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ORIGINAL ARTICLE

Estimation of Adherent Chloride Ion Amount on Concrete Surface for Bridge Maintenance by Using GIS Data and Meteorological Data

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Abstract**:** Lots of the bridges in the coastal area are affected by the flying salt from the sea, and it is necessary to evaluate the stability of concrete to know the extent of salt damage. Measurement of the chloride ion content in hardened concrete is one of the standard methods for evaluating the soundness of concrete structures. In addition, the amount of chloride ion adhering to the concrete surface obtained from this measurement is used to predict deterioration of bridges. However, this method will damage the concrete structure because it needs the test cores obtained by drilling the concrete structure. The amount of chloride ions adhering to the concrete surface is determined by the distance from the coast except this measurement in Japan. Additionally, it is considered that the degree of chloride ion adhered differs depending on the environment around the bridge, such as the wind condition, the presence or absence of precipitation, and the distance from the coastline. Therefore, this research aims at developing a system to estimate the chloride ion amount adhering to the concrete surface from the location environment around the bridge which is evaluated by GIS data and meteorological data. The procedures of estimation of adherent chloride ion amount are proposed as follows: Firstly, samples are collected from concrete surface of bridges by using grinder and then the adherent chloride ion amount is measured. Secondly, the location environments of each bridge are evaluated by using GIS data and meteorological data. Finally, estimate and evaluate the amount of chloride ions adhering to the target bridge from the existing calculation model of chloride ion amount. As a verification result, estimation result by using MSM was 0.71 on correlation coefficient of wind speed and correlation coefficient of rainfall amount was 0.69 and 0.71. Difference of adherent chloride ion amount was 4.2mg/m^2 between measured value and estimated value. However, estimation of wave data cans not using intended period and location for seawater aerosol production process. In addition, verification is inadequately because number of collecting sample is low on. Therefore, in order to verify the estimation accuracy of chloride ion amount, it is necessary to collect a sampling at several bridges in a different period.

Keywords: GIS, meteorological data, adherent chloride ion amount

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1. Introduction

Lots of the bridges in the coastal area are affected by the flying salt from the sea, and it is necessary to evaluate the stability of concrete to know the extent of salt damage. Measurement of the chloride ion content in hardened concrete is one of the standard methods for evaluating the soundness of concrete structures. In addition, the amount of chloride ion adhering to the concrete surface obtained from this measurement is used to predict deterioration of bridges. However, this method makes damage the concrete structure because it needs the test cores obtained by drilling the concrete structure. Without this measurement, in Japan, the amount of chloride ions adhering to the concrete surface is determined by the distance from the coast. However it is considered that the degree of chloride ion adhered differs depending on the environment around the bridge, such as the wind condition, the presence or absence of precipitation, and the distance from the coastline.

1.1 Objectives

This research aims at developing a system to estimate the chloride ion amount adhering to the concrete surface from the location environment around the bridge, which is evaluated by GIS data and meteorological data. Therefore, GIS data and weather data are used to reproduce the environment around the bridge. The final goal is to make clear the strength of a correlation between the estimated amount of attached chloride ion and the bridge deterioration situation.

2. Methodology

Procedure of this study is as follows: Firstly, samples are collected from concrete surface of bridges by using disc cutter and then the adherent chloride ion amount is measured as data for verification. Secondly, the location environments of each bridge are evaluated by using GIS data and meteorological data. Finally, estimate and evaluate the amount of chloride ions adhering to the target bridge from the existing calculation model of chloride ion amount. In this study, target bridge is the Monobe-ohashi Bridge in Kochi prefecture, Japan. This bridge is constructed in 1976 by Kochi prefecture and bridge length is about 530 m. Figure 2.1 shows location of the Kochi prefecture and Figure 2.2 shows location of the Monobe-ohashi Bridge.

