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Evaluation of Sea Salt Amounts on I-shaped Bridge Girders Using WRF and CFD

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Abstract

It is necessary to evaluate the amount of airborne sea salt adhering to each structural member to achieve effective maintenance of a bridge. In this study, the authors sought to propose a method to estimate salt conditions on I-shaped bridge girders without on-site observation. The estimation was based on airborne sea salt concentrations and wind conditions obtained by a mesoscale meteorological model (WRF), and a steady flow of wind around the cross-section of the bridge by a computational fluid dynamics (CFD) technique. The WRF model is required to evaluate salt conditions at arbitrary locations in a wide area without on-site observation. The estimated salt amounts adhering to bridge girders showed the same tendency with the observed ones in distribution on the sea-side surfaces of the webs, but not on the cliff-side surfaces. Additionally, the relationship between the amounts on the upper and lower surfaces of the bottom flanges was reproduced. However, the salt amounts were overestimated than the other values; the observed values, and the estimated ones using the data from the on-site observations as input. Additional CFD calculations are necessary to consider the complex terrain-affected wind for improving wind speeds at the bridge site and the salt deposition.

Introduction

The deterioration of bridges has become an important subject in Japan. The percentage of bridges aged 50 years or older will reach 67% by 2033 [7]. Thus, a great deal of attention has been paid to the durability of bridges. Because Japan is a mountainous country and surrounded by sea, infrastructure is concentrated within coastal areas and are likely to suffer corrosion of steel components due to airborne sea salt particles. Therefore, it is important to accurately evaluate airborne sea salt concentrations and the salt amounts on structural members of a bridge for effective maintenance.

Thus, many studies have sought to estimate salt conditions of bridges using a numerical simulation [1, 10], and a wind tunnel experiment technique [4]. The authors have also tried to predict the amounts and distribution of salt on I-shaped bridge girders [9].

However, even if it succeeds to develop an accurate estimation method for the amounts of salt, it will not be easy to conduct long-term predictions as long as meteorological data and airborne sea salt concentrations are required as input. Generally, it is also not easy to acquire those data for a long term such as several decades by on-site observations. Moreover, a number of bridges in a wide area should be maintained and managed simultaneously by local governments. Thus, it is preferable that each bridge be managed without on-site observation or monitoring to save their budget.

In this study, the authors sought to propose a method to estimate the amount of salt on each member of individual I-shaped bridge girders without on-site observation. A mesoscale meteorological model was used to obtain airborne sea salt concentrations and meteorological data. Additionally, a computational fluid dynamics (CFD) technique was employed to calculate a steady flow of wind around the cross-section of the study bridge. On the basis of these results, the authors estimated the amounts of salt on each member of the bridge girders and discussed the validity of the calculation.

Study bridge

Figure 1 shows the road bridge in Wakayama prefecture, Japan, that was assessed in this study (33.52°N, 135.54°E). As shown in figure 2, the study bridge is near to a shoreline facing the Pacific Ocean and at ~8 m elevation [3]. Figure 3 shows the I-shaped cross-section of the girders. The bridge axis is in a north-northwest to south-southeast direction. Because of the surrounding topography, the prevailing wind direction is from the west or west-southwest, that is the sea side. The bridge length is 50 m and the main span length is ~38 m. For this bridge, airborne sea salt concentrations, wind direction, wind speed, precipitation, and salt amounts on each structural member have been measured every 1–3 months. To obtain airborne sea salt concentrations, the tubular collecting device (TCD), developed by the authors, was used. The TCD has a total length of 1.0 m and a diameter of 100 mm. 10 gauze layers are in the middle part to collect sea salt particles entering the inside of the TCD [9].

Figure 1. Exterior of the study bridge with three steel I-shaped girders.

