飛来塩分シミュレーションおよびコンクリート内拡散モデル

[Aerosol Chloride Simulation & Chloride Ingression Model]

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Abstract

According to the Japan Coastal scenery, the variety of chloride attacks by typhoon in the Pacific Ocean induced aerosol chlorides formation along east coast and windy condition in winter season along Japan Sea coastline. Many structures were detected the damage due to chloride attack on bridge structures constructed in land. Dealing with this problem, a systematic life-span simulation limited by the initiation of steel bars corrosion is established for the structural degradation. The degradation of bridge structures is due to the aerosol chlorides ingression in concrete induced corrosion and crack. Thus, the mechanism of aerosol chlorides formation, transport and ingression in concrete is systematically purposed by taking the environmental loads, structural layout and concrete properties into account. During typhoon periods, the wave height and wind speed are dramatically large which results to a large amount of aerosol chlorides transported to the structural members at a long distance. 2-D sea salt aerosol (SSA) particles with height-distance distribution are proposed at the wave breaking location. The SSA particles for the products generally contain the distribution in the range of 1-300μm diameter. SSA particles transport along-wind flow considering the gravitational sedimentation and turbulent vertical eddy diffusivity. SSA particles are transported and accumulated on the surface of structure. Rain effect on the surface chloride dissolution on the front girder and along rain drainage path is also taken into account. The SSA penetration in concrete is referred to the Fick's 2nd Law of diffusion. If the limitation of chloride threshold at the steel bars position were defined, the initiation of steel bars corrosion for each member would be predicted. This model aims to predict the performance of the existing structures in Japan and to estimate the serviceability for any structures.

Introduction

The sustainability in design is therefore important for asset management on the optimization of materials, total cost against with long-life serviceability. The performance-based simulation and design contributes to the life-span prediction of a structure under severe environment. The performance-based simulation of bridge structures under marine environment is mentioned in this research. The analysis of structural deterioration is depending on the process of aerosol chloride formation and transportation, aerosol chloride ingression, steel bars corrosion and rust induced crack, respectively. The research is divided into three categories, 1) aerosol chloride formation at the seashore, 2) aerosol chloride transportation, and 3) chloride ingression in concrete [3,5].

Model of Life-span Simulation

1) Aerosol chloride formation at the seashore

The first step of systematic simulation starts with the aerosol chlorides formation. The weight of airborne chlorides is presented in a height distribution according to four main parameters of breaking wave height, wind speed, wind directions and breakwater. However, the breaking wave height at the surf zone is calculated based on the wave transformation from the transition zone to seashore. The wave height transformation and the energy dissipation in the shallow water zone play the necessity to define the wave height during breaking. Plenty of models on wave transformation were purposed in singular wave approach and spectral wave approach. In this paper, the singular wave approach which means a sinusoidal wave with the significant wave height ($H_{1/3}$) is applied. $H_{1/3}$ commonly represents the wave height as provided by the Japan Meteorological Agency (JMA). The wave energy conservation is applied to explain the mechanism of wave transformation in this paper as shown [1-3],

$$\frac{\partial(E.c_g \cos\omega - E_f - E_t)}{\partial x_i} = -D_B \qquad (1)$$

where, E is the wave energy density, c_g is the group velocity which is proportioned with the wave phase speed, ω is the mean wave diffraction angle, x is the distance in cross shore direction, E_f is friction energy loss, E_t is tearing loss and D_B is the energy dissipation rate in the surf zone.

The amount of airborne chlorides generated at a low level is large and decreases in a high level. A proper method is to propose the aerosol chlorides distribution in the air by the power function as;

$$W_{h(t)} = \gamma[a h_{air}^{\alpha_1} + b].r_{wind} \qquad (2)$$

$$a = -\alpha_2 \cdot \frac{b}{3.5} \qquad (3)$$

$$b = \alpha_3 \times (\frac{U^3}{10}) \times H_b^2 \times [0.450e^{0.025T}] \qquad (4)$$

where, $W_{h(t)}$ is hourly aerosol chloride content ($mg/dm^2/hr$). h_{air} is the reflected height from ground (m). U is wind speed at 10m height at seashore. a is particles dispersion factor. b is amount of droplets on ground. H_b is breaking wave height (m) calculated by the wave propagation. γ is salt concentration ratio = 1.0 at 3% salt concentration. α_1 is the functional height coefficient (~0.7). α_2 is 1.0 if none of breakwater is involved. α_3 is 0.75 for sandy beach. r_{wind} is 1.0 if a wind direction could transport the airborne particles from seaside, otherwise it is defined as null. T is sea surface temperature (°c) affecting sea surface viscosity.

