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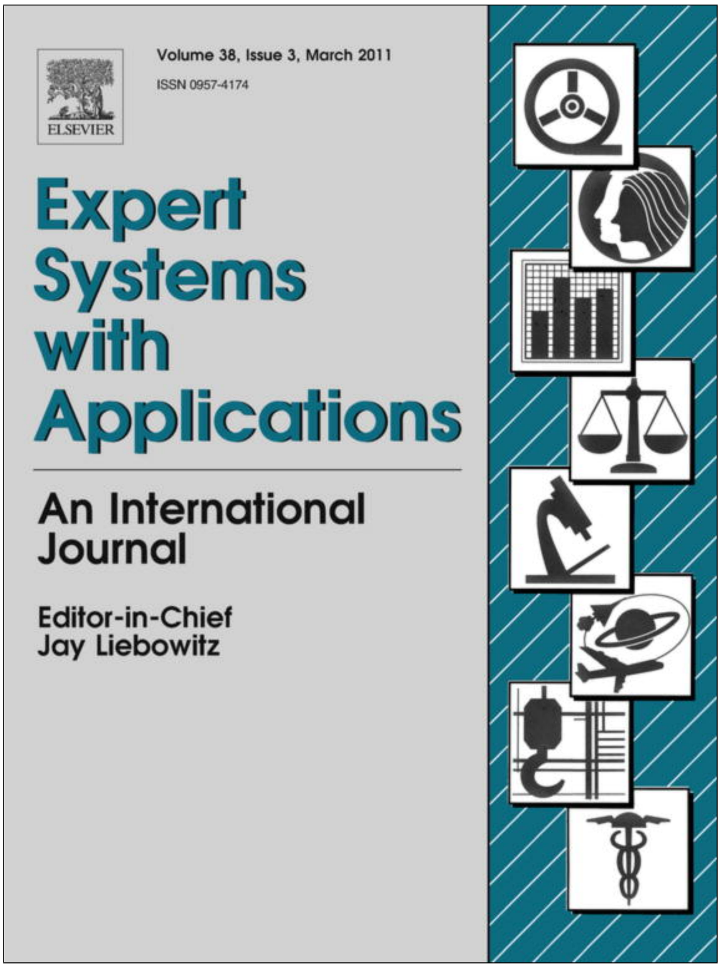

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Systematic image quality assessment for sewer inspection

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ABSTRACT

Closed circuit television (CCTV) has been applied in many developing or developed counties for sewer inspection due to its low setup cost and technical requirement. Several automated diagnosis systems of sewer pipe defects had been developed to assist the technicians in interpreting or classifying sewer pipe defects. However, many researchers pointed out that good image quality is the prerequisite for accurate interpretation and diagnosis of CCTV inspection but has not a proper evaluation approach. In this paper, a CCTV image quality index considering both of the luminance distortion and the contrast distortion of a CCTV image compared by reference images is proposed and was applied to assess the image quality of the CCTV images shot for a sewer house-connection project. The experimental result indicates that rather than luminance contrast plays a more important role in the CCTV image quality that can be effectively improved by contrast enhancement. Since CCTV image quality can hardly distinguished by human eyes, the proposed image quality index can provide helpful information to efficiently assist the on-site technicians in precisely shooting better CCTV images for the pipe defection. Additionally, a sensitivity analysis of contrast stretch was implemented to quantify the CCTV image quality improvement. CCTV imaging conditions, such as pipe materials and imager status, are found as the factors affecting the CCTV image quality. In the future, a real-time CCTV image quality assessment will be developed by modifying the CCTV image quality index as an instantaneous reference for imaging adjustment that can be expected to be practicable for the on-site sewer inspection because of the extremely short computation time.

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1. Introduction

Sewer systems are one of the most important infrastructures of a modernizing city (Ostojic-Skomrlj & Margeta, 1995). However, implementing sewer rehabilitation, including sewer inspection, assessment of structural conditions, computation of structural condition grades, and determination of rehabilitation methods and substitution materials, is often difficult because sewer systems are buried underground (Wirahadikusumah, Abraham, Iseley, & Prasanth, 1998; Yang & Su, 2006; Yang, Su, & Chen, 2005). Sewer inspection is the first step and has the greatest impact on efficacy of sewer rehabilitation. Nowadays, closed circuit television (CCTV) and sewer scanner evaluation technology (SSET) mounted on robots are the most popularly inspection equipments to produce video records or/and digital images for pipe defection (Iyer & Sinha, 2005; Sinha & Fieguth, 2006). Having similar mechanics with SSET system, CCTV technology has been applied in many developing or developed counties in sewer rehabilitation projects for a long time due to its low setup cost and technical requirement.

Traditionally, pipe defects are generally detected and classified by human interpretation on sewer inspection images. However, human interpretation could often cause incorrect or subjective inspection results (Iyer & Sinha, 2005; Yang & Su, 2008, 2009). Several automated diagnosis systems of sewer pipe defects had been developed to assist the technicians in interpreting or classifying sewer pipe defects (Gokhale & Graham, 2004; Iyer & Sinha, 2005; McKim & Sinha, 1999; Shehab & Moselhi, 2005; Sinha & Fieguth, 2006; Wirahadikusumah et al., 1998; Xu, Luxmoore, & Davies, 1998; Yang & Su, 2008, 2009). Xu et al. (1998) developed a computer vision for automatic sewer pipe-joint assessments based on the CCTV survey and revealed that the poor image quality causes an incomplete pipe-joint boundary while being extracted. Wirahadikusumah et al. (1998) used different inspection systems including CCTV, infrared thermography system, sonic distance measurement, ground penetrating radar, and SSET, to assess the structural conditions of sewer pipes. Also, the quality of information obtained from CCTV depends on the experience and skill of the technician and the reliability of CCTV. Many researchers pointed out that good image

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quality is the prerequisite for accurate interpretation and diagnosis of CCTV inspection and discussed the causes of poor quality images. However, a systematic evaluation approach of CCTV image quality remains to be developed for an automated diagnosis system of pipe defects that is proposed in this paper.

2. Methodology

2.1. Data acquisition

Several CCTV inspection video streams were acquired from a sewer inspection and rehabilitation project for connection house in Taichung city, which is the largest city in the central Taiwan. Most of the buried sewer pipes are made of either vitrified clay pipe (VCP) or polyvinyl chloride (PVC) pipe in Taichung city. According to the field investigation, most of the pipe defects were diagnosed as either open joints or cracks by the on-site technicians. Among the CCTV inspection video streams, the images of open joints and cracks are found to be usually shot under the collimation condition of the camera being parallel to the centroid of the sewer pipes and being approximately perpendicular to the sewer pipe walls, respectively.