Figure 2.1 Location of the Kochi prefecture

Figure 2.2 Location of the Monobe-ohashi Bridge

2.1 Measurement of chloride ion content from samples of concrete surfaces

2.1.1 Material sampling from concrete surface

The sample of concrete surface was collected 10 grams by using a disc cutter. Figure 2.3 shows appearance of the disc cutter.

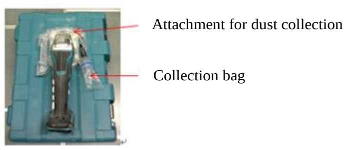

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Figure 2.3 Appearance of disc cutter

Samples were collected from all faces of pier. In addition, the height of collection position is 1.5 to 2-meter high from ground and the size is 50 square centimeter. Figure 2.4 shows collection position of pier.

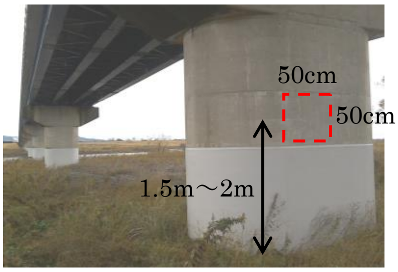

Figure 2.4 Collection position

Estimation of collecting depth in material sampling is the most important. In this study, depth of material sampling is estimated using following equations (1).

$$d = \frac{S_{total}}{2.3 \times A} \qquad (1)$$

d = depth of material sampling (mm)

S_{total} = *total amount* of material sampling (g)

2.3 = weight per unit volume of concrete (g/cm^3)

A = collection area (cm^2)

2.1.2 Measurement of chloride ion content

The amount of chloride ion was measured by the method called "measuring of the total salt content in hardened concrete" according to Japanese Industrial Standard (JIS). In this method, the amount of chloride ion was computed by multiplying concentration of chloride ion obtained from coulometric titration by weight per unit volume of concrete. Figure 2.5 shows an appearance of instrument for determining concentration of chloride ion.

Figure 2.5 Appearance of instrument for determining

The unit of chloride ion content is weight per unit volume. Therefore, it was necessary to convert weight per unit volume to weight per unit area. Chloride ion content was multiply by depth of material sampling. Figure 2.6 shows conceptual diagram of the conversion.

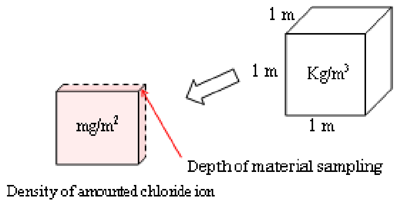

Figure 2.6 Conceptual diagram of conversion.

2.2 Evaluation of location environment of the target bridge by GIS data

In this study, we estimated the geographical conditions of target bridge such as shortest distance, cross-section view and land cover by using GIS data. Shortest distance and cross-section view were used for estimating transportation distance and height of the flying chloride ion. Land cover was used for correcting wind speed and wind direction.

2.2.1 Distance from coastline to bridge

The shortest distance from shoreline to the target bridge was calculated using coastline data, which is one of the digital national land information by Ministry of Land, Infrastructure, Transport and Tourism. The shortest distance from the location of the target bridge is calculated by extracting the coordinates of coastline. Figure 2.7 shows the shortest distance from coastline to target bridge.

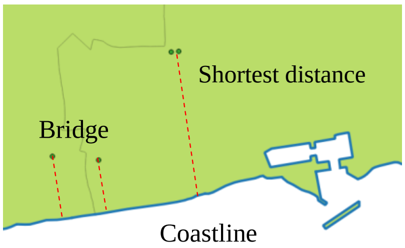

Figure 2.7 Shortest distance from coastline

2.2.2 Elevation and water depth data

The cross-section view of elevation and water depth along the extended line of shortest distance was drawn by digital elevation model (DEM) by Geospatial Information Authority of Japan and water depth data by Japan Oceanographic Data Center. Both data are grid format data and each grid interval is 10 meters as for the digital altitude model and 500 meters as for the depth of the water data. Water depth data was interpolated 10-meter grid interval and then it is converted to a raster map. Sea-bottom slope was calculated from cross-section view of water depth and used to estimate chloride ion amount of emergence. Figure 2.8 shows elevation and water depth data.