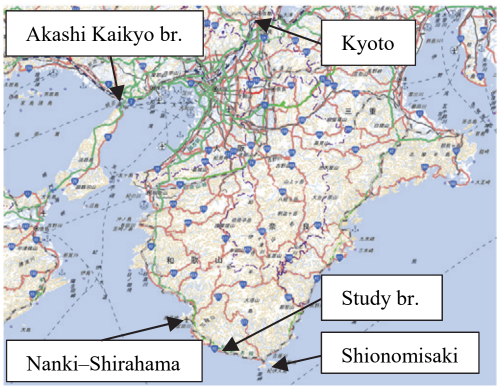

Figure 2. Location of the study bridge [2].

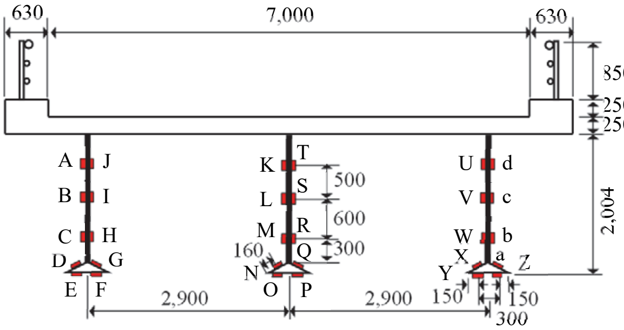

Figure 3. Cross-section of the study bridge and measurement points for salt amounts (A–d).

Algorithm for calculating amount of airborne sea salt on bridge girders

Figure 4 shows the algorithm for calculating salt deposition on each structural member at 10-min intervals. The procedure in each interval is explained as below. First, the approaching wind speed, V_{0i}, wind direction, D_{0i}, and airborne sea salt concentrations, C_{0i}, near the study bridge obtained by a mesoscale meteorological model were used as inputs. Second, the steady wind velocity field around the cross section of the study bridge, obtained by CFD simulation, was used to evaluate wind speed near a surface of each structural member. The approaching wind speed in this simulation was set to 2 m/s. Assuming that the flow pattern around the bridge would hardly depend on the wind speed, the steady flow field for an arbitrary approaching wind speed can be evaluated by considering the ratio of 2 m/s and the approaching wind speed in each 10-min period [9]. Finally, the obtained wind velocity field and airborne sea salt concentration were evaluated with respect to the amount of salt adhering to a surface, Q_i. Additionally, the washing-out effect due to raindrops was applied to the outer members of the study bridge, A–D and a–d, when precipitation was observed [9]. The procedure above was conducted repeatedly during the observation period of 1–3 months to compare with the observed salt amounts. Details of each procedure are given in the following sections.

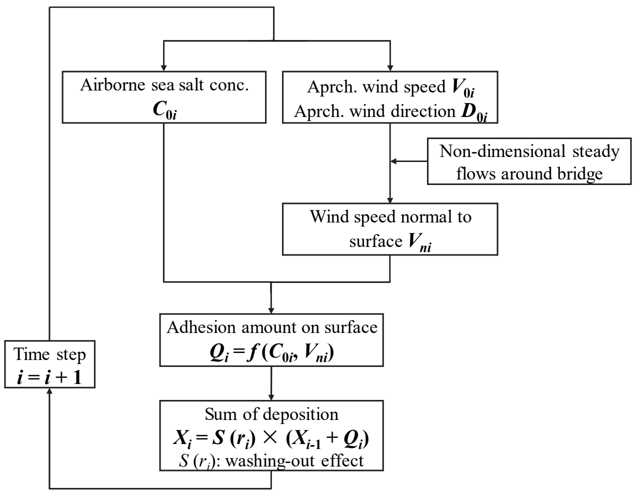

Figure 4. Calculation algorithm for sea salt amounts adhering on surfaces.

Calculation of airborne sea salt concentrations and meteorological data using WRF

A mesoscale meteorological model is an effective tool to acquire airborne sea salt concentrations as well as meteorological data, such as wind speed, wind direction, and precipitation, without on-site observation. Additionally, because it can calculate those data for arbitrary locations in a wind area at the same time, it will contribute to simultaneous maintenance and management of many bridges by local governments. In this study, the Weather Research and Forecasting model, WRF [14], was introduced to obtain meteorological data and airborne sea salt concentrations at the study bridge site and some other locations.