A CCTV inspection video stream consists of 1000 frames of CCTV images. Some of them were human distinguishable and marked with pipe defects, whereas most images remain un-interpreted in the field. For this pioneer study, only 60 frames of CCTV images, which consist of 30 frames of interpreted images and 30 frames of non-interpreted image, were retrieved from the CCTV inspection video streams by a video stream processing software – VirtualDub (SourceForge.net, 2009).

2.2. CCTV image quality assessment

Poor image quality usually sources from image compression, inadequate luminance, inadequate contrast, or noise (Pappas & Safranek, 2000). The mathematical definitions such as mean squared error (MSE), peak signal-to-noise ratio (PSNR), root mean squared error (RMSE), mean absolute error (MAE), and signal-to-noise ratio (SNR) had been widely used to measure the image qualities because they are simple to calculate, have clear physical meanings, and are mathematically convenient in the context of optimization (Wang & Bovik, 2002; Wang, Bovik, Sheikh, & Simoncelli, 2004). However, they are not very well matched to perceived visual quality so that other image quality assessment methods had been developed by taking advantage of known characteristics of the human visual system (HVS) which is highly adapted for extracting structural information (Wang, Bovik, et al., 2004). Wang and Bovik (2002) presented an image quality index which was designed by modeling an image distortion as a combination of three factors: loss of correlation, luminance distortion, and contrast distortion.

This paper proposes an image quality index considering luminance and contrast distortions (or similarity with ideal images), whereas correlation is not taken into consideration due to a low correlation between one CCTV inspection image and others. The schematic procedure for CCTV image quality assessment is shown in Fig. 1. First of all, a reference image data set should be estab-

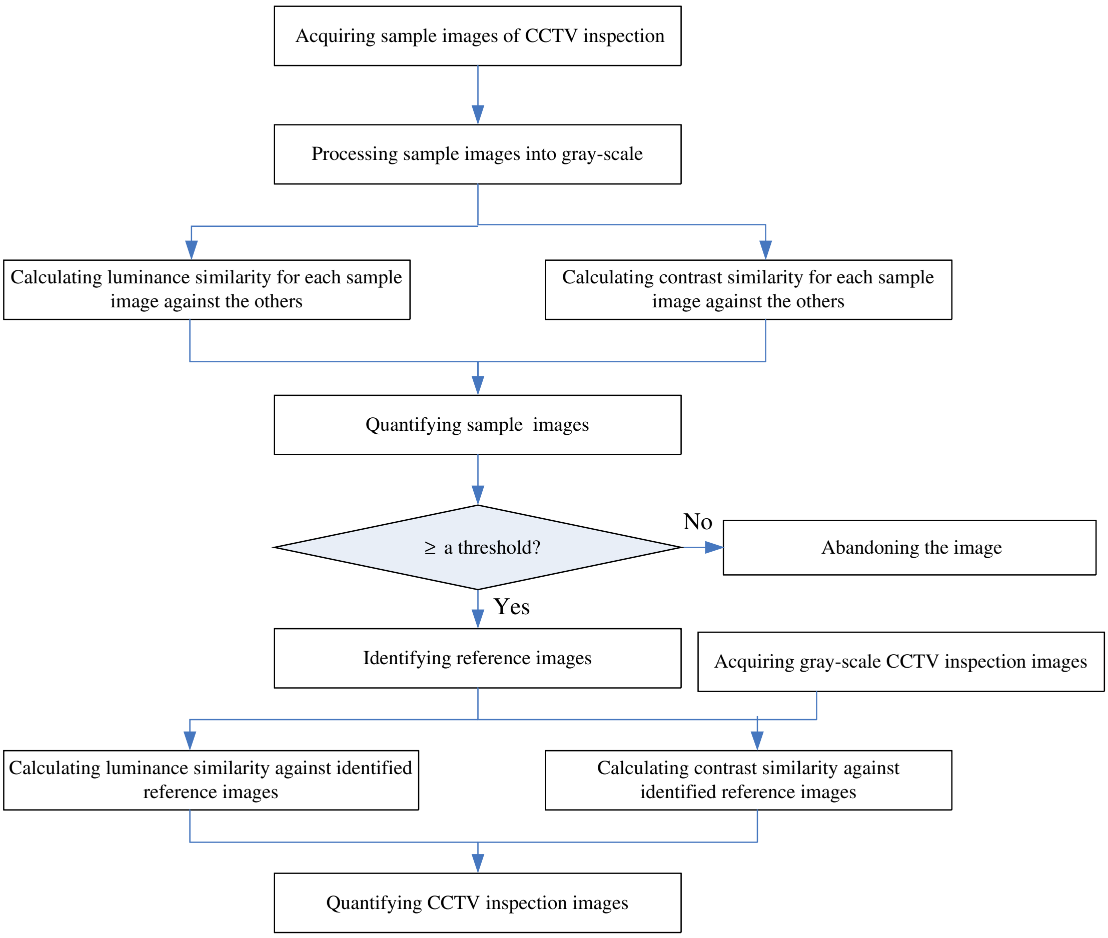

Fig. 1. The proposed approach of image quality assessment of sewer inspection.

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lished and provides as the ideal image for quality assessment. These sample images were converted into gray images and implemented an intra image quality assessment that calculates image quality index (Q) for each sample image against the others. With a Q value above a threshold, a sample image can be identified as an ideal reference image for later image quality assessment. Finally, the image quality of CCTV inspection images is quantified by the image quality index against all identified reference images.