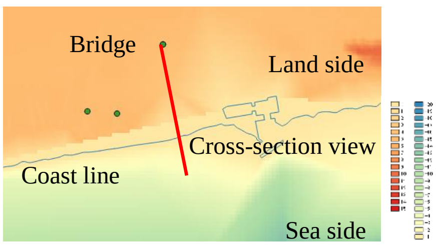

Figure 2.8 Elevation and water depth data

2.2.3 Land cover data

Wind speed is changed by roughness degree of surface, and it can be represented by state of land cover. Therefore, it is necessary to calculate the area present in each of land cover categories around the bridge. The aggregation area of land cover categories was 100 meter buffer along a center line of bridge. The land cover categories of the highest percentage of area were represented as land cover around the bridge. Figure 2.9 shows conceptual diagram extracted area from land cover.

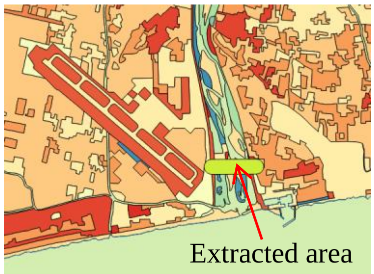

Figure 2.9 Extracted area from land cover

2.3 Evaluation of location environment of the target bridge by Meteorological data

In this study, we estimated the meteorological conditions around target bridge such as wind speed, wind direction and rainfall amount. Wind speed and wind direction were used for estimating amount of transportation and rainfall amount was used for estimating presence or absence of transportation of chloride ion. In addition, the hydrographic conditions at coast such as breaker height and breaker depth were estimated for calculating amount of emergence chloride ion.

2.3.1 Meso Scale Model

Figure 2.10 shows location of meteorological observation stations of Japan Meteorological Agency (JMA) in Kochi prefecture. Wind speed and wind direction are exert influence transportation of chloride ion occurred at the coast. Therefore, it is necessary to estimate wind speed and wind direction at the location of target bridge. However, it is difficult to estimate wind speed and wind direction at the target bridge location because the distant from nearest meteorological observation station to its location is approximately 2.6 km. Therefore, wind speed and wind direction were estimated by using Meso Scale Model (MSM) data. MSM is one of the meteorological forecast models by JMA. Grid interval of MSM data is 5 kilometers at surface and grid point has data such as zonal wind and meridional wind per 1 hour at 10-meter high from ground. Figure 2.11 shows grid of MSM.

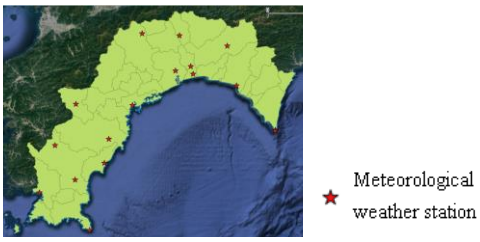

Figure 2.10 Location of meteorological observation stations in Kochi prefecture

Figure 2.11 Grid of MSM

2.3.2 Estimation of wind speed and wind direction

Wind speed and wind direction at target bridge is estimated by arithmetic average from nearest 4 grid points of MSM. The calculation process is summarized by follows equations.

$$D_{GX} = D_X \times we_{ratio} \times rd_{ratio} \quad (2)$$

$$D_{GY} = D_Y \times we_{ratio} \times rd_{ratio} \quad (3)$$

$$V = \sqrt{D_{GX}^{\ 2} + D_{GY}^{\ 2}} \quad (4)$$

$$\theta = \tan^{-1}\left(\frac{D_{GY}}{D_{GX}}\right) \quad (5)$$

D_{GX} = zonal wind of Bridge (m/s)

D_{GY} = meridional wind of Bridge (m/s)

D_X = zonal wind of MSM (m/s)

