A quantitative health inspection and assessment system for tunnel lining

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Abstract: To ensure the safety and the serviceability of underground structures, routine inspections and maintenance processes are essential for their optimal use. Presently, the practical inspection of tunnels depends on human-based methods, which has inherent limitations. This study proposed a quantitative system for the health inspection and assessment of the tunnel lining. The system is capable of acquiring and extracting cracks or other defects efficiently, drawing crack charts automatically and assessing the situation of tunnel lining with a much more accurate index. The consistency of the cracks automatically extracted by the proposed tunnel lining inspection system is verified with the investigation of two tunnels using different construction methods. For the health assessment of tunnel lining, a valid index is introduced to evaluate the lining status according to the fractal dimension of cracks. Results of the comparative tests and field tests indicate the validity of crack fractal dimension D . In addition, results of several real cases on field tests demonstrate its practicability. Such a system can achieve time-saving automated surveying solutions with fast data acquisition, identification and documentation of cracks as well as detection of structural changes. For an all-around assessment of the health situation for tunnel lining, the influence of strength characteristics of the tunnel lining due to its irregular shape should be taken into consideration in future research.

Keywords: lining concrete; health status; inspection and assessment

1. Introduction

In the last few decades, a large number of tunnels (water supply, metro, railway, road, etc.) have been constructed. Take Japan as an example, the total number of the operational transportation tunnels had grown up to 10,302 with the overall length of 4,532 km until 2017 [1]. Over time, many of them show signs of deterioration due to aging, environmental factors,

23 increasing loading, change in use, artificial and natural impacts, inadequate or poor
24 maintenance, or deferred repairs [2]. Deterioration to the tunnel lining will decrease its
25 integrity and may increase the risk of tunnel lining to eventually collapse [3-5]. Therefore, the
26 inspection, assessment and maintenance of tunnel lining are of necessity to guarantee tunnel
27 serviceability and user safety and have become one of the greatest challenges that engineers
28 have to face [6-8].

29 In the case of mountain tunnels, the stability of the tunnel lining is mainly surveyed using
30 periodic inspection as a general way. These inspection tasks are predominantly performed by
31 periodic visual inspection and by hammer knocking on abnormal locations [5,9]. To perform
32 these inspections, trained personnel are usually required. As a result, the inspection results
33 depend on the experience of engineers, making the assessment qualitative, even leading to
34 possible inaccuracies, false or missing detection. The modernization of the inspection,
35 assessment and maintenance methods is now an urgent business due to a shortage of labor and
36 the aging of maintenance workers, especially in Japan. To overcome the disadvantages of
37 manual inspection, automated tunnel inspection systems using photographic equipment,
38 photogrammetric and computer vision techniques, such as laser beams, silt cameras, line
39 sensor cameras, CCD cameras etc., as well as radar technology have been proposed [5,
40 10-15].

41 Efficient automatic extraction of lining cracks is a crucial step to present further assessment of
42 the tunnel lining status and to perform reasonable maintenance. Therefore, there is an
43 increasing interest in image processing technique for the automatic extraction technique. Four
44 edge-detection algorithms (fast Haar transform (FHT), fast Fourier transform (FFT), Sobel

filtering, and Canny filtering), wavelet transform-based method, mathematical morphology, probabilistic relaxation and adaptive thresholding, k-NN classifiers, 3-D scene reconstruction, high-speed percolation, and Principal Component Analysis (PCA) have been introduced [16-24]. These methods can be classified into four categories namely integrated algorithm, morphological approach, percolation-based method, and practical technique [25-26]. Each has its own advantage, such as being anti-noise, high efficiency, and obtaining robust detection results, deserving further investigation and attention.

On the other hand, health assessment for tunnel lining can be conducted based on the extraction results of lining cracks or other defects. An integrated resiliency assessment model was proposed by Huang et al. for tunnel deformational performance that fully uses field data from non-intrusive inspection and real-time monitoring systems [27]. In addition, since the mechanical stability of a tunnel is greatly influenced by the severity of cracks in the lining, quantification of tunnel lining degradation degree has been tried from the information of the crack by TCI (Tunnel lining Crack Index) drawn based on crack tensor theory [28-29]. TCI takes into account the width, length and direction of cracks on the lining surface, thus is able to judge the maximum width and length of crack, the distribution and direction of cracks. The health assessment using TCI is reasonable to some extent and has a wide application in Japan. In reality, the diversely and complex distribution of cracks makes the crack intersection prevalent, which could greatly influence the stability of tunnel lining. However, the intersection of cracks was not considered in TCI. Thus, more alternative assessment methods and health indexes are needed to provide a more comprehensive assessment of the stability of tunnel lining.