Figure 5 shows the computational domain for the WRF calculation. The study bridge is located at the centre of this domain. The two-way nesting system was employed with the three domains, the respective size (and the grid size) of which were 621 km × 621 km (9 km × 9 km), 207 km × 207 km (3 km × 3 km), and 63 km × 63 km (1 km × 1 km). Thus, the number of horizontal grids for each domain is 69 × 69, 69 × 69, and 63 × 63. Additionally, the number of vertical grids are 29 for all the domains. Dataset of the Mesoscale Model Grid Point Value (every 0.05° × 0.05° and 3 hours) [6], the Final Operational Global Analysis (every 1° × 1° and 6 hours) [8], the Global 30 Arc-Second Elevation [13], and the land use mesh (every 100 m × 100 m) [3] was introduced to give the initial and boundary conditions. The physics schemes were determined as shown in table 1. The Global Ozone Chemistry Aerosol Radiation and Transport model (GOCART) was selected for calculating chemical species such as airborne sea salt concentrations. The calculation was conducted for March 15, 2013–March 22, 2014.

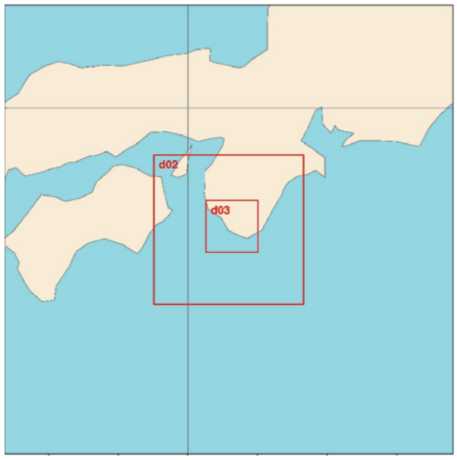

Figure 5. Computational domain for the WRF calculation.

Physics option	Employed model
Microphysics	WSM5
Cumulus Parametrization	Grell 3D
Surface Layer	MM5 similarity theory
Land-Surface	Noah Land Surface Model
Planetary Boundary Layer	Yonsei University Scheme
Longwave Radiation	Rapid Radiation Transfer
Shortwave Radiation	Dudhia scheme

Table 1. Physics options employed for the WRF calculation.

Figure 6 shows comparisons of monthly mean wind speeds at some locations between the WRF simulation and the observed values. The observed wind speeds were obtained by the authors at the study bridge site, and by the Japan Meteorological Agency (JMA) at Nanki–Shirahama and Shionomisaki, respectively [5]. Both the simulations and the observations show that the wind speeds are different among the locations due to the individual surrounding topography. However, the estimated values at the study bridge site was larger than the observed ones, while they were relatively in good agreement in the other locations. This is because the study bridge is located between the Pacific Ocean and a cliff, which generates a complex terrain-affected wind. Additionally, the minimum horizontal resolution of 1 km for the WRF simulation in this study was to coarse to consider the terrain-affected wind sufficiently at the study bridge site. Thus, it is necessary to conduct an additional simulation by using a CFD technique to focus on a smaller scale for improving the estimation accuracy of wind speeds.

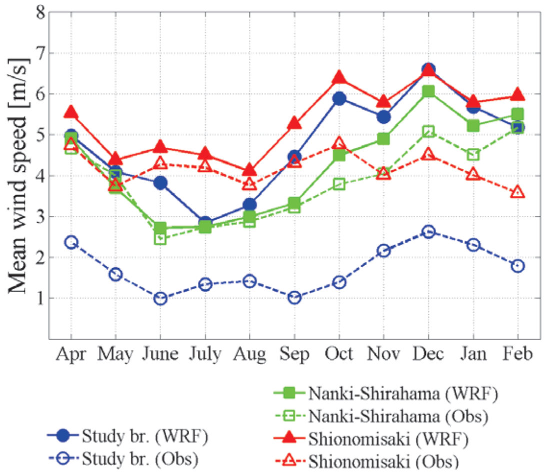

Figure 6. Mean wind speeds obtained by on-site observations and WRF calculations.