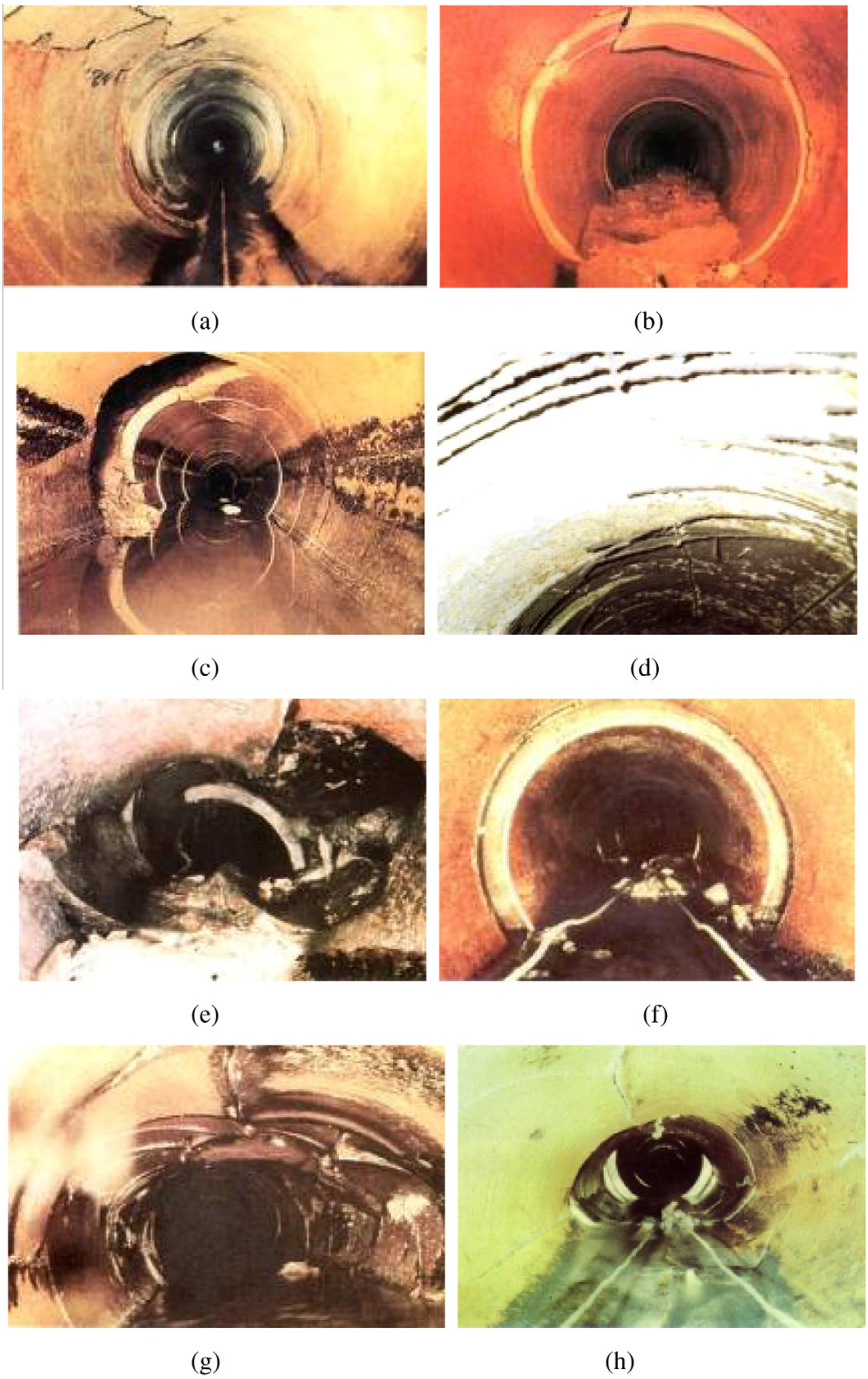

Fig. 2. Sample images of sewer inspection offered by the manual of sewer condition classification. (a) Fractures multiple; (b) Debris; (c) Hole; (d) Spalling Large; (e) Collapse; (f) Open joint; (g) Broken and (h) Deformed sewer.

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Table 1
Intra image quality assessment of the CCTV sample images.

Pipe defect	FM	D	H	SL	C	OJ	B	DS	Q
FM	1	0.8047	0.9383	0.9436	0.9503	0.9825	0.9556	0.9957	0.9387
D	0.8047	1	0.9173	0.6372	0.7603	0.8172	0.7939	0.8232	0.7934
H	0.9383	0.9173	1	0.7918	0.9402	0.9636	0.9605	0.9385	0.9215
SL	0.9436	0.6372	0.7918	1	0.8652	0.9084	0.8851	0.9393	0.8530
C	0.9503	0.7603	0.9402	0.8652	1	0.9886	0.9962	0.9299	0.9187
OJ	0.9825	0.8172	0.9636	0.9084	0.9886	1	0.9949	0.9763	0.9474
B	0.9556	0.7939	0.9605	0.8851	0.9962	0.9949	1	0.9268	0.9304
DS	0.9957	0.8232	0.9385	0.9393	0.9299	0.9763	0.9268	1	0.9328

P.S. "FM", "D", "H", "SL", "C", "OJ", "B", and "DS" represent the pipe defects of Fractures multiple, Debris, Hole, Spalling Large, Collapse, Open joint, Broken, and Deformed sewer, respectively.