Therefore, a comprehensive and integrated health inspection and assessment system can pave way for effectively and accurately monitoring and assessing the health status of underground structures, thereby ensuring a high level of safety. The ultimate goal of the present study is to develop such an integrated system for tunnel lining. It can acquire and extract lining cracks efficiently, draw crack charts automatically and assessing the situation of tunnel lining accurately. It consists of an inspection system for tunnel lining, a quantitative methodology of tunnel lining crack, and a health assessment method of tunnel lining with the fractal dimension D of cracks. Such a system aims to achieve time-saving automated surveying solutions with fast data acquisition, identification and documentation of cracks as well as detection of structural changes.

2. Development of inspection system for tunnel lining

We aim at developing a tunnel lining inspection system, which does not influence the surrounding traffic inside the tunnel when it works and can detect the lining deformations accurately. During the system development, four primary targets that were taken into account are as listed in Table 1.

Performance for target A is to achieve a photographing speed of up to 100 km/h. It can guarantee a normal and safe traffic flow inside the tunnel. Performance for target B aims at an invisible illumination without dazzling light. It can avoid an inattentive driving of neighboring traffic vehicles at the time of photographing. Fig.1 shows the traditional inspection system with a dazzling light. It has a serious light disturbance on the neighboring vehicle, even results in a traffic accident when it works inside the tunnel.

Performance for target C is to capture the fine outline of closed cracks or cracks with the risk

of falling down of lining concrete. With a high resolution of 0.5 mm/pixel, it is capable of achieving photographing versatility for tunnels with various sectional shapes. Performance for target D aims at the development of an automatic extraction technique and an accurate record method of lining deformation. The proximity visual inspection requires too much labor and the results are often influenced by individual difference. The targeted crack width with the automatic extraction system is 0.2 mm, which is about half width of one pixel due to the high resolution of 0.5mm/pixel.

The inspection system for tunnel lining consists of a lining surface photography subsystem, a lining surface image creation software and a crack automatic extraction software. With this system, it is possible to photograph the lining surface while traveling in the tunnel at a maximum speed of 100 km/h and to extract cracks from the photographed lining surface image automatically and accurately.

2.1 Lining surface photography subsystem

Camera is introduced to be the photographing equipment of the photography subsystem, and half-circumference of the tunnel is captured using a number of cameras. Fig. 2 illustrates a photography example of a two-lane tunnel. The photography system travels on the left and right lanes, respectively, then photograph half of the lining surface each time.

(1) Selection of photographing camera

To select the photographing camera, a comparison of the area sensor camera and line sensor camera is conducted, as listed in Table 2. For the area sensor camera, the sensor shape is a rectangle and the photographing datum is a moving image. The moving image is converted to

a still image to generate one lining surface image and synthesis of images with adjacent cameras along the photographing proceeding direction is necessary. For the line sensor camera, the sensor shape is a line and the photographing datum is a still image taken continuously in the photographing proceeding direction. Therefore, without performing the image conversion process and image synthesis in the photographing proceeding direction, the line sensor camera is capable of saving labor for the image synthesis process. Take a tunnel lining with upper radius of 5.5 m and spring line height of 1.6 m (the perimeter is about 20.5 m) as an example, the total pixel of a lining surface image with a resolution of 0.5 mm/pixel is about 41,000. Therefore, a number of cameras is required. Based on Eqs. (1) and (2), the number of area sensor camera and line sensor cameras required are estimated.

$$L \approx (n-2) \times g \times (1-a \times 2) + 2 \times g \times (1-a) \quad (1)$$

$$n \approx \left(\frac{L}{g} - 0.3 \right) / 0.7 \quad (2)$$

where, L is pixel number in the tunnel circumferential direction, n is the required number of the camera, g is the pixel number of the camera (1,920 pixels for area sensor camera and 4,096 pixels for line sensor camera) and a is the overlap rate of adjacent cameras which is 15%. Such an overlap rate could satisfy the alignment requirement [30]. Fig. 2 shows a schematic diagram of number estimation of the camera, as well.