Figure 7 shows airborne sea salt concentrations obtained by the WRF simulation at three locations, and those observed at the study bridge site using the TCD. Conducting the WRF simulation, salt environment at some locations were evaluated simultaneously without on-site observation. Thus, acquiring meteorological data and airborne sea salt concentrations by a mesoscale meteorological model, such as WRF, contributes to effective maintenance and management, and to saving budget of local governments. Additionally, the observed and estimated values at the study bridge site are in good agreement, while the estimated one was underestimated in the period of 8/29–10/18. Because a typhoon struck the study bridge site in that period, it might affect the observation accuracy due to a direct entry of seawater into the TCD. Therefore, the accuracy of the concentrations observed by using TCD should be investigated.

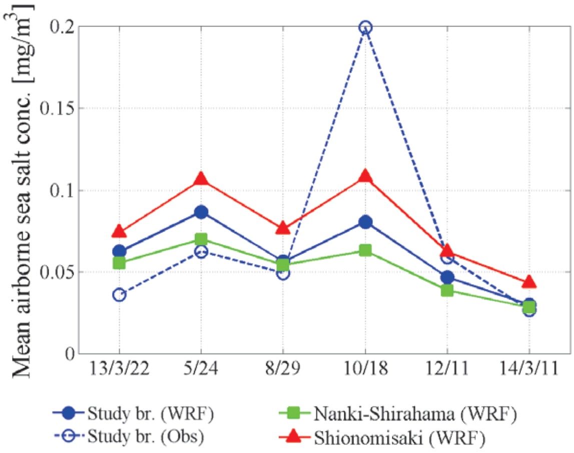

Figure 7. Airborne sea salt concentrations obtained by on-site observations and WRF calculations (month/day).

Numerical simulation of steady flow around the study bridge using CFD

The WRF simulation obtained a macro distribution of wind conditions and airborne sea salt concentrations as above. On the other hand, it is still necessary to evaluate a local environment of wind and salt in the vicinity to each structural member of a bridge. In this study, steady flows around the study bridge were calculated to evaluate the salt deposition on the girders during the observation periods of 1–3 months, because the salt deposition can be affected by wind conditions over a long-time scale, and because deterioration of structural members due to airborne sea salt can be a long-term phenomenon. Additionally, steady flows are easier to calculate than unsteady flows in terms of computational resources. Thus, in this study, airborne sea salt concentrations around the bridge were also supposed to be independent of time.

Steady flows around the study bridge were calculated by three-dimensional calculations, solving the Reynolds-averaged Navier–Stokes (RANS) equations using OpenFOAM (ver. 2.1.0) [9]. Figure 8 shows an example of four different computational domains, considering approaching wind angles relative to the perpendicular line of the bridge axis of 0, 22.5, 45, and 67.5°. '0°' means that the approaching wind is perpendicular to the bridge axis. The I-shaped girders and the simplified surrounding topography were realized in each domain. Their dimensions were 280 m (main flow direction) × 200 m (normal to the main flow direction in the horizontal surface) for 0°, 100 m × 200 m for 22.5°, 100 m × 300 m for 45°, and 100 m × 450 m for 67.5°, respectively. The vertical dimensions were 300 m for all the domains. Additionally, the numbers of grids were approximately 6.89 million, 3.91 million, 4.38 million, and 5.83 million, respectively. Because flows from the west side prevail at the study bridge site due to a cliff near the bridge, flows from the opposite side were not considered in calculating the salt amounts. The collocated grid system and the standard *k–ε* turbulent model were used and a logarithmic law was introduced in the vicinity of wall surfaces.

