P_{l,g}$ through Eqs. (2) and (3) and $P_g = P_a + P_v$. The thermal conductivity λ generalizes the conduction properties of different phase ($\lambda_i, i = sk, w, g$), taking the following expression (Fabbri et al., 2008),

$$\lambda = \lambda_{sk} \left(1 + \frac{\phi}{\frac{1-\phi}{3} + \frac{\lambda_{sk}}{s_l \lambda_l + s_g \lambda_g - \lambda_{sk}}} \right) \quad (8)$$

2.2. Fluid transport

The fluid phases include dry air (gas), vapor (gas) and pore solution (liquid). The mass conservation of dry air writes,

$$\frac{\partial m_a}{\partial t} = -\text{div}(w_a) \quad \text{with } m_a = \phi(1 - s_l) \rho_a \quad (9)$$

The conservation of total REV mass, m_{tot} , writes,

$$\frac{\partial m_{tot}}{\partial t} = -\text{div}(w_l + w_v + w_a) \quad \text{with } w_l = -\rho_l \frac{k_{int} k_{rl}}{\mu_l} \nabla P_l \quad (10)$$

with the gas flux $w_{a,v}$ given by Eq. (7). The total mass m_{tot} is the addition of the mass of fluid phases $m_a + m_v + m_l$ and the mass of solid phases in skeleton m_{sk} . Note that the transport of pore solution can induce the dissolution and precipitation of solid phases as well as the ion adsorption onto solid phases. Thus, the solid phases are further divided into the unsolvable phases m_{sk}^{un} , the solvable phases m_{sk}^{so} , the adsorbed ions m_{sk}^{ad} and the solution precipitation m_{sk}^{pr} . Accordingly, the total mass m_{tot} writes,

$$m_{tot} = \sum_{i=a,v,l}^{fluid} m_i + \sum_{i=un,so,ad,pr}^{solid} m_{sk}^i \quad (11)$$

with $m_v = \phi_g \rho_v$. In this study, the solid solvable phases refer to cement hydrates CH and C–S–H; the adsorption of ions refers to the adsorbable ion species in sea water and pore solution; the solution precipitation refers to the formation of Mg(OH)₂ (MH) due to migration of Mg²⁺ from sea water to pore solution. Thus these mass

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