The estimated number is 30 for the area sensor camera (15 cameras installed on photography vehicle) and 14 for the line sensor camera (7 cameras installed on photography vehicle). As a result, a line sensor camera is a better choice considering image synthesis efficiency and cost of equipment. In order to capture images with a resolution of 0.5 mm/pixel at the photography vehicle speed of 100 km/h (Target A and C), a line rate of 56 kHz or more is required for the

line sensor, which could avoid image blur. In addition, in order to realize automatic crack extraction (Target D), priority should be given to the size of dynamic range capable of expressing cracks with sharper contrast in a monochrome image. With such requirement, line sensor camera named ELiiXA 8K/4K HDR from TELEDYNE E2V with high resolution is adopted for photographing. Table 3 lists the selection results of the photographing equipment.

(2) Adjustment mechanism of camera lens

Since cross-sectional dimensions of different tunnels are not the same, a zoom lens is required. It can adjust the view to obtain images with the specified resolution (0.5 mm/pixel) with different cross-sectional geometries. However, for the line sensor camera, there are no lenses with autofocus and zoom mechanism. Therefore, we develop a mechanism to automatically control the zoom ring of the lens before photographing. The mechanism consists of a gear and motor. The adjustment for different dimensions of tunnel cross-sections is done automatically based on the distance from the detection point to the focus plane before photographing. Once the system starts to work, the zoom and focus mechanisms are fixed for the whole duration of the data capture. The zoom and focus control mechanism is shown in Fig. 3.

(4) Near-infrared ray illumination

To prevent inattentive driving when photographing, the near-infrared ray is adopted as photography illumination to make the photography process invisible with human naked eyes. A bandpass filter is installed on the sensor front side of the camera so that it can shoot only in the wavelength range of near infrared ray illumination. Fig. 4 illustrates the wavelength range of sunlight and a bandpass filter. The available wavelength range can also be effective to suppress the influence of sunlight at the entrance of the tunnel by excluding the available

wavelength range out of the sunlight wavelength range.

For the light source of near infrared ray illumination, we adopt reflection type LEDs (light-emitting diode) considering light collecting property, quality and safety. An illumination unit is developed by arranging 60 LEDs in a line and condensing with a linear Fresnel lens. Furthermore, combining the camera and illumination unit together, we develop the photography unit. With this unit, the photographing axis of the line sensor camera equipped with the camera lens adjustment mechanism can match the optical axis of the illumination unit, as shown in Fig. 5.

(5) Simulation software for photography unit layout

As mentioned before, tunnels are with different geometries due to different geological or other conditions. For different tunnels, optimum values of angle, zoom and focus of the seven photography units have to be determined before photographing. Therefore, a software capable of simulating their optimum values is developed. Fig. 6 provides one simulation result of the photography unit layout.

(6) Adjustment mechanism for photography unit angle

Based on the photography unit layout simulation result, an automatic adjustment mechanism is developed as shown in Fig. 7. It consists of an elevating mechanism and a support mechanism. The elevating mechanism adjusts the orientation of the camera by rotating the photography unit with the rotational axis of the mechanism as the center. The support mechanism controls the adjustment for the orientation of the photography unit to obtain the lining surface image effectively and accurately even if the shape and dimension of the tunnel surface changes. In addition, the support mechanism could suppress the shaking of the

176 photography unit due to vibration of the running vehicle during photographing.

177 (7) Photography control software

178 According to the photography unit layout simulation result, a control software for
179 photographing is developed. The software controls each photography unit based on an
180 operation signal, acquires a lining surface image from each camera, and stores it in an image
181 storage unit. It can also give the command to the photography unit angle adjustment
182 mechanism to adjust the photography operation. In addition, the image quality and overlap of
183 adjacent cameras can also be checked by this software.