Breaking wave starts from wave crest and increases to overall breaking while it is entering the shoreline. The weight of aerosol chlorides in x-distribution is proposed as a proportional to the area under the standard normal distribution (N_{dist}) and the distance of wave breaking initiation (x') is assumed z = -3.0. At breaking of wave, SSA size distribution has also commonly been reported that none of formulation is standardized. In this paper, the particle size distribution is idealized as circular relation with the spume drops (d_i) in the size range 0-300 μm. Total distribution of aerosol chloride content is illustrated in **Fig.1**.

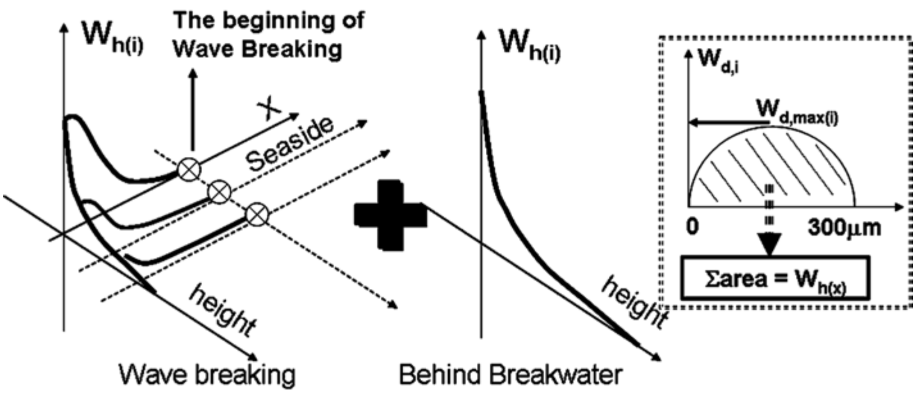

Fig.1. Superposition method for aerosol chlorides formation with height, distance and particle sizes distribution (d_i = 0-300 μm) by wave breaking and breakwater

2) Aerosol chloride transportation [5]

In this paper, only spume droplets are mentioned on the influence to the chloride attack of structures. The spume droplets are large in size which the sedimentation is rather important than the particles diffusivity. The mass equilibrium of each particle is proposed in 2-dimensional free space movement including the eddy diffusion from the turbulence of wind flow as shown in **Eqs.5-6**. The aerosol chlorides transport is modeled by simulating the movement of an individual particle. The total amount of aerosol chlorides at a certain height and distance ($W_{h,x}$) can be obtained by integrating the amount of all particle sizes by **Eq.7**.

$$\frac{\partial W_{d,h,x}}{\partial t} + U\frac{\partial W_{d,h,x}}{\partial X} + v\frac{\partial W_{d,h,x}}{\partial h_i} = D_{eddy}\frac{\partial^2 W_{d,h,x}}{\partial h_i^2} \quad (5)$$

$$D_{eddy} = (5\times 10^{13})\, d_i^4 \quad (6)$$

$$W_{h,x} = \zeta\,\eta.\int_{x'}^{0}\int_{0}^{300} W_{d,h,x}\, dd_i\, dx \quad (7)$$

where, $W_{d,h,x}$ is weight of aerosol chlorides formed in a height and distance of a single particle size (μg/m^2/sec). v is vertical velocity (uplifted velocity – terminal velocity), which the terminal velocity of particles were purposed by Clift et al [18]. The compressible wind flux in a specific landscape can be computed by the Navier-Stoke's Equation. U and v could be simply assumed a constant value for free-space simulation. D_{eddy} is eddy turbulence represented by eddy diffusion coefficient (dm^2/s) which depends on particle size. In the surface layer, the dominant stresses are due to turbulence and are nearly independent of height; D_{eddy} is referred to as the constant value with height of a few tens of meters. According to the individual particle movement assumption, the degree of eddy diffusion is related with the particles size diffuse in the air (bigger particle, larger chloride ions composition). $W_{h,x}$ is total weight of aerosol chlorides at a certain height and distance from seashore. ζ is the SSA reduction factor due to the deposition on the obstacles along the transportation path. η is the coefficient of SSA deposition on a structural member due to structural shape. The girders and slab surfaces might not have the same amount of SSA deposition due to the wind stream path under the bridge. Vortex streets might be one of the factors to cause the variation of SSA deposition. The wind flow characteristic passing under the bridge is varying with the girder height (h_g) to slab span (w) ratio. The obstacle and structural member impacts on the deposition of SSA particles are neglected in this paper (ζ and η =1.0), because the mechanism is still unknown.

