Damage Quantification of Concrete Surface Layers by Semi-Variogram Analysis

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ABSTRUCT

Degradation of concrete surface layers could occur due to external effects, which normally lead to change physical properties. The degree of damage, in most case, evaluated as defects of structural surface. In order to maintenance and management of concrete structures, it is desirable to evaluate not only defects but also the degree of damage. In this study, quantitative damage evaluation of concrete is proposed by applying infrared thermography method and the semi-variogram analysis of geo-statistics. The semi-variogram analysis is a quantitative evaluation method of the special distribution of physical properties. The two damaged concrete water channel walls were examined. The semi-variogram appeared different semi-variance characteristics depending on the damage degree; the damage level could be reasonably quantified with the semi-variance. By evaluating the damage from the semi-variogram analysis using infrared image, the damage of concrete surface layer is quantitatively evaluated.

1. INTRODUCTION

In recent years, early degradation of concrete structures has become a social problem, and necessity of maintenance and repair has increased. In order to verify the effectiveness of maintenance, nondestructive evaluation methods using elastic or electromagnetic waves have been used [1, 2]. However, whether or not the data obtained from the nondestructive evaluation properly represent the entire structure has been rarely discussed. Measured values generally vary with “data dispersion” and “spatial distribution of data”. Data dispersion is evaluated by inferential statistics and frequency distribution. Regarding spatial distribution of data, spatial correlation is evaluated by geo-statistics using semi-variograms [3]. Physical properties of concrete change with the effects of external environment and local damages after being used for many years become overt [4, 5]. In service structures not only the average physical properties but also the local damage data should be evaluated. For data evaluation, spatial distribution of the physical properties should be considered.

In this study, physical properties of concrete walls in different damage conditions were measured by infrared thermography method, and the spatial distributions of the measured properties were evaluated using semi-variogram. The thermal image was divided into 80 sections to show differences in local surface temperature. Relationship between skewness and kurtosis, and semi-variogram were used as statistical indicators. Using these statistical indicators obtained, the characteristics of the concrete wall damage were investigated and the effectiveness of repair was verified. The spatial distribution of thermal characteristics of concrete before and after repair work was also quantitatively evaluated.

2. DAMAGE CHARACTERISTICS AND DETECTION IN CONCRETE WATER CHANNEL STRUCTURES

The concrete materials, which are exposed to water flow, have undergone damages such as wear and component elution. The main causes of the damages are flow of gravel sediment and cavitations. **Photo 1** shows an example of surface damage of a concrete water channel, which has been used for 74 years. The exposed coarse aggregates and reinforcing bars can be observed. In such existing concrete channel walls and bases, which are affected by water flow, exposed local damages are observed. Damage of concrete surface becomes overt with progress of the damage of inner-concrete materials, such as corrosion of reinforcing bars and cracks resulting from changes of external environment, shoddy construction, etc.

In recent years, infrared thermography method, a nondestructive evaluation method using electromagnetic waves has been recognized to be effective for evaluating two-dimensional damage of concrete structures [1]. In infrared thermography method, surface temperature distribution of the structure is measured and damaged areas are evaluated by detecting irregular temperature distribution. This method is effective in detecting regional damaged areas of concrete structures. Regarding damage depth, this method can detect damage from the surface to a depth of about 10 cm, with measurement accuracy varying with moisture conditions of the surface and damage levels [1, 2]. Concrete walls and bases of water channels are generally constructed as linearly continuous structures. Therefore, when damage is evaluated by infrared thermography method, the detection range and the moisture conditions should be considered.

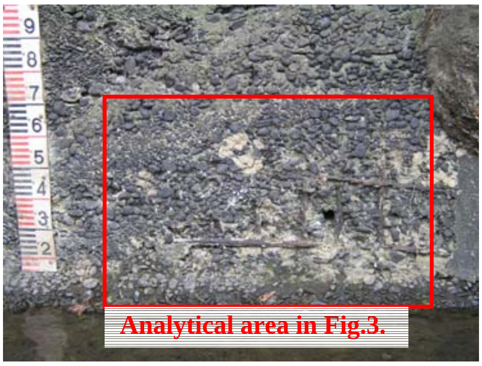

Photo 1 Overview of damaged concrete water channel wall in damaged section.