184 (8) Photography vehicle for tunnel lining surface

185 The development specifications of the photography vehicle are shown in Table 4. It consists
186 of a cab, a photographing operation room, and a device room. In the photographing operation
187 room, a dedicated purpose computer within a built-in photography control software is
188 installed. In the device room, seven photography units with the photography unit angle
189 adjustment mechanism are installed. The arrangement of the tunnel lining surface
190 photography vehicle is shown in Fig. 8. Before photographing, the photography unit is
191 adjusted to the optimum arrangement automatically following a command from the
192 photography control software. During photographing, meandering and speed change of the
193 vehicle may lead to deviations from the simulation setting in the focus and line rate. For these
194 deviations, distance measurement to the lining surface by the distance sensor and speed data
195 by non-contact speedometer are collected into the photographing control software, as
196 illustrated in Fig. 8. In response to distance changes between the vehicle and lining surface
197 and vehicle speed changes, a mechanism to control the focus and line rate during

photographing is developed. In this way, the change of depth-of-field can be controlled, as well. The photographing situation of the tunnel lining surface is shown in Fig. 9. Since the photography illumination is not visible with naked eyes, the situation in Fig. 9 was shot via the infrared filter in order to visualize the near-infrared ray illumination described in section 2.1 (4).

2.2 Lining surface image creation software

During tunnel inspection, a large amount of photographic data is generated, which needs to be effectively organized. A typical solution is to apply image mosaicking [5]. The processing procedure of the lining surface image creation software is as follows: 1) Unification of luminance level by shading correction; 2) cancellation of image distortion by inverse projection; and 3) alignment of adjacent photographed images. After alignment, the images are attached to each other to form a single image. More details on the algorithms involved in each step are given in the followings.

(1) Unification of luminance level by shading correction

Non-uniform luminance of the photographed images often exists due to the following conditions: lowering of peripheral light quantity around the lens, luminance unevenness of the LED lighting (lowering of the peripheral light quantity), distance variation from the photography unit to the lining surface, luminance gradient due to the inclination of the photography unit, luminance lowering due to the dirty condition of the lining surface. Therefore, a shading correction algorithm is applied as a pre-processing step to adjust the uneven illumination present in this environment [31]. For the correction, the average

luminance and the dispersion value are calculated from the photography data captured by the 14 cameras. Then luminance difference of each image could be obtained. Afterwards, the luminance difference is used to compensate luminance of each pixel. Then an image with uniform illumination is generated to eliminate the luminance difference. The luminance unification is programmed to process automatically.

Fig.10 shows the image before and after the correction. Due to the difference in the distance and direction between the cameras, luminance levels of different images by different cameras and different part in one image is uneven (Fig. 10a). After correction, the luminance difference is eliminated, and the luminance level of each image becomes uniform (Fig. 10b).

(2) Cancellation of image distortion by inverse projection

Image distortion often happens because of lens aberration and uneven resolution by the inconsistent distance between camera and lining surface and tilt photographing. By inversely projecting the photographed images to the tunnel shape data obtained by the distance sensor and the data of the relative position between each camera and lining surface, the distortion can be eliminated.

(3) Alignment of adjacent photographed images

The position alignment procedure for synthesizing adjacent photographed images accurately can be stated as followings. At first, cut out the boundary of both ends of each span exactly, and perform a homograph transformation. The span boundary is transformed vertically into a rectangle with four corners at the upper and lower ends of the span boundary. Following the transformation, extract the edge component in the horizontal direction. The image captured by the former camera is used as a supervisory signal to identify coincident feature from the latter

adjacent camera data. Meanwhile, document the coordinates of the coincident points. Set them as the matching points of the images. The position alignment procedure is programmed to process automatically.

In general, after aligning the photos using image registration, the images have to be attached to each other, such that they are composed into one single image. Blending is therefore required to make the transition between the images as smooth as possible [31]. However, since the shading correction technique makes the illumination in both images very similar, the adjacent images can be stitched directly even without blending. This eliminates the computation time. Fig.11 shows the alignment result of the adjacent photographed image. There are no points lost in the image (b), the visually lost points are due to the location difference of the two adjacent images. Area A in Fig.11a belongs to the lower image, while area B in Fig.11a belongs to the upper image. After alignment, area C in Fig.11a, in which points seems lost, can be found in Fig.11b (area C'). In addition, the image deviation is eliminated, as well.