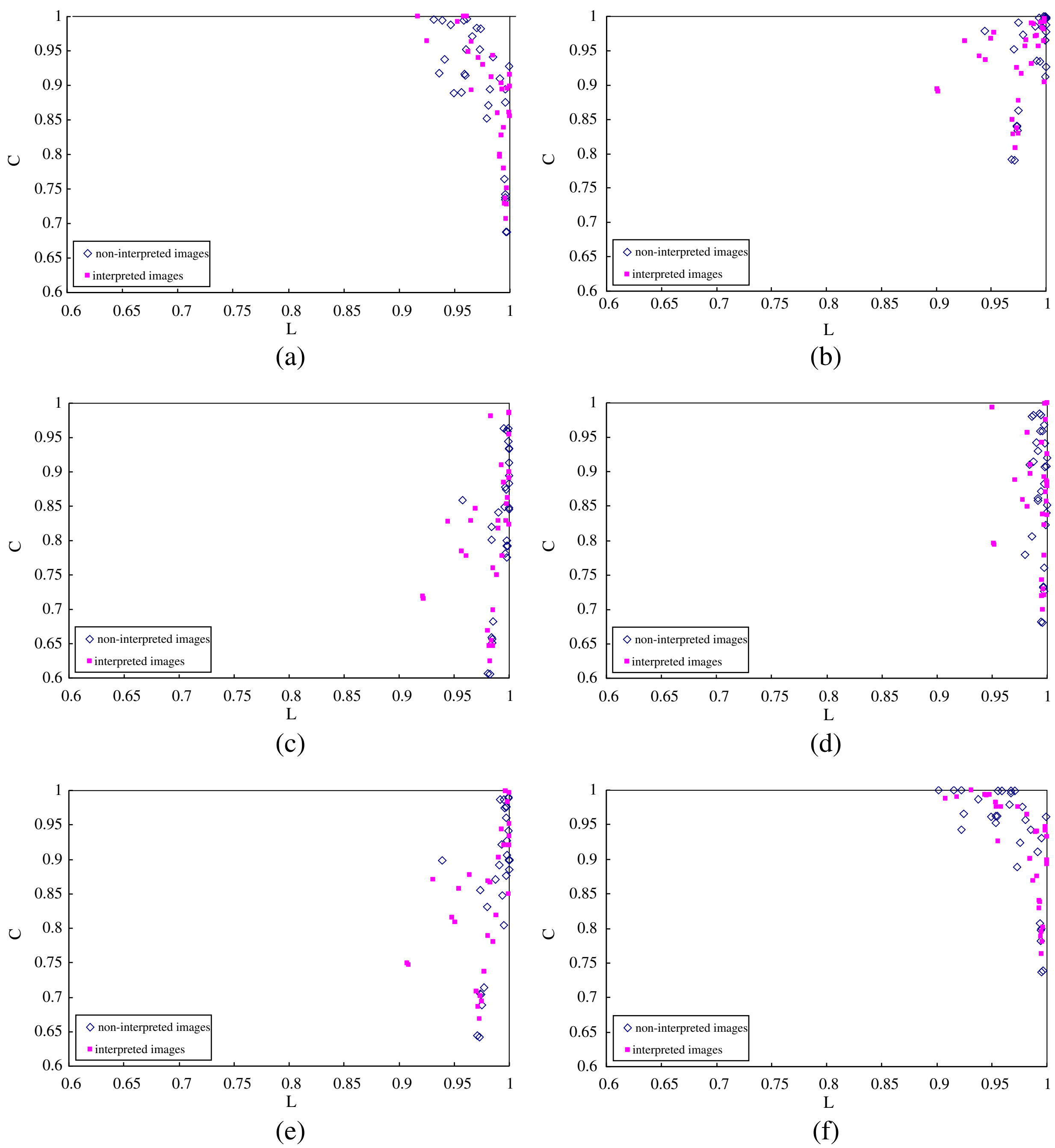

Fig. 3. *L* and *C* values of assessed CCTV images against each reference image of (a) Fractures multiple; (b) Hole; (c) Collapse; (d) Open joint; (e) Broken and (f) Deformed sewer.

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2.3. Image quality index

Let **X** and **Y** be the reference and assessed images, respectively. Also, $x = \{x_i | i = 1, 2, \ldots, N\}$ and $y = \{y_i | i = 1, 2, \ldots, N\}$ express the gray values between 0 and 255, and N represents the number of pixels. The proposed image quality index takes both luminance and contrast similarities into consideration and is defined as:

$$Q = L \cdot C, \tag{1}$$

where

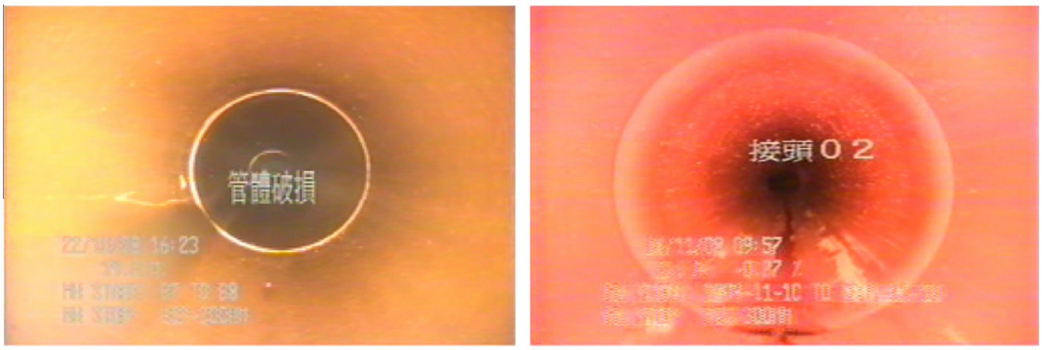
$$L = \frac{2\bar{x}\bar{y}}{(\bar{x})^2 + (\bar{y})^2}, \tag{2}$$

$$C = \frac{2\sigma_x\sigma_y}{\sigma_x^2 + \sigma_y^2}, \tag{3}$$

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i, \quad \bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i,$$

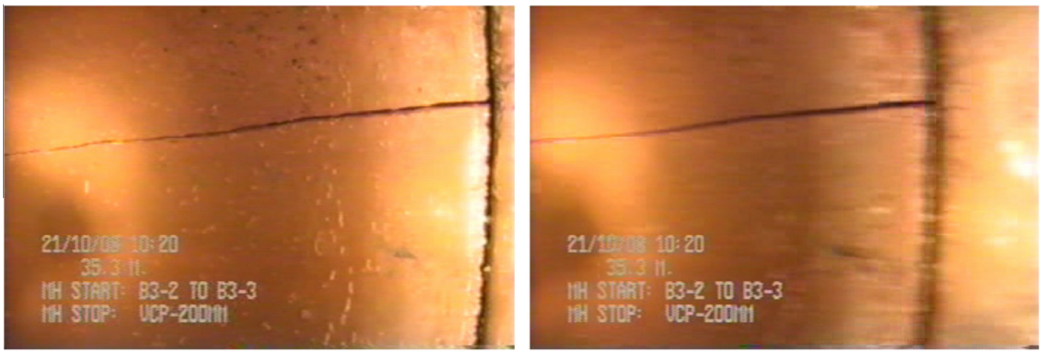
$$\sigma_x^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2 \quad \sigma_y^2 = \frac{1}{N-1}\sum_{i=1}^{N}(y_i - \bar{y})^2.$$

With a value range of [0 1], L represents the luminance similarity between x and y because gray levels are usually regarded as variations of image luminance (Strasburger, Wüstenberg, & Jäncke, 2002; Wang, Lu, & Bovik, 2004; Zhang, Lin, & Xue, 2005). With a value range of [0 1], C represents the contrast similarity of the images due to σ_x and σ_y being regarded as estimate of the contrast of X and Y (Franti, 1998; Wang & Bovik, 2002; Wang, Lu, et al., 2004). With L and C values approaching to 1, the assessed image has a high similarity of luminance and contrast, respectively, that represents better image quality.



(a) (b)

Fig. 4. (a) CCTV imaging inside VCP pipe and (b) CCTV imaging inside PVC pipe.



(a) (b)

Fig. 5. CCTV imaging inside VCP pipe in (a) a static state and (b) a rotating state.

Table 2
Results of the CCTV image quality assessment.

Ref. images	Interpreted images						Non-interpreted images					
	L		*C*		*Q*		*L*		*C*		*Q*	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
FM	0.9813	0.0219	0.8755	0.0890	0.8578	0.0755	0.9722	0.0214	0.8931	0.0952	0.8670	0.0822
H	0.9729	0.0272	0.9330	0.0567	0.9081	0.0674	0.9888	0.0143	0.9469	0.0667	0.9368	0.0737
C	0.9818	0.0216	0.8079	0.1051	0.7941	0.1114	0.9929	0.0094	0.8256	0.1093	0.8202	0.1125
OJ	0.9897	0.0150	0.8649	0.0890	0.8560	0.089	0.9938	0.0052	0.8693	0.0941	0.8638	0.0930
B	0.9765	0.0258	0.8455	0.1018	0.8270	0.1127	0.9888	0.0139	0.8697	0.1075	0.8607	0.1131
DS	0.9757	0.0268	0.9111	0.0756	0.8876	0.0600	0.9658	0.0278	0.9286	0.0831	0.8954	0.0688