D_Y = meridional wind of MSM (m/s)

V = correction wind speed (m/s)

θ = correction wind direction

we_{ratio} = ratio of wind effect per azimuth direction

rd_{ratio} = ratio of wind speed

Correction of wind speed by roughness degree was performed using equations (Kobayashi, 1988). The roughness degree type was estimated by aggregation of land cover. Figure 2.12 shows conceptual diagram of power law of wind speed, and Table 2.1 shows boundary layer height and power index according to classification of roughness degree. (Architectural Institute of Japan, 2004)

$$V_{Z1} = V_{R1} \times \left(\frac{Z_1}{Z_{R1}}\right)^{\alpha} \quad (6)$$

$$V_{R2} = \frac{V_{Z2}}{\left(\frac{Z_2}{Z_{R2}}\right)^{\alpha}} \quad (7)$$

$$rd_{ratio} = \frac{V_{R2}}{V_{R1}} \quad (8)$$

Z_i = boundary layer height (m)

Z_{Ri} = elevation (m)

V_{Ri} = wind speed (m/s)

$V_{Z1} = V_{Z2}$ = wind speed at boundary layer (m/s)

α = power index

rd_{ratio} = ratio of wind speed

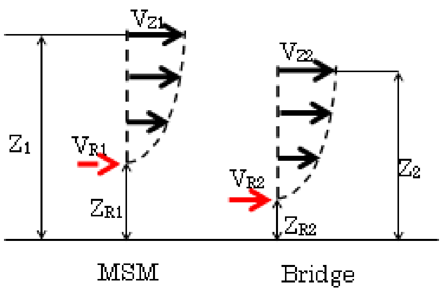

Figure 2.12 Power law of wind speed

Table 2.1 Classification of roughness degree

Roughness degree	Z_i (m)	α
sea and coast area	250	0.10
rural area	350	0.15
housing area	450	0.20
urban area	550	0.27
big city area	650	0.35

Correction of wind speed by terrain was performed using equations. Wind effect value means degree of topographic exposure, and it estimated by using calculation algorithm of SAGA GIS (Boehner, 2009). Figure 2.13 shows map of wind effect by south wind. The red area in this map means it has high ratio of topographic exposure.

$$we_{ratio} = \frac{we_{Bridge}}{we_{MSM}} \qquad (9)$$

we_{ratio} = ratio of wind effect per azimuth direction

we_{MSM} = value of wind effect at grid of MSM

we_{Bridge} = value of wind effect at location of Bridge

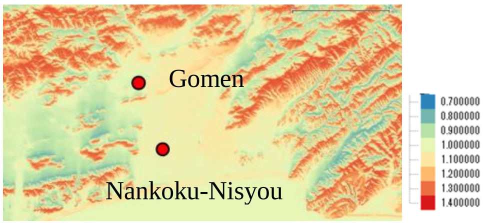

Figure 2.13 Wind effect by south wind

2.3.2 Amount of rainfall

Presence or absence of amount of rainfall is exert influence transportation of chloride ion occurred at the coast, therefore it's necessary to estimate amount of rainfall per mesh of MSM. Amount of rainfall per hour in mesh unit was estimated by arithmetic average from 4 grid points of MSM.

2.3.3 Wave data

Figure 2.1.4 shows location of the wave recorder. Breaker height and breaker depth at coastline are necessary to estimate chloride ion amount of emergence. The breaker height and breaker depth were estimated using the data of significant wave height and wave period by Nationwide Ocean Wave information network for Ports and HArbourS. However, data of significant wave height and wave period are not open to public since January, 2017. Therefore, data of significant wave height and wave period was estimated using those average values of Kochi port in every month of 2016, and breaker height and breaker depth are calculated by computational software.