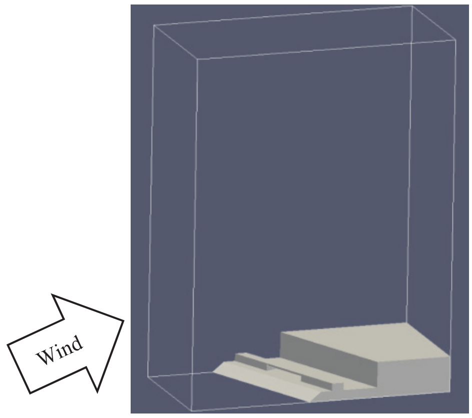

Figure 8. Computational domain for calculating a steady flow around the study bridge in the case of approaching wind angle relative to the perpendicular line of the bridge axis being 22.5°.

Evaluation method for the salt amount on a surface

Airborne sea salt particles, described as airborne sea salt concentrations in this study, adhere to a structural surface due to their inertial and diffusive actions as expressed by equation (1) [9]. The amount of salt deposition due to inertial action can be modelled as the product of the airborne sea salt concentration, C, and the wind speed normal to the surface, V_n. The amount due to diffusive action is described by using the deposition speed, $(D/\pi t)^{½}$, obtained by solving the one-dimensional diffusion equation of salt concentration [12]. The first term also explains the effect of gravity on sea salt particles. The salt deposition is dominated by inertial actions rather than diffusive ones.

$$Q = C(V_n + V_g \cos\theta)\Delta t + C\int_0^{\Delta t}\sqrt{\frac{D}{\pi t}}dt \qquad (1)$$

where C is the airborne sea salt concentration (mg/m^3), V_n is the wind speed normal to and 35 mm away from the surface (m/s), V_g is the terminal velocity of a sea salt particle (m/s), obtained by considering gravity and the air resistance acting on a sea salt particle in calm conditions, θ is the slope of a member to the horizontal line, and D is the coefficient of kinematic viscosity of air (1.5×10^{-5} m^2/s).

Estimation result of the amount of salt and comparison with observations

The amount of airborne sea salt adhering to each member of the study bridge girders, A–d, was estimated and shown in figure 9, following the calculation algorithm shown in figure 4. In each time step (10 min), the authors referred to airborne sea salt concentrations and meteorological data from the WRF simulation, and the steady flows around the study bridge by CFD ("Calc. with WRF" in figure 9). The estimated salt amounts were compared with those using airborne sea salt concentrations and meteorological data from the on-site observations as input instead of the WRF results ("Calc. with observed data" in figure 9). The observed salt amounts on the bridge girders were also shown as "Observation" in figure 9 for the comparison.

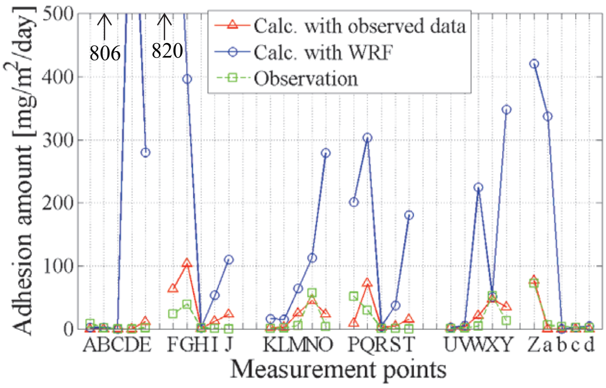

Figure 9. The amounts of salt on each member of the study bridge.

First, "Calc. with observed data" was in good agreement with the observed values [9]. For example, the estimated values showed the same tendency with the observed ones in distribution on the sea-side surfaces of the webs, but not on the cliff-side surfaces. Additionally, the relationship between the amounts on the upper and lower surfaces of the bottom flanges was reproduced. Consideration of the spatial distribution and changes over time of airborne sea salt concentrations and wind should improve the estimation accuracy of the salt amount.