3) Chloride ingression in concrete

The aerosol chlorides transported to surfaces of structural members ingress into concrete time-dependently described by Fick's 2nd Law of diffusion. The aerosol chlorides transported to the structure member which is calculated from above models, is the initial chlorides penetrating through concrete. The free chlorides flux movement penetrated into concrete by diffusion and advection. For indoor structures, the advection flux of bulk water movement is neglected due to the gradually change of saturation in concrete. During raining, the surface chloride is dissolved with the drainage flow. Rain causes the reduction of the total surface chlorides ingress in concrete and prolongs the steel bars corrosion time. Thus, rain or water flushing method on the structure might be a simple method to prolong the structural life. This statement can be proved by the chlorides diffusion equation including rain effect as follows,

$$\frac{\partial C_{free(x,t)}}{\partial t} = \frac{\partial F_{(x,t)}}{\partial x} \quad (8)$$

$$F_{(x,t)} = D_{(t)}.[\frac{C_{free(x,t)} - C_{free(x+1,t)}}{dx}] \quad (9)$$

$$D_{(t)} = D_{cl}\,\phi_{pore}.S.e^{[2285.(\frac{1}{293}-\frac{1}{(273+T_k)})]} \quad (10)$$

$$F_{(0,t)} = C_{free(0,t)}\,.\,dt \quad (11)$$

where, $C_{free(x,t)}$ is free chloride concentration at a distance x and time t (mol/l). $F_{(x,t)}$ is flux of free chlorides movement. $D_{(t)}$ is diffusion coefficient of free chloride (cm^2/day). D_{cl} is diffusion coefficient of chloride ions in pore water (=0.0259cm^2/day]. ϕ_{pore} is ratio of pore volume in a unit of concrete. S is degree of saturation (=1.0 for saturated pore). T_k is concrete temperature (°c) which affects to the diffusivity as referred to the Arrhenius's Law. $F_{(0,t)}$ is flux from aerosol chloride adsorption on concrete surface. Free chloride concentration could be computed as referred in Maruya et al [6]. $C_{free(0,t)}$ is the amount SSA on surface of concrete ($W_{h,x}$) or the dissolution of surface chlorides by rain which is -1.9x10^{-6} mol/l.day [4] at a specific time.

Experimental Work

In the simulation, the environmental data of wind and wave in year 2003 from Japan Meteorological Agency; JMA is represented as annual cycle of hourly inputs in the calculation. The high aerosol chloride contents appear during the typhoon no. 2, 4, 6, 7, 14 and 17 as shown in **Fig.2**. This leads us to understand the main aerosol chlorides are produced dramatically according to high swell and windy conditions. The amount of SSA is dependent with the severe level of each typhoon including the direction of wind-flux. This affirmation is strongly recommended that the numbers of typhoons should be mainly performed a function in the macro-scaled SSA estimation. The aerosol chloride deposition on concrete surface is considered as the initial chloride ions flux. The 1-year aerosol chlorides simulation is used to calculate the surface chloride content and distribution in concrete of Ananai Bridge at 37 years old. The simulation results are illustrated in **Fig.3** which is compared with the experimental data in **Fig.4**. The estimated surface chloride content is 9.2kg/m^3 at 37 years which comparatively precise with the maximum observed data at bottom-girder no.2 and front-girder no.3-5. In the simulation of chloride ingression including rain effect, the surface chloride dissolution is taken into account for raining days. The raining duration (> 5mm/day) is totally counted as 76 days in year 2003, same proportion as 1-day wet to 5-days dry. The simulated result is shown that the surface chloride content is dropped to the level of 3.74 kg/m^3. This result could be compared with the measured data from the front-side of the first girder which subjects to rainfall or drainage path. The simulation shows overestimation of rain effect which might be thought as the effect of roof by top flange.