Photo 2 Overview of non-damaged concrete water channel wall in normal section.

3. ANALYTICAL METHOD

3.1 EVALUATION OF SPATIAL DISTRIBUTION OF PHYSICAL PROPERTIES BY VARIOGRAM

In geo-statistics, data are regarded as occurrences in a random field $Z(x)$ in the domain D. Stochastic variables $Z(x_1)\cdots,Z(x_n)$ at the measuring points $x_1,x_2,\cdots,x_n$ are regarded as measured data and can be applied to geo-statistical method, on the following two hypotheses:

(1) $E[Z(x)] = \mu$

In the target domain, the expectations of variables are constant.

(2) $E\left[\{Z(x) - Z(x+h)\}^2\right] = 2\gamma(h) < \infty$

The expected difference between the variables at two points with a distance of vector h is finite, and can be expressed by a function of h. 2γ is variogram, and γ is semi-variogram. In this study, a semi-variogram model described in Section 3.2 is used to evaluate the spatial distribution. The spatial distribution evaluation method using semi-variogram is a method for quantitatively evaluating temporally and spatially variable physical properties.

3.2 SEMI-VARIOGRAM MODEL

In geo-statistics, semi-variogram model is generally used to analyze spatial dependence of physical properties. Semi-variogram is a graph with lag h, sampling interval on the X axis and semi-variance $\gamma(h)$ on the Y, and used for evaluating the relationship between lag h and semi-variance $\gamma(h)$ (**Fig. 1**). The semi-variance $\gamma(h)$ expresses the degree of variation in evaluated values for $N(h)$, all the combinations of two measuring points with a distance of h.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_{i+h})]^2 \qquad (1)$$

When measurements are conducted at equal intervals on a straight line and the measured values at x_i and x_{i+h} are expressed as $Z(x_i)$ and $Z(x_{i+h})$, Equation (1) can be written as

$$\gamma(h) = \frac{1}{2(n-h)} \sum_{i=1}^{n-h} [Z(x_i) - Z(x_{i+h})]^2 \qquad (2)$$

In this study, the physical properties are considered to be spatially continuous unless concrete walls have local damages. Therefore, concrete walls without local damages, continuous semi-variogram is obtained, as shown in **Fig. 1**. The semi-variance increases with increasing lag and in most cases reaches the maximum at a certain distance. This maximum value is called "sill", expressing the internal variation in data, and the lag at the time of the sill is called "range". A range shows a boundary of spatial dependency. In other words, a range is an extent where data can be interpolated. Semi-variance at lag 0 is called "nugget effect", showing random variations such as experimental errors. Each parameter can be obtained based on the relationship between lag and semi-variance by regression analysis using least squares method. Spherical or exponential models are generally used [6]. In this paragraph, the spherical model used in this study is shown.

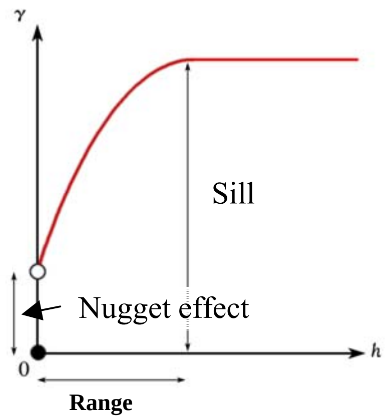

Fig.1 Semi-variogram model.

$$\gamma(h) = C_0 + C\left[\frac{3}{2}\frac{h}{a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right] \qquad (0 < h \le a) \qquad (3)$$

$$\gamma(h) = C_0 + C \qquad (h > a) \qquad (4)$$

Here, C_0: nugget effect, C_0+C: sill, and a: range.

4. MATERIALS AND METHOD

A spatial damage distribution of concrete was measured by thermal images obtained by infrared thermography method. The thermal monitoring was conducted in service concrete water channel walls. These monitored concrete walls were constructed in 1934 and 1961 at Kanagawa prefecture, Japan. The structural conditions are shown in **Table 1**. The monitoring structures were repaired by surface coating method (using material: polyurethane resin) in December 2006. The thermal image was divided into 80 sections to show differences in local surface temperature (**Fig. 2**). The number of one sections data was 960. The measurement was conducted in 15 minutes (heating: 3minutes; radiation: 12 minutes). The meteorological condition in the measurement period was the temperature 20.0 degrees C, and wind velocity 4.21m/s and isolation 0.49kW/m^2 on average.