However, the salt amounts obtained by using the WRF results ("Calc. with WRF") were overestimated than the other values; the observed values, and the estimated ones using airborne sea salt concentrations and wind conditions from the on-site observations as input ("Calc. with observed data"). This is because wind speeds were overestimated by the WRF simulation than those obtained by the on-site observations, as shown in figure 6. The overestimation of the salt amounts also highlight necessity of considering the complex topography around the study bridge for the flow simulation. Thus, it is necessary to conduct additional CFD calculations to take into account the complex terrain-affected wind for accurate evaluation of the salt amounts on bridge surfaces and effective maintenance of a bridge.

Conclusions

In this study, the authors sought to evaluate the amount of salt on each member of the I-shaped bridge girders without on-site observation. As a result, by using a mesoscale meteorological model, WRF, and a CFD technique, the amounts of salt on the study bridge girders were estimated only with numerical calculations. Additionally, airborne sea salt concentrations and meteorological data at some locations in a wide area were obtained simultaneously by using WRF. Thus, the method proposed in this study should be effective in maintenance and management of bridges.

However, the estimated amounts of salt were overestimated than the observed ones because of the overestimation of wind speeds calculated by WRF. Thus, it is necessary to consider the complex terrain-affected wind by an additional CFD calculation to complement the WRF result for improving the estimation accuracy of the salt amounts on the bridge girders.

Acknowledgments

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References

[1] Cooperative Research Centre for Construction Innovation, *Learning system for life prediction of infrastructure—Final report.*, *Rep. No. 2005-003-B-12*, Icon. Net Pty Ltd, 2007.

[2] Geospatial Information Authority of Japan, *Digital Japan basic map*, <http://maps.gsi.go.jp/>, 2013.

[3] Geospatial Information Authority of Japan, *Land use mesh*, <http://nlftp.mlit.go.jp>, 2015.

[4] Hasebe, H., Sakakibara, Y., Yamaya, K., Sone, R., Haruki, Y., and Nomura, T., Wind tunnel experiment to estimate the amount of airborne sea salt adhering to the surface of a bridge, in *Proc., 14th Int. Conf. on Wind Engineering: ICWE14*, International Association for Wind Engineering: IAWE, 2015.

[5] Japan Meteorological Agency: JMA, http://www.data.jma.go.jp/obd/stats/etrn/index.php, 2015.

[6] Japan Meteorological Business Support Center, *Mesoscale model grid point value: MSM-GPV*, http://www.jmbsc.or.jp/jp/online/file/f-online10200.html, 2017.

[7] Ministry of Land, Infrastructure, Transport and Tourism, *Efforts for prevention and preservation*, <http://www.mlit.go.jp/road/sisaku/yobohozen/yobo1_1.pdf>, 2013. (in Japanese).

[8] National Centers for Environmental Prediction: NCEP, *Final Operational Global Analysis: NCEP FNL (ds083.2)*, https://rda.ucar.edu/datasets/ds083.2/, 2015.

[9] Noguchi, K., Shirato, H. & Yagi, T., Numerical evaluation of sea salt amounts deposited on bridge girders, *J. Bridge Eng.*, **22**(7), 2017, 04017021-1–13.

[10] Obata, M., Li, G., Watanabe, Y., and Goto, Y., Numerical simulation of adhesion of sea-salt particles on bridge girders, *Struct. Infrastruct. Eng.*, **10**(3), 2014, 398–408.

[11] OpenCFD Ltd (ESI Group), *Open source Field Operation And Manipulation: OpenFOAM.* <http://www.openfoam.com/>, 2004.

[12] Japan Association of Aerosol Science and Technology (editor), *Aerosol gaku no kiso (Fundamentals of Aerosol)*, Morikita Publishing Co., Ltd, 2003. (in Japanese).

[13] United States Geological Survey: USGS, *Global 30 Arc-Second Elevation*, <https://lta.cr.usgs.gov/GTOPO30>, 2015.

[14] The Weather Research & Forecasting Model, <http://www.wrf-model.org/index.php>, 2016.