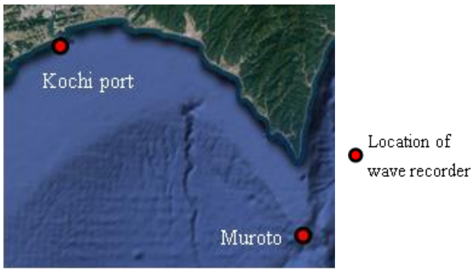

Figure 2.14 Location of wave recorder

2.4 Estimation of adherent chloride ion amount

Calculation model for airborne chloride ion prediction consists of three processes such as seawater aerosol production process, translation process and adhesion process (Kokubo, 2009). Figure 2.15 shows conceptual diagram of the calculation model for estimating amount of adherent chloride ion.

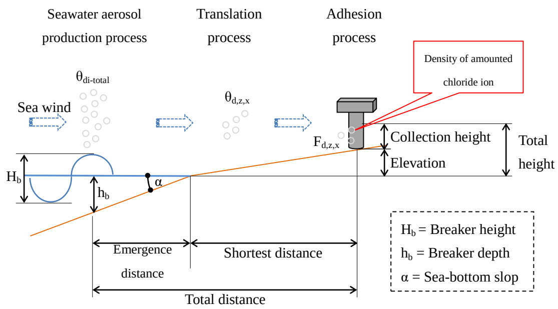

Figure 2.15 Conceptual diagram of the calculation model for airborne chloride ion

In this study, flux of chloride ion, $F_{d,z,x}$ (kg/m²/sec), was converted to density of chloride ion (kg/m^2). It was calculated to chloride ion flux multiply by wind duration time.

2.4.1 Total number of produced seawater aerosol

Total number of produced seawater aerosol can be calculated by Equation (10).

$$\theta_{total} = \delta \cdot \theta_0 \cdot f(H_b) \cdot (1/T) \qquad (10)$$

θ_{total} = Total number of produced seawater aerosol (aerosol/m^3/sec)
δ = coefficient on the place of seawater aerosol production (= 7)
θ_0 = referent number of produced seawater aerosol (aerosol/m^3) (= 1.0×10^4)
$f(H_b) = C \times H_b$
$C = 1, H_b$ = breaking wave height (m)
T = wave period (sec)

2.4.2 Total number of produced seawater aerosol density of diameter

Total number of produced seawater aerosol density of diameter can be calculated by Equation (11).

$$\theta_{d_i-total} = \theta_{total} \cdot \frac{\int_{d=d_i-\frac{\Delta d}{2}}^{d=d_i+\frac{\Delta d}{2}} \frac{1}{d_a} \exp\left(-\frac{1}{d_a} \cdot d\right) dd}{\int_{d=0}^{d=\infty} \frac{1}{d_a} \exp\left(-\frac{1}{d_a} \cdot d\right) dd} \qquad (11)$$

$\theta_{di-total}$ = total number of produced seawater aerosol density of diameter d_i(aerosol/m^3/sec)
d = diameter of seawater aerosol (μm)
d_a = average diameter of seawater aerosol (μm) (= 50)

2.4.3 Amount of transportation of chloride ion

Seawater aerosol number density which reaches on target point can be calculated by Equation (12).

$$\theta_{d,z,x} = \theta_{d-total} \cdot \frac{1}{z_a} \exp\left[-\frac{1}{z_a} \cdot \left\{Z + w_d\left(\frac{X}{U}\right)\right\}\right] \qquad (12)$$

$\theta_{d,z,x}$ = seawater aerosol number density of diameter d at height z and translation distance x (aerosol/m^3/sec)
Z_a = average height of vertical distribution of seawater aerosol (m) (= $6H_b$)
Z = total height (m)
W_d = terminal velocity seawater aerosol of diameter(m/s)
X = total distance (m)
U = wind velocity(m/s)

2.4.4 Conversion from the seawater aerosol number density to chloride ion flux

Conversion from the seawater aerosol number density to chloride ion flux can be calculated by Equation (13) and (14).