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In this research, L and C values are calculated for the assessed CCTV images against each identified reference image of the total M frames of reference images. Thus, the proposed image quality index can be rewritten as:

$$Q = \frac{1}{M}\sum_{j=1}^{M}\frac{4\overline{(x)}_j\bar{y}(\sigma_x)_j\sigma_y}{[(\sigma_x^2)_j+\sigma_y^2][(\bar{x})_j^2+(\bar{y})^2]}. \tag{4}$$

3. Application of CCTV image quality assessment

3.1. Identification of reference images

In the beginning, this study adopts eight typical defect CCTV images of sewer inspection to be the candidates of the reference images from the manual of sewer condition classification (UK water industry engineering and operations committee, 1994) as the candidates of the reference images (see Fig. 2). In order to assure the reference images with acceptable qualities, these eight candidate images were executed an intra image quality assessment before the image quality assessment of sewer inspection. Table 1 shows the intra image quality assessment result in-between the sample images. Q value was calculated for each CCTV sample image by averaging all individual similarities against the other seven sample images as a symmetrical matrix (see Table 1). Table 1 shows that the Q values of "Debris" and "Spalling Large" are below the threshold of 0.9. Furthermore, the sample images of "Debris" and "Spalling Large" compared to the other six sample images have the significantly lower Q value of 0.6372 which is obtained by multiplying the L value of 0.865 by the C value of 0.7367. Thus, the images of "Debris" and "Spalling Large" were abandoned and the other six sample images remain in the ideal data set as reference images.

3.2. Analysis of image quality

For the sewer inspection project, most CCTV images were calculated with Q values above 0.8 that represents an acceptable image

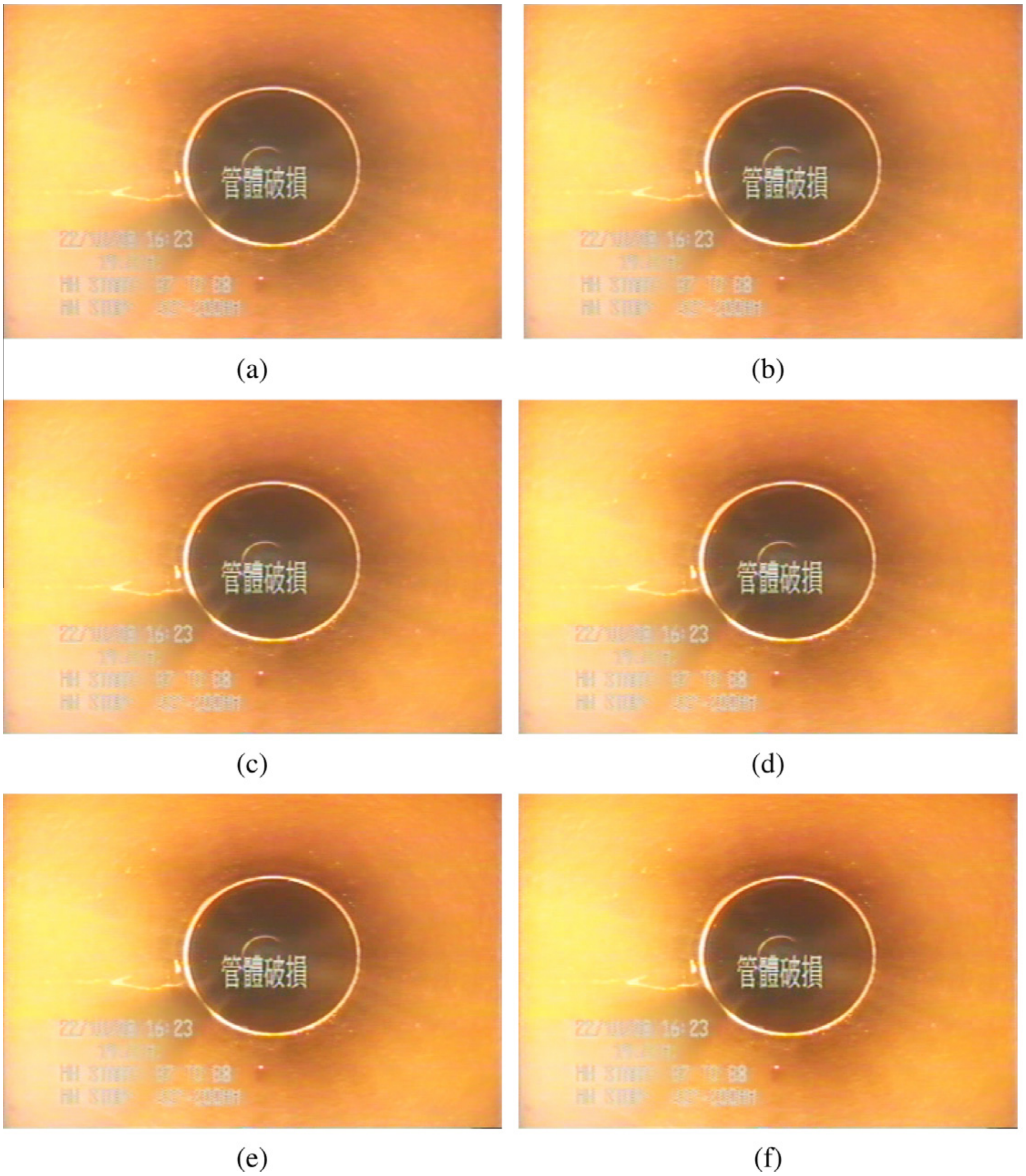

Fig. 6. Contrast enhancement for the VCP image by (a) +10%; (b) +20%; (c) +30%; (d) +40%; (e) +50%; (f) +60%; (g) +70%; (h) +80%; (i) +90%; (j) +100%.