Conclusion

This life-span simulation indicated as time of corrosion initiation is proposed in a systematic calculation of wave transformation and breaking, SSA formation, transportation, and ingression into concrete. Each mechanism doesn't only depend on the concrete strength and covering, but also the environmental characteristic of wind/wave, landscape, temperature, pressure and etc. Especially during typhoon attack; windy condition, high swell, high temperature season and low in atmospheric pressure are cumulative circumstance to create large amount of aerosol chloride and deposit on structural surface. Total amount of aerosol chloride deposition is equaled with the amount of chloride distributed along the covering depth. In this free-space transportation model, an average aerosol chlorides distribution at a certain distance can be computed. The variation of surface chloride contents of bridge members is due to aerosol chloride particles moving under vortex shedding. Unfortunately, this phenomenon is not well understood at this moment, thus the further work on this subject is truly necessary. Furthermore, the aerosol chloride ingression into concrete is simply expressed in Fick's 2nd Law of diffusion considering the coupling of bound and free chlorides. Finally, a simple estimation of chloride distribution in concrete at any ages can be succeeded in order to indicate time of corrosion initiation as threshold limited serviceability.

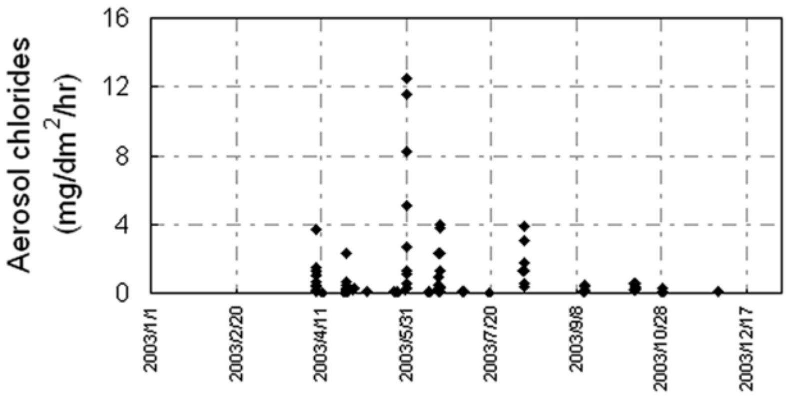

Fig.2. 1-year effective SSA content at Ananai bridge girder level

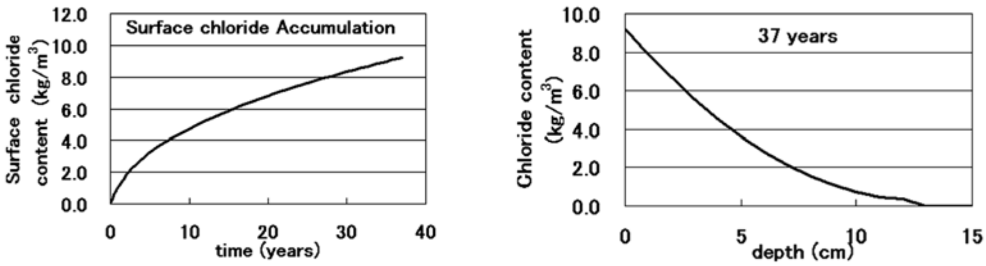

Fig.3. Estimated surface chloride concentration and chloride distribution (kg/m^3) at 37 years simulation

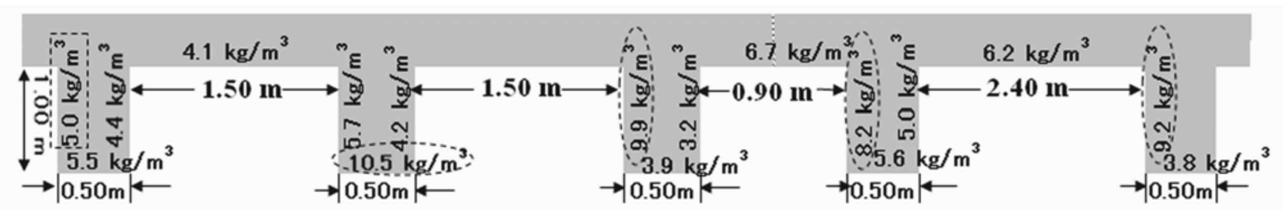

Fig.4. Structural monitoring on surface chloride contents of Ananai Bridge (kg/m^3) after 37 years

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