2.3 Automatic crack extraction software

To extract and draw cracks automatically from the photographed images, an automatic crack extraction software is developed. The software analyzes the synthesized image to extract and detect what type of cracks present on the lining surface. The process of the crack automatic extraction software is shown in Fig. 12. Its basic principle is as follows. (1) Calculate the average luminance of the images and convert it to the specified luminance value (Fig. 12b). (2) Detect the area above the average value of luminance and fill it with the average value to

eliminate choking (Fig. 12c). (3) Perform filtering by filter kernel of crack outline to detect the longitudinal component of thin line (Fig. 12d). (4) Detect omnidirectional thin lines by performing filtering when rotating the image (Figs. 12e and 12f). (5) Remove artificial lines, such as tunnel facility objects and mold traces, from the omnidirectional thin line images by using distance sensor data and straight line detection algorithm. Remove line segments with short length as noise. Then connect the other thin lines (Fig. 12g). (6) Expand the line width to make it easy to identify the connected thin lines as crack (Fig. 12h). This step has no effect on the true crack width.

However, cracks cannot be extracted automatically in the following situations: (a) no reflected light or the back side of the repaired part (A in Fig. 13a); (b) insufficient contrast with the lining surface due to water leakage, efflorescence or high luminance (B in Fig. 13a); (c) the crack width less than 0.2 mm; (d) insufficient contrast because of soot dirt (Fig. 13b); (e) camera out of focus. For such situations, manual visual inspection for the status of the lining surface is needed. In addition, re-shoot for the lining surface is necessary for the out-of-focus case.

2.4 Accuracy verification of automatic crack extraction method

To verify the automatic crack extraction accuracy, 10 spans of two tunnels with different construction methods were investigated using the periodic inspection and the automatic crack extraction system, respectively.

Table 5 lists the results of the periodic inspection and automatic crack extraction of A tunnel using NATM. The comparison results using both methods are shown in Fig. 14. The

maximum and average matching rate are 96% and 93%. It indicates the practicability of the automatic extraction results. In addition, areas with dot line in Fig. 14b extracted using the automatic crack extraction method are not recorded using periodic manual inspection due to overlooking, record missing or individual difference in extraction. It can be concluded that there is a possibility of solving the above-mentioned problems using this automatic extraction method.

Table 6 lists the results of the periodic manual inspection and automatic extraction of B tunnel using sheet pile method (SPM). The comparison results are shown in Fig. 15. A high matching rate is also obtained for B tunnel with an average value of 88%, a bit lower than that of A tunnel using NATM. The reason for the difference in matching rate between A and B tunnels is that some cracks on lining surface of the tunnel using SPM cannot be extracted due to the insufficient contrast. Sometimes on the lining surface of tunnel using SPM, there are bubbles, dark mold trace or greasy dirt with insufficient contrast. To complement the inconsistency, inspection engineers can check the automatic crack extraction result and make an edit on the un-extracted and mis-extracted cracks.

3. Crack quantification of tunnel lining

In fractal geometry, fractal dimension analysis is a ratio providing a statistical index of complexity. It could explain how the detail in fractal pattern changes with the scale which it is measured [4]. It could find regularity from ambiguous images and give a mathematical model for complicated shapes by the fractal dimension scale. In this study, the fractal dimension is taken as a valid health assessment index to quantify the crack distribution in tunnel lining. The box-counting dimension, also known as the Minkowski dimension, is used to determine

the fractal dimension [32].

To calculate the fractal dimension D , imagine the expansion plan of the lining surface image lying on an evenly spaced grid with scale r and count the box number $N(r)$ with at least one crack included in the box as illustrated in Fig. 16. Then the box-counting dimension is defined as:

$$D = \lim_{r \rightarrow 0} \frac{\log N(r)}{\log(1/r)} \quad (3)$$

4. Application of the proposed inspection system and quantification of health assessment based on fractal dimension D

For the periodic inspection technique by Japan Expressway Company Limited (NEXCO), the inspection technician observes lining surface image and traces crack manually. Sometimes, cracks extracted automatically from the lining surface image have different linear shapes with those drawn manually using NEXCO periodic inspection. Since the crack difference may influence the result of the health assessment, the feasibility of our proposed system should be tested and checked. Therefore, to know whether the automatic crack extraction result can be applied to the health assessment, we compared the health assessment results based on different extraction methods. In addition, fractal dimension D is compared with TCI to verify its validity as a valid assessment index for tunnel lining. Here, seven tunnels in Japan were investigated, as listed in Table 7. Three kinds of crack density range are set for the target spans with a total number of 110.