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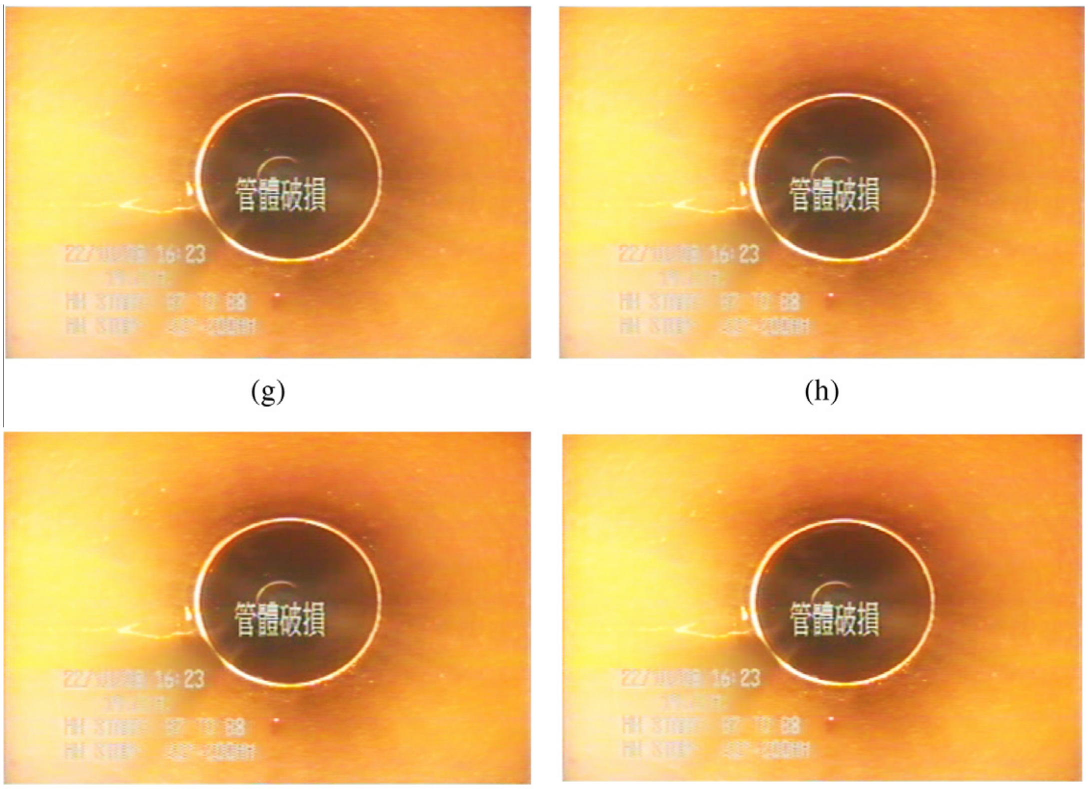

(g) (h)

(i) (j)

Fig. 6 (*continued*)

quality. Fig. 3 shows the scatter diagrams of luminance similarity versus contrast similarity of the interpreted and non-interpreted CCTV images. The closer to the top right corners of the diagrams the spots are, the more similar the reference and assessed images are. Comparing the diagrams in Fig. 3, we found that most spots on Fig. 3(b) are significantly closer to the top right corner of the diagram than the spots on the other diagrams. It indicates that most of the 60 assessed CCTV images are extremely similar to the reference image of "Hole" in both luminance and contrast. Additionally, C values are found with a wider distribution than L values that reveals contrast as a quality control factor rather than luminance. We also examined the luminance and contrast similarities for all assessed CCTV images and found that most CCTV images with C values below 0.85 were shot inside the PVC pipes. Fig. 4 shows two CCTV images of "pipe-joints" for example that were shot inside the VCP and PVC pipes. The L, C, and Q values of the VCP and PVC images are 0.9757, 0.8971, 0.8754 and 0.9853, 0.7317, 0.7209, respectively. Due to a comparatively low C value, PVC image has a low image quality that can be efficiently improved by enhancing image contrast.

Sometimes the CCTV imager was rotated to take an insight shot for the pipe defects. Fig. 5 shows two CCTV images which were respectively shot in a static state and a rotating state. Obviously, the CCTV image taken in a rotating state looks blurring. The rotated imager caused a less luminance distortion (with L value of 0.9823 decreasing from 0.984 in a static state) but a large contrast distortion (with C value of 0.8752 decreasing from 0.909 in a static state) that is the major reason resulting in lower CCTV image quality.

In order to estimate the difference of the image quality between the 30 interpreted CCTV images and the 30 non-interpreted ones, the means and standard deviations of L, C, and Q values are calculated as Table 2. The Q values of the interpreted images are slightly worse than those of the non-interpreted ones that is opposite to our expectation to take better images for defect inspection. The image quality of the interpreted images remains to be improved to be more distinguishable. Expectedly, this image quality index can direct the on-site technicians of sewer inspection to concisely adjust contrast and luminance to take better CCTV images. Furthermore, the deviations of the L values are significantly smaller than those of the C values for all assessed CCTV images. In other words, the contrast enhancement for image quality improvement has a larger impact than luminance enhancement. For a CCTV sewer inspection project, offering the CCTV images with a proper luminance is much easier than acceptable contrast that needs a great effort. Therefore, this research implemented a sensitivity analysis of contrast enhancement to observe the improvement of the CCTV image quality.

3.3. Sensitivity analysis of contrast stretch for image quality

Due to the larger deviations of the C values compared to the L values, a sensitivity analysis of contrast stretch were implemented on those two CCTV images in Fig. 4 to observe the image quality improvements. Based on the image histograms, both CCTV image contrast were enhanced from 0% through 100% at an interval of every 10% stretch (see Figs. 6 and 7). Fig. 8 is the sensitivity analysis result of contrast stretch and shows that the image contrast enhancement decreases the contrast distortion and improves the CCTV image quality in spite of the worsen luminance distortion. Especially for the image of PVC pipe, the image quality improvement significantly depends on the enhanced contrast (see Fig. 8(b)). Fig. 8 also reveals that the efficiency of the contrast enhancement varies with the sewer pipes materials. Contrast adjustment performed better on the sewer pipes made of PVC than

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VCP due to their reflectance characteristic. Also, the sensitivity analysis data as Table 3 shows that the enhanced contrast from 10% through 100%, the quality of the images of VCP and PVC pipes were improved 5% and 12%, respectively. In conclusion, the image quality can be effectively improved just by contrast adjustment.

4. Discussion and conclusions

In the past, on-site technicians usually do not pay great attention to the CCTV image quality of sewer inspection or even have no idea about how to assess the CCTV image quality. Taking luminance distortion and contrast distortion into consideration, this paper proposes an image quality index which has been successfully applied to CCTV images from sewer inspection of a house-connection project. Adopting six frames of CCTV sample images as reference images after an intra image quality assessment, we established the ideal CCTV image data bank to assess CCTV image quality by comparing the similarity of luminance and contrast. There are 60 (30 interpreted and 30 non-interpreted) frames of CCTV images were retrieved from the CCTV inspection video streams to be examined through the CCTV image quality assessment. We found that the image quality of the interpreted CCTV images are little poorer than those of the not-interpreted ones that remains a great progress to make better image quality for interpretation.

Based on the analysis of image quality, it is also concluded that contrast compared to luminance has the larger impact on the CCTV inspection image quality. Moreover, the imaging environments of sewer inspection, such as pipe materials and imager status, also would cause a great difference of image contrast. A sensitivity analysis of contrast stretch illustrates that contrast enhancement can efficiently improve the CCTV image quality even though a slight luminance distortion could occur.

