Estimation of Spatial Damage in Concrete Structures using Semi-Variogram Analysis

Tetsuya Suzuki¹, Tatsuo Naka² and Masayasu Ohtsu³

¹ Nihon University, Fujisawa, Japan
² National Institute for Rural Engineering, Tsukuba, Japan
³ Kumamoto University, Kumamoto, Japan

ABSTRACT: Degradation of concrete surface layers could occur due to external effects, which normally lead to changes physical properties. 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. The semi-variogram analysis is a quantitative evaluation method of the spatial distribution of physical properties. In situ examination was conducted in the two agricultural concrete canal walls. 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 (JCI TC994 (2001); JSNDI (1994)). 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-variogram model (Hans Wakernagel (2004)). Physical properties of concrete change with the effects of external environment and local damages after being used for many years become overt (Suzuki, T. et al (2006); Suzuki, T. et al (2004)). 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 are evaluated using the semi-variogram model. The thermal image is divided into 80 sections to show differences in local surface temperature. Relationship between skewness and kurtosis, and semi-variogram are 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.
IDENTIFICATION OF CONCRETE DEFECTS CAUSED BY WATER FLOW

The concrete materials, which are exposed to water flow, have undergone damages such as wear and compound erosions. The main causes of the damages are flow of gravel sediment and cavitations. Figure 1 shows an example of surface damage of a concrete water canal, which has been used for 74 years. The exposed coarse aggregates and reinforcing bars can be observed. In such existing concrete canal 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, nondestructive evaluation methods using electromagnetic wave (such as infrared thermography method) have been recognized to be effective for evaluating two-dimensional damage of concrete structures (JCI TC994, 2001). 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 for 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 (JCI TC994 (2001); JSNDI (1994)). Concrete walls and bases of water canals 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.

ANALITICAL PROCEDURE

3.1 Evaluation 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(x₁), ⋯, Z(xₙ) at the measuring points x₁, x₂, ⋯, xₙ 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) \[ E[(Z(x) - Z(x + h))^2] = 2\gamma(h) < \infty \]

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 \( h \). \( 2\gamma \) is variogram, and \( \gamma \) is semi-variogram.

Figure 1. Overview of testing damaged concrete wall.
In this study, the semi-variogram model described in next 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 $\gamma(h)$. 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 $h$.

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

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

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

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. 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 0.0 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 (Matsuoka, S. (1998)). In this paragraph, the spherical model used in this study is shown.

$$\gamma(h) = C_0 + C \left( \frac{3h}{2a} - \frac{h}{a} \right)^2 (0 < h \leq a)$$  

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

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 infrared thermography method. The thermal monitoring was conducted in service concrete water canal walls. These monitored concrete walls were constructed in 1934 and 1961 at Kanagawa prefecture, Japan. The structural conditions are shown in Table 1 (overview image: Figure 3). The monitoring structures were repaired by surface coating method (using material: polyurethane resin) in December 2006. The thermal image is divided into 80 sections to show differences in local surface temperature. The number of one sections data is 960. The measurement was conducted in 15 minutes (heating: 3 minutes; 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/m² on average.
Figure 2. Overview of non-damaged concrete wall.

Figure 3. Comparison between surface coating and non-repaired conditions in monitoring water canal.

Table 1. Monitoring site properties.

<table>
<thead>
<tr>
<th>Monitoring site</th>
<th>Construction</th>
<th>Compressive strength (N/mm²)</th>
<th>Repair work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damaged section (Figure 1)</td>
<td>1934</td>
<td>16.2</td>
<td>surface coating</td>
</tr>
<tr>
<td>Normal section (Figure 2)</td>
<td>1961</td>
<td>27.6</td>
<td>non-repair work</td>
</tr>
</tbody>
</table>
5 RESULTS AND DISCUSSION

5.1 Thermal Properties

The surface temperature in experimental non-damaged wall (normal section) is 21 to 23 degrees C, while in damaged sections it is 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 are affected by damage. In order to evaluate local thermal distribution, thermal images are divided into 80 sections and the relationship between skewness and kurtosis is obtained based on statistics values for each section. In the normal sections, the distribution of skewness and kurtosis is centered on 0.0 (Figure 4). In the wear sections, skewness is -0.5 to 1.0 and the kurtosis is -1.0 to 4.0. In the sections where reinforcing bar was exposed, the degree of distortion is confirmed to be higher than in the wear sections. When damaged sections were repaired with surface coating, the distribution of skewness and kurtosis is 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 are exposed to water flow, the distribution of the surface temperature ranged wider due to local damages, which caused the data distribution patterns to change (Figure 4). 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 (Figure 5). It is also 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 are evaluated based on the relationship between semi-variance $\gamma(h)$ and lag $h$ of semi-variogram model.

![Figure 4. Comparison of skewness and kurtosis in damaged section.](image1)

![Figure 5. Comparison of skewness and kurtosis in damaged section treated after surface coating.](image2)
5.2 Evaluation of Spatial Damage by Semi-Variogram Model

The primary characteristic of semi-variogram is that it can evaluate spatial dependence of measured data. In this Section, 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. Figure 6 shows the semi-variogram of damaged concrete after surface coating treatment. The target area of 40 cm × 50 cm is divided laterally into 10 sections with a pitch of 5 cm, and lag $h$ is set at 5 cm from the top end toward the base for each section. Then, semi-variance $\gamma(h)$ is calculated using Equation (2). The analytic values are evaluated using a spherical model. The nugget effect is 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 $h$ is 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 Figure 7. Semi-variance $\gamma(h)$ is calculated for Section (A) with only wear and Section (B) with reinforcing bar being exposed (in Figure 1) in the same manner as in Figure 7. Figure 7 shows that semi-variances $\gamma(h)$ varied between 0.38 and 1.56 in Section (A), showing no clear range, while in Section (B) $\gamma(h)$ reached between 4.24 and 4.70 at $h$=5 to 10 cm. 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 Figure 7, 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-varigrams. 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 experiments, the method suggested in this study, where intact sections and local damaged sections of concrete are compared using the semi-variogram, is confirmed to be effective.

5.3 Quantitative Evaluation of Repair Effects using Thermal Images

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 is confirmed to be higher, compared with wear sections (Figure 4). After surface coating treatment, the distribution of skewness and

![Figure 6: semi-variogram in damaged section treated after surface coating.](image_url)
Kurtosis is centered on 0.0 (Figure 5). Therefore, appropriately treated damaged concrete showed a narrow thermal characteristic distribution and the distribution of skewness and kurtosis is centered around 0.0. Also, a range is clearly shown in the relation between $\gamma(h)$ and $h$ in semi-variogram of appropriately treated damaged concrete (Figure 6).

6 CONCLUSIONS
Quantitative evaluation of damage in structural concrete is developed, applying infrared thermography method and the semi-variogram model. It is well demonstrated that damages of concrete can be quantitatively evaluated. Conclusions are summarized below:

1) In concrete water canal structures, surface concrete is damaged due to wear with water. The degree of damage conditions can be evaluated based on the surface thermal characteristics. In sections with high degree of wear and corrosion of reinforcing bars, higher temperature was measured than in normal sections.

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

3) The analytical results of semi-variograms of after surface coating treatment in damaged concrete showed a clear range, suggesting feasibility of verification of repair effectiveness using variograms.

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

References

Figure 7. Comparison of wear part and exposed steel part by Semi-variogram analysis.