4.1 Comparison of automatically extracted cracks, manually extracted cracks and proximity visual cracks

21 spans of Mekari tunnel (No.1 in Table 7) were investigated for both external force and exfoliation assessment points. Both the assessment points are calculated based on width, length and distribution of crack, crack direction, crack shape pattern, efflorescence and leakage. Considering the width, length and distribution of crack and crack direction, TCI was calculated based on the calculation method by Shigeta et al. [29]. Fig. 17 illustrates some typical extracted results by the automatic extraction method and the periodic inspection.

Fig. 18 shows the assessment point results for automatically extracted cracks, manually extracted cracks and proximity visual cracks. The points in Fig.18 are the average value of the 21 spans. For the proximity visual, the percentage of assessment point based on cracks is 88% at the external force assessment, and 58% at the exfoliation assessment. This indicates that the crack external force assessment point has a significant effect on the total assessment point. The assessment point of the proximity visual cracks and automatically extracted cracks are 43 and 41 at the external force assessment, 22 and 21 at the exfoliation assessment. The slight difference results from a small difference in the length and angle components for the same extracted crack by different extraction methods. On the other hand, the assessment point of cracks extracted automatically equals to that of cracks extracted manually.

For a further comparison between the manual and automatic extraction method, more cases are collected and discussed. Here, 100 spans of first six tunnels (Nos. 1~6 in Table 7) are considered to calculate and compare TCIs for the cracks extracted automatically and manually. And their correlation of TCIs is discussed, as well.

Fig. 19 shows the correlation of crack TCIs for the cracks extracted automatically and manually. The correlation is positive with a coefficient of 0.99, indicating that the automatic extraction method is effective. TCI for cracks extracted automatically tends to be higher with an increment of about 8% with respect to the TCI for cracks extracted manually. This is thought to be the result of the highly sensitive of TCI value to the difference in crack line shape.

Fig. 20 presents the assessment point ratios between these two extraction methods for external force and exfoliation calculated based on crack width, length and distribution. Most of the ratios are in the range from 0.9 to 1.1. For the external force assessment, spans with point ratio of 0.98 are the most frequently observed as shown in Fig. 20a. And for the exfoliation assessment, the most frequently observed spans are with point ratio of 1.0, as shown in Fig. 20b. It can be concluded the automatic extraction method can obtain almost the same health assessment result as the manual extraction method.

Fig. 21 presents the assessment point ratio between these two extraction methods for external force and foliation calculated based on crack direction. It is revealed that almost the same health assessment result can be obtained because the result of the assessment point ratio is 1.0 for almost all the spans.

Therefore, it can be concluded that excessive health assessment results are seldom reached since somewhat lower assessment points are often obtained using automatic extraction method. Besides, the health assessment with automatic extraction method has been compared with the NEXCO health assessment and the health diagnosis classification of tunnel periodic inspection by the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MILT),

this proposed inspection system can be easily utilized for periodic inspection by local governments including the MILT.

4.2 Correlation verification between TCI and fractal dimension D

In the previous section, TCI calculated by using automatic extraction method has been confirmed to be applicable to NEXCO health assessment for tunnel lining. In this section, the correlation between the fractal dimension D of cracks and the TCI of the same span is examined by investigating Hidake tunnel (No. 7 in Table 7) with 10 spans. Three typical types of spans within the three crack density ranges are shown in Fig. 22.

The fractal dimension D and TCI of the 10 spans in Hidake tunnel are calculated and listed in Table 8. Fig. 23 shows the correlation between D and TCI. The results of the two different methods can be fitted as a power function with a correlation coefficient of 0.91. For most of the test spans, the results of the two different methods are consistent with each other. However, for some spans, the assessment results are quite different based on these two indexes. For span 16, several cracks occur and there is no wide crack. The crack density is only 0.11 m/m^2 . In result, the TCI is 2.0397×10^{-5} . The small TCI indicates the lining is in a safe state. But due to the penetration of these cracks in the entire lining, it is obvious that the assessment is underestimated. While the fractal dimension D is 1.1210, a significantly larger assessment point. For Span 42, the TCI is quite large (10.0495×10^{-5}), indicating the risk degree is large. While the risk degree is small considering the small fractal dimension (1.0961) for this span. Since several small and independent cracks occur in Span 42 with a small crack density of 0.20 m/m^2 , the actual risk is not serious. It is clear that the assessment results by the

valid index are more consistent with the actual state of the tunnel lining. Therefore, the fractal dimension is a promising method to quantify the crack distribution in the health assessment of tunnel lining.