Due to the simplified mathematic calculation of the CCTV image quality index, only less than 0.1 s is taken to process the MATLAB

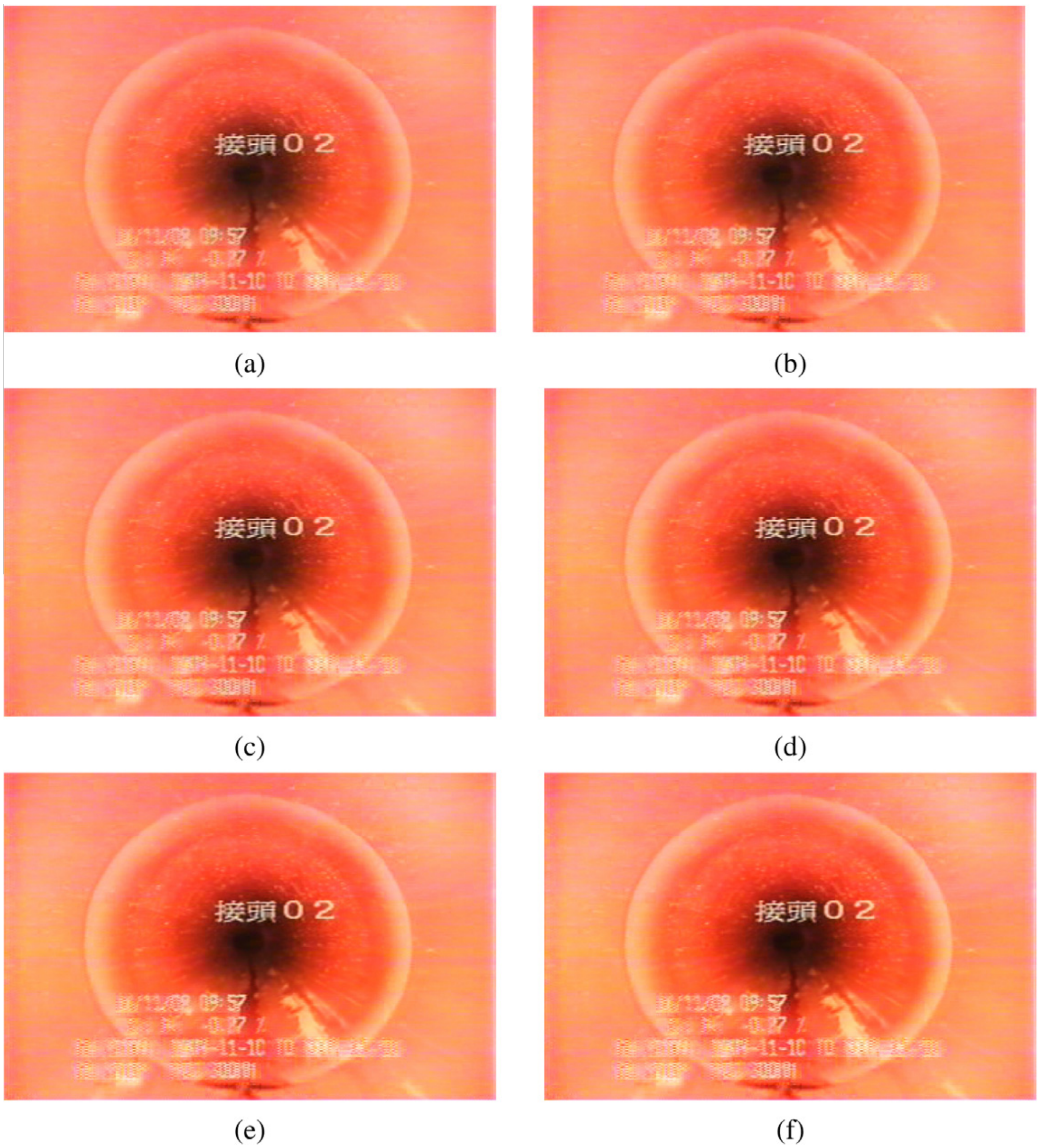

Fig. 7. Contrast enhancement for the PVC image by (a) +10%; (b) +20%; (c) +30%; (d) +40%; (e) +50%; (f) +60%; (g) +70%; (h) +80%; (i) +90%; (j) +100%.

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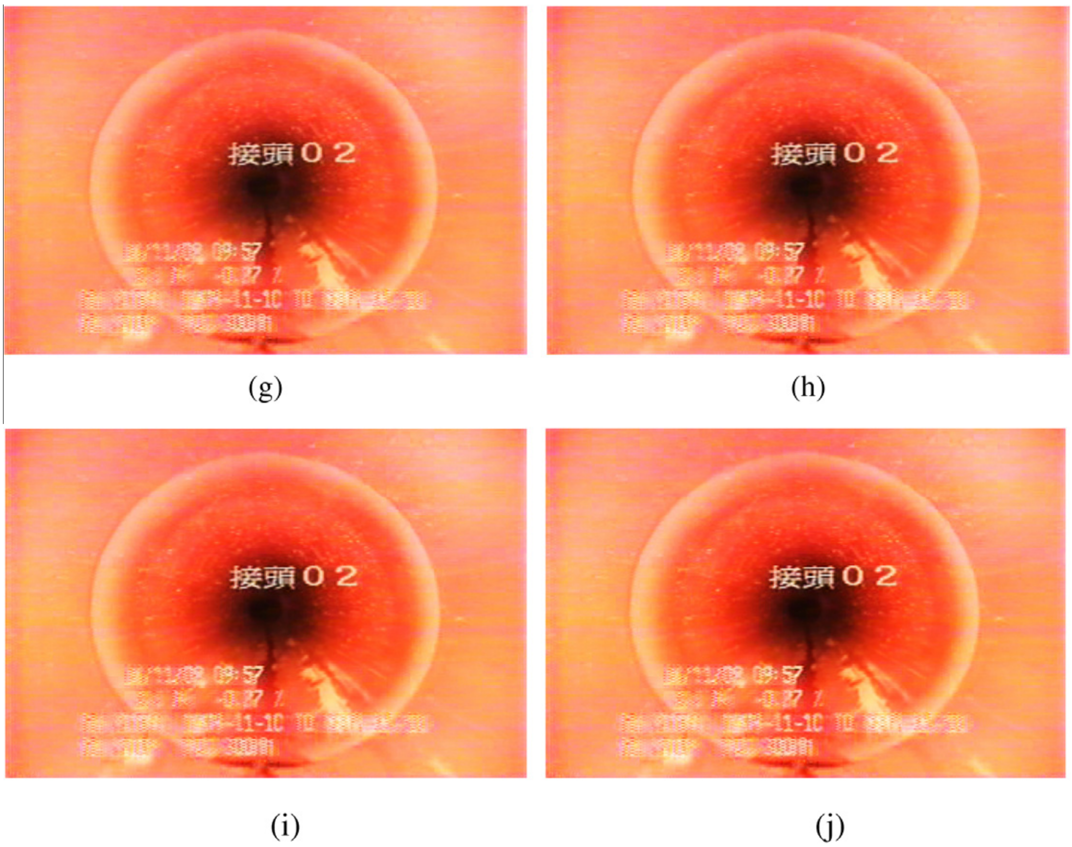

Fig. 7 (*continued*)

Table 3
Sensitivity analysis of contrast stretch for the images of VCP pipe and PVC pipe.