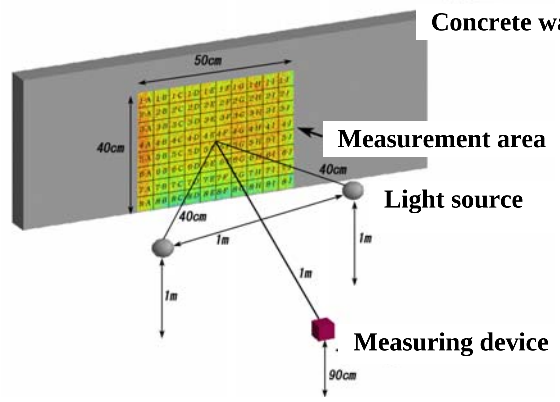

Fig.2 Outline of Infrared thermography monitoring (●: Light source, ■: Measuring Device).

Table 1 Monitoring site properties.

Monitoring site	Construction	Compressive strength (N/mm^2)	Repair work
Damaged section (**photo 1**)	1934	16.2	surface coating
Normal section (**photo 2**)	1961	27.6	non-repair work

5. RESULTS AND DISCUSSION

5.1 THERMAL PROPERTIES OF DAMAGED CONCRETE WALL

Fig. 3 (visible image: **Photo 1**) and **Fig. 4** (visible image: **Photo 2**) show thermal images before heating. It is clearly shown that a damaged section, such as steel being exposed and defect concrete, was heated to a higher temperature. In normal sections, the upper part of the concrete walls marked higher temperature, compared to the lower part of the walls. The surface temperature distribution is shown in **Figs. 5** and **6**. The surface temperature was 21 to 23 degrees C in normal sections, while in damaged sections it was 20 to 30 degrees C, showing a wide variation. It is found that in concrete where damages progress, the surface temperature ranged widely and the microscopic thermal distribution were affected by damage. In order to evaluate local thermal distribution, thermal images were divided into 80 sections and the relationship between skewness and kurtosis was obtained based on statistics values for each section. In the normal sections, the distribution of skewness and kurtosis was centered around 0.0 (**Fig. 7**). In the wear sections, skewness was -0.5 to 1.0 and the kurtosis was -1 to 4. In the sections where steel was exposed, the degree of distortion was confirmed to be higher than in the wear sections. When damaged sections were repaired with surface coating, the distribution of skewness and kurtosis was centered around 0.0 with a slightly larger variation than that for the normal sections. The relationship between skewness and kurtosis revealed that when concrete walls were exposed to water flow, the distribution of the surface temperature ranged wider due to local damages (**Figs. 5** and **6**), which caused the data distribution patterns to change (**Fig. 7**). The sections with surface coating treatment and the normal sections showed the similar distribution, suggesting that the effectiveness of surface coating treatment could be verified by examining the distribution of the surface temperature (**Fig. 8**). It is also

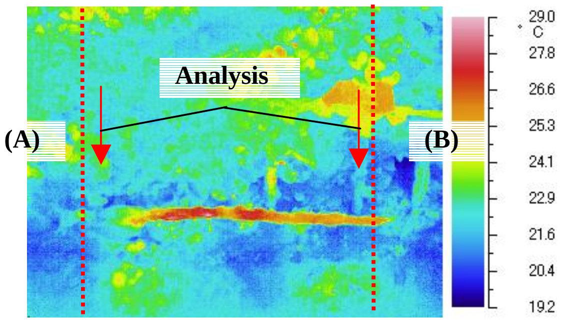

Fig.3 Result of thermal image before heating in damaged section.

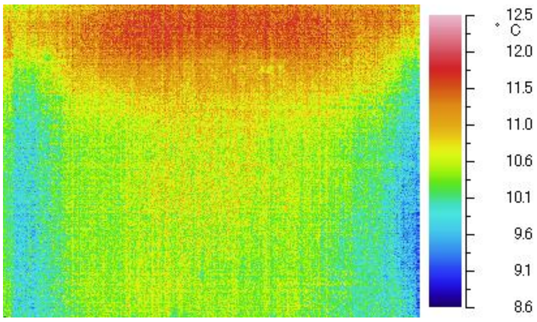

Fig.4 Thermal image (Normal section).