5. Conclusions

A quantitative health inspection and assessment system is proposed. This system is capable of acquiring and extracting cracks efficiently, drawing crack charts automatically and assessing the situation of tunnel lining surface with the crack fractal dimension D . Such a system achieves time-saving automated surveying solutions with fast data acquisition, identification and documentation of cracks as well as detection of structural changes by realizing the following matters.

A maximum speed of 100 km/h of the photographing vehicle makes it possible to acquire the lining surface image without traffic inhibition. In order to prevent inattentive driving of traffic vehicles during photographing, the near-infrared ray is adopted as photography illumination to make the photography process invisible with human naked eyes. Acquisition of a lining surface image with a resolution of 0.5 mm/pixel improves the precision of crack detection. Combination of high-resolution image and automatic crack extraction method makes it possible to extract and draw the distribution of complicated cracks occurring on the lining surface automatically and accurately.

NEXCO health assessment using cracks extracted automatically by the proposed system is proved to be able to obtain almost the same results as those using cracks extracted manually. This automatic extraction method is applicable to the NEXCO health assessment. In addition, since the fractal dimension D has a strong correlation with TCI, the fractal dimension can

describe the crack actual status as a promising health assessment index quantitatively and accurately.

Since irregular shape of the tunnel lining, such as voids between the tunnel lining and its surrounding rock mass, is of significance affecting the strength of the concrete lining, an all-around inspection and assessment system including the health status of the lining surface and strength characteristic of the concrete lining is one important issue for the future research.

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525 NATM.

526 Table 6. Results of the manual inspection and automatic extraction of B tunnel using SPM.

527 Table 7. Tunnels in Japan used for verification.

528 Table 8. The fractal dimension D and TCI of the 10 spans in Hidake tunnel.

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531 **Figure Captions**

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533 Fig.2 Photography example for a two-lane tunnel (white and blue lines) and its schematic
534 diagram of number estimation of camera (red line).

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536 Fig. 4 Wavelength range of sunlight and bandpass filter.

537 Fig. 5 Photography unit.

538 Fig. 6 One simulation result of the photography unit layout.

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541 Fig. 9 Photographing situation of the tunnel lining surface with invisible illumination.

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543 Fig. 11 The alignment result of adjacent captured images. (a) Image before alignment; (b)
544 Image after alignment.

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546 normalization; (c) choking elimination; (d) detection of longitudinal component of thin lines;
547 (e) image rotation (50° for this image); (f) detection of omnidirectional thin lines; (g) thin line
548 connection and noise removal; (h) expanding of the line width to draw crack.

549 Fig. 13 Examples of cracks which cannot be extracted automatically by the automatic crack
550 extraction method. (a) Leakage, efflorescence and illumination; (b) lining surface with
551 remarkable soot dirt.

552 Fig. 14 Extracted crack comparison using the periodic manual inspection and automatic
553 extraction of A tunnel (Span No. 1). (a) The result of the periodic manual inspection; (b) The
554 result of the automatic crack extraction.

555 Fig. 15 Extracted crack comparison using the periodic manual inspection and automatic
556 extraction of B tunnel (Span No. 1). (a) The result of the periodic manual inspection; (b) The
557 result of the automatic crack extraction.

558 Fig. 16 Schematic diagram of the Box-Counting method. (a) Crack image; (b) $r = 1$, $N(1) =$
559 86 ; (c) $r = 2$, $N(2) = 34$; (d) $r = 4$, $N(4) = 14$.

560 Fig. 17 Typically extracted results by the automatic extraction method and periodic inspection.

561 (a) periodic inspection result ($H_i = 0.18 \text{ m/m}^2$); (b) automatic extraction result ($H_i = 0.18$
562 m/m^2); (c) periodic inspection result ($H_i = 0.85 \text{ m/m}^2$); (d) automatic extraction result ($H_i =$

563 0.85 m/m²).

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565 proximity visual cracks.

566 Fig. 19 Correlation of crack TCIs for the cracks extracted automatically and manually.

567 Fig. 20 Assessment point ratios between manual and automatic extraction methods for
568 external force and foliation based on crack width, length and distribution. (a) Assessment
569 point ratio for external force; (b) Assessment point ratio for foliation.