Image	Contrast enhancement (%)	*L*		*C*		*Q*	
		Value	Improvement	Value	Improvement	Value	Improvement
VCP pipe	0	0.9757	–	0.8971	–	0.8754	–
	+10	0.9745	−0.0012	0.9043	0.0072	0.8814	0.0060
	+20	0.9731	−0.0026	0.9120	0.0149	0.8875	0.0121
	+30	0.9716	−0.0041	0.9187	0.0216	0.8927	0.0173
	+40	0.9701	−0.0056	0.9253	0.0282	0.8978	0.0224
	+50	0.9685	−0.0072	0.9315	0.0344	0.9023	0.0269
	+60	0.9669	−0.0088	0.9372	0.0401	0.9064	0.0310
	+70	0.9652	−0.0105	0.9428	0.0457	0.9101	0.0347
	+80	0.9635	−0.0122	0.9478	0.0507	0.9134	0.0380
	+90	0.9616	−0.0141	0.9528	0.0557	0.9164	0.0410
	+100	0.9597	-0.0160	0.9572	0.0601	0.9189	0.0435
PVC pipe	0	0.9853	–	0.7317	–	0.7209	–
	+10	0.9850	−0.0003	0.7409	0.0092	0.7298	0.0089
	+20	0.9848	−0.0005	0.7507	0.0190	0.7392	0.0183
	+30	0.9844	−0.0009	0.7596	0.0279	0.7478	0.0269
	+40	0.9841	−0.0012	0.7688	0.0371	0.7566	0.0357
	+50	0.9838	−0.0015	0.7776	0.0459	0.7650	0.0441
	+60	0.9834	−0.0019	0.7861	0.0544	0.7730	0.0521
	+70	0.9830	−0.0023	0.7947	0.0630	0.7812	0.0603
	+80	0.9826	−0.0027	0.8026	0.0709	0.7886	0.0677
	+90	0.9822	−0.0031	0.8111	0.0794	0.7967	0.0758
	+100	0.9818	−0.0035	0.8188	0.0871	0.8039	0.0830

code on a four CPUs of 2.5 GHz PC that is sufficient for providing an in-time imaging direction. Thus, quantifying the CCTV image quality by the proposed image quality index can efficiently assist the on-site technicians in precisely shooting better CCTV images to diagnose the pipe defects. In the future, a real-time CCTV imaging adjustment system based on the image quality index can be expectable and practicable for the practical applications of on-site sewer inspection.

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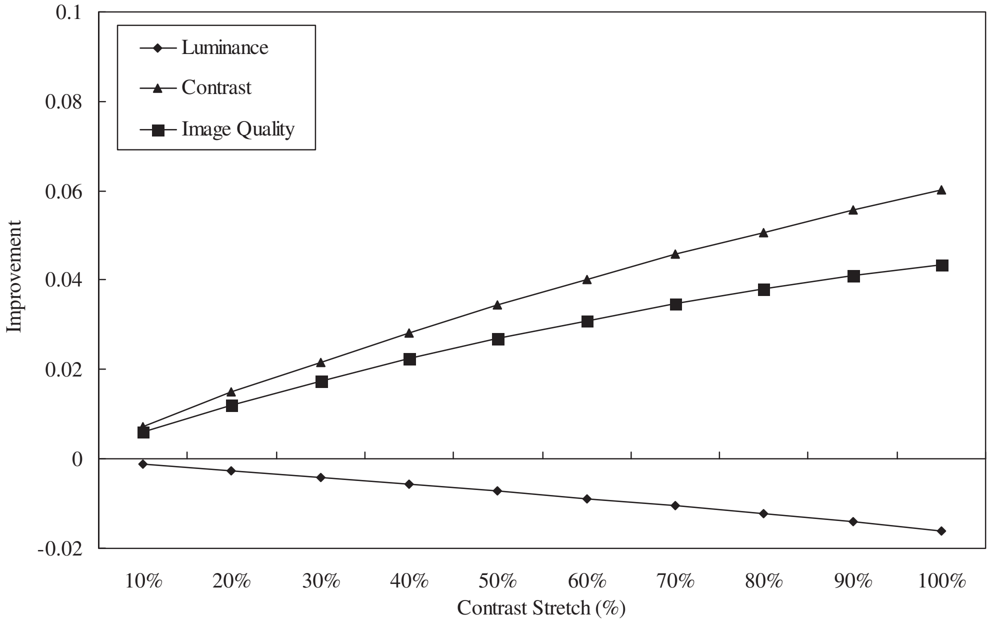
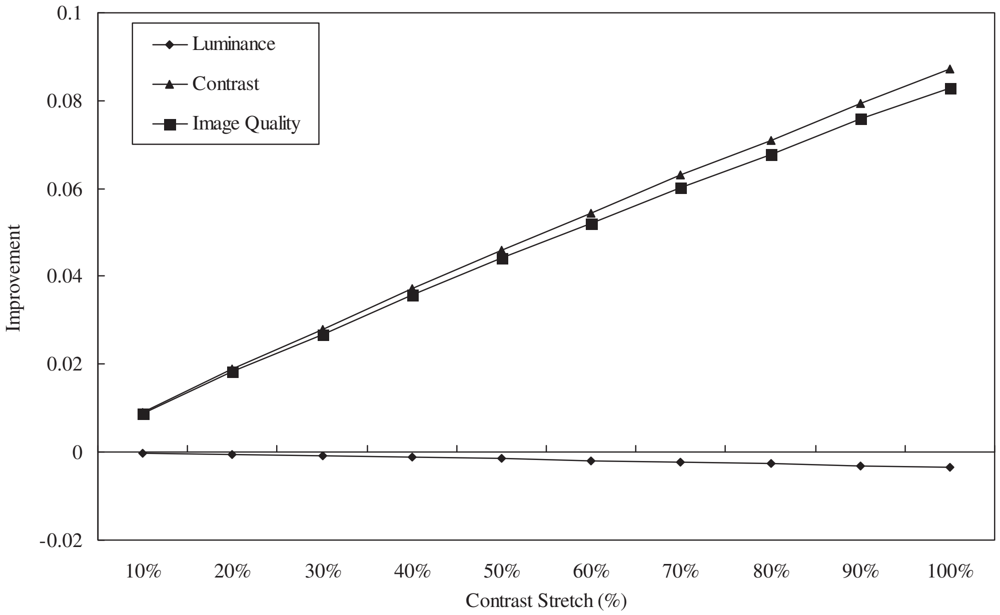


(a)



(b)

Fig. 8. Sensitivity analysis of contrast stretch for (a) VCP image and (b) PVC image.

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