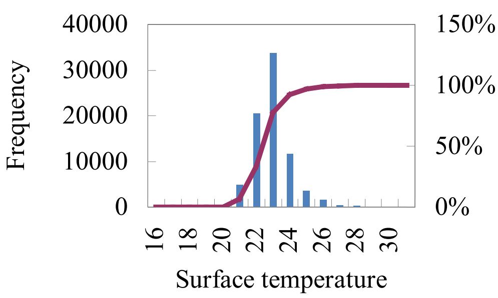

Fig.5 Surface temperature (Damaged section).

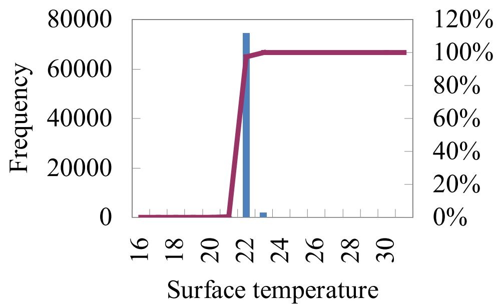

Fig.6 Surface temperature (Normal section).

thought that concrete damage could also be detected effectively as an abnormal section in the spatial distribution of physical properties shown in thermal images.

In this study, the characteristics of spatial distribution of concrete properties were evaluated based on the relationship between semi-variance and lag of semi-variogram model.

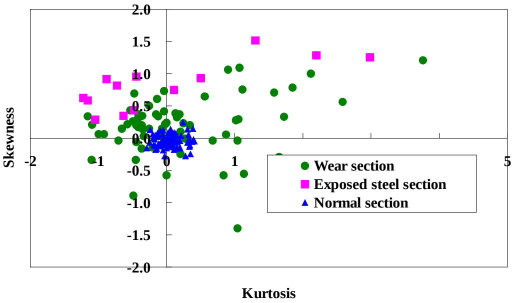

Fig.7 Relation between skewness and kurtosis in damaged portion.

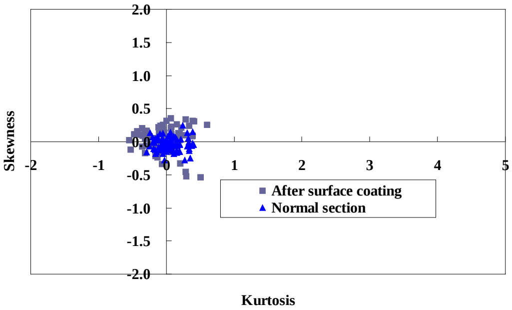

Fig.8 Relation between skewness and kurtosis (After surface coating).

5.2 SEMI-VARIOGRAM CHARACTERISTICS OF THERMAL IMAGE DATA

The primary characteristic of semi-variogram is that it can evaluate spatial dependence of measured data. In Section 5.3, after evaluating characteristics of semi-variogram of damaged sections treated with surface coating, cross-sections of normal sections and damaged sections with treatment are compared. **Fig. 9** shows the semi-variogram of damaged concrete after surface coating treatment. The target area of 40 cm by 50 cm was divided laterally into 10 sections with a pitch of 5 cm, and lag h was set at 5 cm from the top end toward the base for each section. Then, semi-variance $\gamma(h)$ was calculated using Equation (2). The analytic values were evaluated using a spherical model. The nugget effect was assumed to be 0.0. The distribution of the semi-variances $\gamma(h)$ calculated from the measured values expanded as lag h increased. The semi-variance is an indicator, which shows the degree of variation in evaluated values at a certain distance. A large semi-variance means a large variation in measured values. The analytical result using a spherical model suggested that until lag h was about 25 cm, the physical properties of the damage section treated with surface coating should be spatially dependent. The semi-variogram of the damaged concrete before surface coating is shown in **Fig. 10**. Semi-variance $\gamma(h)$ was calculated for Section (A) with only wear and Section (B)