$$M_{d_i,z_j,x} = \theta_{d_i,z_j,x} \times M_{d_i} \qquad (13)$$

$M_{d,z,x}$ = amount of chloride ion included in the diameter d_i aerosol (kg/m^3/sec)
M_{di} = amount of chloride ion included in one seawater aerosol(kg/aerosol)

$$F_{d_i,z_j,x} = M_{d_i,z_j,x} \times U \qquad (14)$$

$F_{d,z,x}$ = flux of the chloride ion (kg/m^2/sec)

3. RESULTS AND DISSCUSION

3.1 Measurement of adherent chloride ion and density of amounted chloride ion

Table3.1 shows result of measurement of chloride ion content and density of chloride ion at the Monobe-ohashi Bridge. In this case, Depth of material sampling was estimated 0.3 millimeter. As a result, density fluctuation of chloride ion was estimated 55 mg/m^2 from April 4, 2017 to May 11.

Table3.1 Measurement of chloride ion content and density of amounted chloride ion

Monobe-ohashi Bridge P7	chloride ion content (kg/m^3)					density of chloride ion (mg/m^2)
	East	West	South	North	Average	Average
April 4, 2017	0.26	0.38	0.16	0.30	0.27	82.50
May 11, 2017	0.30	0.81	0.21	0.46	0.45	133.50

3.2 Extracted shortest distance and cross-section view

Figure 3.1 shows extracted cross-section view about Monobe-ohashi Bridge. As a result of extraction, shortest distance was estimated 610 meter and sea-bottom slope was estimated 1:80.

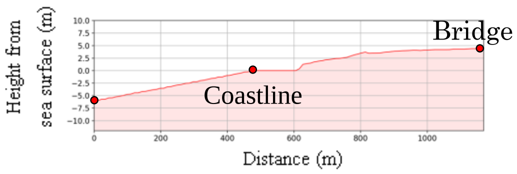

Figure 3.1 Cross-section view

3.3 Aggregation of land cover area and estimation of roughness degree

Figure 3.2 shows aggregation of land cover area around the Monobe-ohashi Bridge. As a result, vegetation was covered 42 percentage of total area, urban area and house was 24 percent and open water is 16 percent. Therefore, highest percentage of classification categories was vegetation and classification of roughness degree type was estimated as rural area.

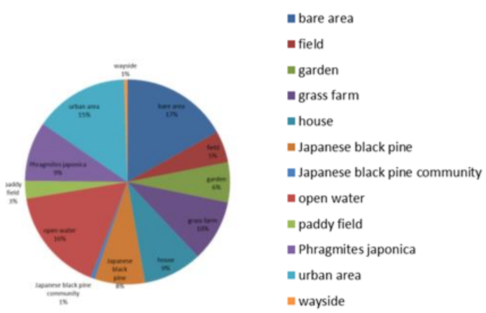

Figure 3.2 Classification of land cover

3.4 Verification of wind effect

Verification of estimated wind effect was carried out by using measurement value of meteorological observation station in Nankoku-Nisyou and Gomen. In this study, we only verified the estimated wind effect of south wind. Firstly, the south wind that was blowing at the same hour in a time span of a year was extracted from measurement value of each meteorological observation station. Secondly, wind effect value in the each meteorological observation station was estimated using GIS every azimuth direction. Finally, correction of wind speed at Gomen was computed by multiplying wind speed at Nankoku-Nisyou by ratio of wind effect. Figure 3.3 shows correlation diagram between measured wind speed and corrected wind speed at meteorological observation station at Gomen. As a result of correlation coefficient was 0.75.

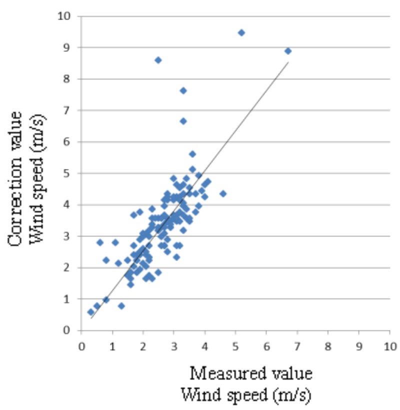

Figure 3.3 the correlation diagram of wind speed between the measured value and the estimation value at Gomen.