570 Fig. 21 Assessment point ratio between manual and automatic extraction methods for external
571 force and foliation calculated based on crack direction. (a) Assessment point ratio for external
572 force; (b) Assessment point ratio for foliation.

573 Fig. 22 Three typical types of spans within the three crack density ranges. (a) $0.2 \geq H_i$; (b) 0.2
574 $< H_i \leq 0.5$; (c) $0.5 < H_i$. (S is short for Span)

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Table 1 Target and its performance of inspection system for tunnel lining.

No.	Target	Target performance
A	Control of traffic inhibition during photographing	Lining surface photography vehicle with photographing speed up to 100 km/h
B	Prevention of inattentive driving of neighboring traffic vehicles during photographing	Lining surface photography vehicle with invisible illumination during photographing
C	Lining surface image with compatible resolution of a reliable crack extraction and photographing versatility for tunnels of various cross-sectional dimensions	Lining surface photographing vehicles capable of acquiring high-resolution images and lining surface image creation software (resolution 0.5 mm / pixel)
D	Extraction of cracks, reduction of recording effort and suppression of individual differences	Crack automatic extraction software (crack minimum width 0.2 mm)

Table 2. Comparison of the area sensor camera and line sensor camera.

Item	Area sensor camera	Line sensor camera
Sensor
Photographing data	moving image	still image
Image	Convert moving image into a still image. Generate 30 pictures per second in the photographing proceeding direction.	Belt continuous image shutter 56,000 times / s in the photographing proceeding direction. (speed of 100 km / h)
Image synthesis	necessary	unnecessary

Table 3. Selection results of the photographing equipment.

Item	Result
Camera name	ELiIXA 8K/4K HDR
Camera type	Line sensor camera
Pixel number	4,096 pixel
Line rate	≥ 56 kHz / 100 km / h
Image color	Monochrome image
Dynamic range	70.7 dB

Table 4. Development specifications of the photography vehicle.

Item	Specification
Running speed	5 ~ 100 km/h
Object vehicle	3.5 t class base vehicle
Riding capability	4 persons
Application standard	JIS, Road Traffic Act, Enforcement Ordinance of the Road Traffic Act, Road Transport Vehicle Act, Vehicles Regulations Order
Protection performance	Equivalent to IP55 standard (dustproof, jet-water proof), a protective structure with the elimination of the near infrared illumination effect on the human body
Air-conditioning management	Air conditioning for normal operation at high temperature and low temperature

Table 5. Results of the manual inspection and automatic crack extraction of A tunnel using NATM.

Span No.	Manual inspection (Pixel number)	Automatic crack extraction method (Pixel number)	Matching rate (%)
1	156523	150241	96
2	255602	245389	96
3	170393	156743	92
4	134652	125209	93
5	132512	117935	89
Average value			93

Table 6. Results of the manual inspection and automatic extraction of B tunnel using SPM.

Span No.	Manual inspection (Pixel number)	Automatic crack extraction method (Pixel number)	Matching rate (%)
1	681985	588553	86
2	196648	181523	92
3	426363	391786	92
4	494301	447468	91
5	327546	262089	80
Average value			88

Table 7. Tunnels in Japan used for verification.

No.	Tunnel name	Length (m)	Service years	Construction method	Target span number by crack density Hi: crack density (m/m^3)		
					$0.2 \geq \text{Hi}$	$0.2 < \text{Hi} \leq 0.5$	$0.5 < \text{Hi}$
1	Mekari tunnel	582	44	SPM	5	8	8
2	Shiratake Second tunnel	201	28	NATM	5	3	1
3	Nakasato tunnel	1,472	13	NATM	5	0	0
4	Okubo tunnel	412	44	SPM	0	0	5
5	Kibaru tunnel	186	32	SPM	0	4	1
6	Kakutou tunnel	6,255	22	NATM	9	27	19
7	Hidake tunnel	780	34	SPM	5	3	2
Total					29	45	36

Table 8. The fractal dimension D and TCI of the 10 spans in Hidake tunnel.

Span	D	TCI (10^{-5})	Span	D	TCI (10^{-5})
1	1.2608	17.3533	35	1.0072	1.8892
12	1.0665	3.9326	42	1.0961	10.0495
16	1.1210	2.0397	49	1.2906	40.2816
18	1.0454	2.6453	58	1.2838	30.6416
20	1.0663	4.163	65	1.2229	26.1172