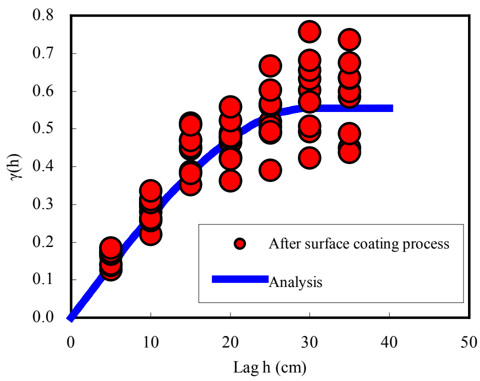

Fig.9 Results of semi-variogram analysis in damaged section treated after surface coating.

with steel being exposed (in **Fig. 3**) in the same manner as in **Fig. 10**. **Fig. 3** shows that semi-variances $\gamma(h)$ varied between 0.38 and 1.56 in Section (A) (**Fig. 3**(A)), showing no clear range, while in Section (B) (**Fig. 3**(B)) $\gamma(h)$ reached between 4.24 and 4.70 at h=5 to 10cm. This is because spatial dependence of thermal image data decreased due to the effect of local concentration of high-temperature sections, such as corroded reinforcing bars. In **Fig. 10**, normal sections showed the similar tendency to wear sections (B). At h=5 to 45 cm, $\gamma(h)$ was 0.01 to 0.04 below the waterline and 0.001 to 0.01 above the waterline where water flow did not affect. From these considerations, it is confirmed by thermal characteristic analysis of concrete walls that intact concrete walls (walls after repair) showed a clear range in semi-variograms. The comparison of local damage sections with normal sections suggests that small lag h could cause $\gamma(h)$ to increase. As a result of the examination, the method suggested in this study, where intact sections and local damaged sections of concrete are compared using semi-variogram, is confirmed to be effective.

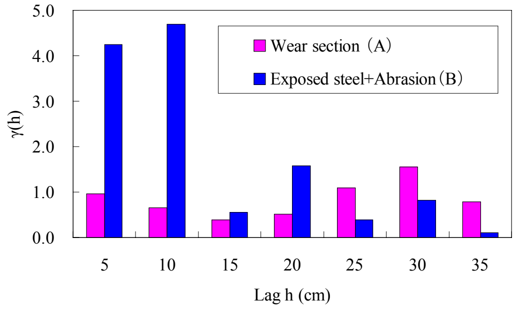

Fig.10 Results of Semi-variogram analysis in damaged section.

Photo 3 Comparison between surface coating and non-repaired conditions in monitoring water channel.

5.3 QUANTITATIVE EVALUATION OF REPAIR EFFECTIVENESS USING SEMI-VARIOGRAM

From these monitored results, it is confirmed that spatial dependence of thermal characteristics of damaged concrete walls treated with surface coating can be evaluated using semi-variogram. The examination of effectiveness of concrete repair work using thermal images revealed that in sections with progressed damage, surface temperature widely distributed and the distribution of skewness and kurtosis expanded from 0.0 in a positive direction. Especially in sections with corroded reinforcing bars, the degree of distortion was confirmed to be higher, compared with wear sections (**Fig. 7**). After surface coating treatment, the distribution of skewness and kurtosis was centered around 0.0 (**Fig. 8**). Therefore, appropriately treated damaged concrete showed a narrow thermal characteristic distribution and the distribution of skewness and kurtosis was centered around 0.0. Also, a range was clearly shown in the relation between $\gamma(h)$ and h in semi-variogram of appropriately treated damaged concrete.

6. CONCLUSIONS

(1) In concrete water channel structures, concrete surface is damaged due to wear with water. The degree of wear conditions can be evaluated based on the surface thermal characteristics.

(2) In sections with high degree of wear and corrosion of reinforcing bars, higher temperature was measured than in normal sections.

(3) In intact or after-repaired concrete, the distribution of skewness and kurtosis of the surface temperature was centered around 0.0, while in damaged sections. This relationship was depending on the degree of wear and corrosion of reinforcing bars.

(4) Semi-variograms of after surface coating treatment in damaged concrete showed a clear range, suggesting feasibility of verification of repair effectiveness using variograms.

(5) As evaluation indicators of concrete repair work or damage, spatial dependency using semi-variogram in geo-statistics can be very effective.

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