3.5 Verification of estimated wind speed and wind direction

Verification of estimated value was carried out using hourly observation value of meteorological observation station at Nankoku-Nisyou in a time span of a month. Figure 3.4 shows the correlation diagram of wind speed between the measured value and the estimation value at meteorological observation station. The correlation coefficient of wind speed is 0.71. Figure 3.5 shows the difference of wind direction, and the horizontal axis represents wind direction error, when the wind direction is represent by 16 direction. About 65 percent of difference of wind direction is in a range of -1 to 1 and the mode is 0. This estimate method of wind speed and wind direction is sufficiently effective.

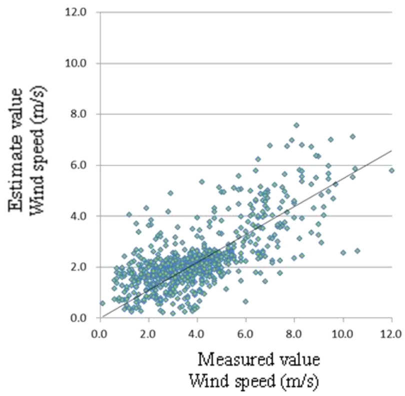

Figure 3.4 the correlation diagram of wind speed between the measured value and the estimation value at meteorological observation station

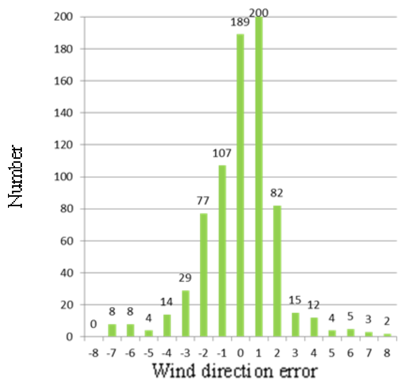

Figure 3.5 Difference of wind direction

3.6 Verification of estimated rainfall amount

Figure 3.8 and Figure 3.9 show correlation diagram of rainfall amount between measured value and estimation value at meteorological observation station.

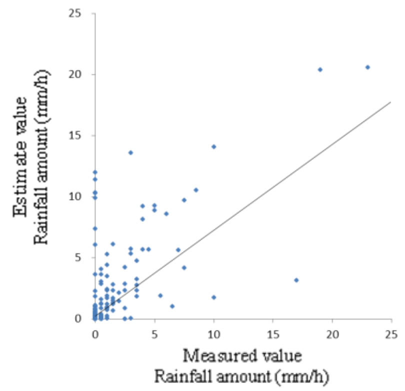

Figure 3.8 Rainfall amount at Nankoku-Nisyou

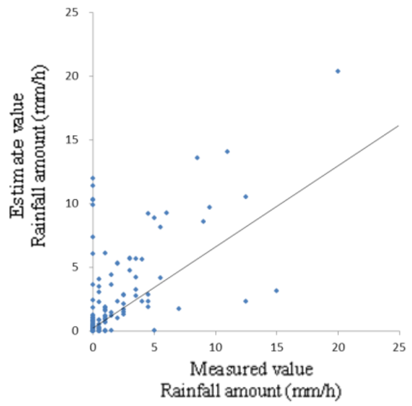

Figure 3.9 Rainfall amount at Gomen

The correlation coefficient of rainfall amount was 0.69 at Nankoku-Nisyou and 0.71 at Gomen.

3.7 Estimation of wave data

Table3.2 shows result of estimation of significant wave height and wave period data by using those average values of Kochi port.

Table3.2 Result of estimation of wave data

estimate value	significant wave height (m)	wave period (s)	wave incidence angle (deg)	offshore wave height (m)	breaker height (m)	breaker depth (m)
April, 2016	0.88	7.1	4	0.96	1.40	1.77
May, 2016	0.75	6.3	23	0.81	1.13	1.43

3.8 Verification of estimated adherent chloride ion amount

Table3.3 shows estimation conditions and result of calculated density of chloride ion. Extraction condition of wind direction is range of sea wind from 101.25 degree to 258.75 degree with no rainfall, and value of wind speed is average out wind duration time. As a result, total density of chloride ion is estimated 55 mg/m^2 from April 4, 2017 to May 11. Table3.4 shows verification of estimated adherent chloride ion amount. As a verification result, adherent chloride ion amount did not show the big difference between measured value and estimated value.

Table3. 3 Estimation conditions and result of calculated density of chloride ion

Estimation data and time	Average wind speed (m/s)	Wind duratiion time (hour)	Density of chloride ion (mg/m^2)	Cumulative total density of chloride ion (mg/m2)
2017/4/5	3.3	13	5.4	5.4
2017/4/6	2.9	8	2.4	7.8
2017/4/6	5.0	1	1.2	9.0
2017/4/7	1.4	1	0.0	9.1
2017/4/8	1.4	2	0.1	9.2
2017/4/13	2.0	7	0.8	10.0
2017/4/13	1.7	1	0.1	10.0
2017/4/14	3.1	13	4.6	14.6
2017/4/15	1.9	8	0.7	15.4
2017/4/16	1.9	9	0.8	16.2
2017/4/17	1.7	2	0.1	16.3
2017/4/18	6.3	2	4.4	20.7
2017/4/18	2.8	5	1.4	22.1
2017/4/20	1.1	11	0.3	22.3
2017/4/21	1.5	10	0.5	22.9
2017/4/22	2.3	8	1.3	24.1
2017/4/23	0.7	1	0.0	24.1
2017/4/23	2.2	12	1.8	25.9
2017/4/24	4.1	7	5.3	31.2
2017/4/25	4.1	4	3.0	34.1
2017/4/25	3.1	4	1.4	35.6
2017/4/25	1.5	3	0.2	35.7
2017/4/28	2.6	9	2.0	37.8
2017/4/29	1.8	3	0.3	38.0
2017/4/30	1.3	1	0.0	38.0
2017/4/30	2.1	9	1.2	39.2
2017/5/1	2.1	6	0.8	40.0
2017/5/2	1.1	1	0.0	40.1
2017/5/2	0.9	2	0.0	40.1
2017/5/2	2.3	11	2.1	42.2
2017/5/3	3.5	10	5.7	47.9
2017/5/4	2.7	11	3.0	51.0
2017/5/5	1.6	10	0.7	51.7
2017/5/6	1.4	9	0.5	52.1
2017/5/7	2.4	7	1.5	53.6
2017/5/8	1.9	7	0.8	54.4
2017/5/10	1.7	10	0.8	55.2

Table3. 4 Verification of density of amounted chloride ion

Monobe-ohashi Bridge P7	density of chloride ion (mg/m^2)	
	Measured value	Estimate value
April 4 to May 11, 2017	+51.0	+55.2

4. Conclusions

In this study, the estimation of adherent chloride ion amount on concrete surface was carried out by using GIS data and meteorological data. As a verification result, difference of adherent chloride ion amount was 4.2mg/m^2 between measured value and estimated value. We estimated the geographical conditions of target bridge such as shortest distance, cross-section view, land cover and roughness degree by using GIS data, and estimated meteorological data around target bridge such as wind speed, wind direction and rainfall amount by using MSM data. Estimation result by using MSM was 0.71 on correlation coefficient of wind speed and correlation coefficient of rainfall amount was 0.69 and 0.71. However, estimation of wave data cans not using intended period and location for seawater aerosol production process. In addition, verification is inadequately because number of collecting sample is low on. Therefore, in order to verify the estimation accuracy of chloride ion amount, it is necessary to collect a sampling at several bridges in a different period.

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