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# Damage assessment for concrete structure using image processing techniques on acoustic borehole imagery

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ABSTRACT

The deterioration of concrete structures is a growing problem worldwide. Drilled cores are usually collected from large dams for testing the concrete and rock foundation underneath to assess their safety. However, the borehole itself can be used to assess cracks and other damage and collect additional information on the surrounding materials. This paper evaluates various edge-detection algorithms, as well as transform and statistical-based methods, for their effectiveness in assessing damage in a concrete dam from digital borehole imagery obtained using an acoustic televiewer. The statistical-based approach was found to be the most efficient technique for damage assessment from acoustic imagery. A clustering technique was used to quantify damage from the imagery, such as vertical cracks, horizontal cracks, voids, stains, and foundation damage. Results were verified using log data. Further damage analysis consisted of determining minimum, maximum and mean crack-width openings.


## 1. Introduction

The deterioration of concrete infrastructure is a growing problem worldwide; many structures are approaching the end of their service lives and need maintenance or rehabilitation in order to remain functional. In spite of recent increases in public infrastructure investments, infrastructure is deteriorating faster than it is being renewed. Factors such as low funding, population growth, tighter health and environmental requirements, poor-quality installation, inadequate inspection and maintenance, and lack of consistency and uniformity in design, construction and operation practices have adverse effects on concrete infrastructure. At the same time, increased loading due to significant growth in some sectors tends to accelerate the structural ageing process while increasing the social and monetary costs of service disruptions due to maintenance, repairs or replacement [1].

Various factors can contribute to the deterioration of concrete infrastructure; mechanical stress and fatigue, and chemical and environmental conditions are among the major causes of concrete distress [2]. Damage, such as cracks, may exist in concrete even before the structure is subjected to any external loading. An excessive water–cement ratio, improper curing, and creation of high temperatures during the hardening process may result in shrinkage, which is the direct cause of cracking. These cracks later expand and widen during service due to freeze and thaw cycles and the intrusion of moisture. This process is especially critical for large concrete structures, such as dams, due to the placement of massive amounts of concrete during construction. Even an initially sound concrete dam can develop cracks during its service life. Since a concrete dam is always in contact with water, relatively small-sized cracks will eventually become wider and develop into holes or delaminations, presenting future safety and serviceability problems for the dam [3].

Large dams are among the most critical structures. Their safety and stability are closely related to their resistance to sliding, which strongly depends on the condition of the concrete and bedrock along horizontal (or sub-horizontal) planes formed by concrete cold joints generated by step-wise successive construction, dam foundation, and decompression joints or bedding in the shallow bedrock.

Assessing the safety of concrete gravity dams against sliding requires a detailed investigation of the cracks and other discontinuities in the concrete structure and the rock foundation underneath. This is achieved through characterization of the mechanical properties of the materials (concrete and rocks), and especially the shear strength of the different types of discontinuities found throughout the structure and the foundation.

Traditionally, a log is kept of the discontinuities found in cores drilled from the investigated structure. This method has the

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advantage of providing specimens for petrographic examinations and allows the testing of specific properties, such as compressive strength, Young modulus or permeability. However, information on the condition of the discontinuities is sometimes altered or lost due to drilling operations, even if a triple-tube coring system is used. For instance, cracks might be created during drilling or transportation of the samples. Also, planes of cohesive weakness can separate after drilling, which modify the evaluation of the shear properties of the structure. The orientation of the core is another parameter that can be lost during drilling, if the procedure is not properly done.

Since drilled cores are usually collected from dams for testing concrete and rocks, the borehole itself can be used to perform a detailed investigation and collect additional information on the surrounding materials. Borehole geophysical logs have been used for more than 50 years, mainly for oil mining. These methods provide continuous quantitative and statistical measurement of the depth, thickness, and orientation of features such as fractures and joints. Borehole imaging can actually provide better data than core samples, since the equipment used (the *televiewers*) depict in-situ conditions, and are not subjected to incomplete core recovery. Furthermore, tools are magnetically referenced to true north, thus eliminating the need for oriented cores.

## 2. Image analysis in NDT

Non-destructive testing (NDT) of materials is the characterization, discrimination and prediction of material defects non-destructively [4]. NDT techniques are used to assess the condition of concrete structures, predict future performance, and monitor repair systems.

With the growing popularity of digital signal processing throughout the last few decades, image analysis methods have been increasingly used in NDT problems. The use of image processing techniques on NDT image data is a relatively new field of research in the development of models for monitoring and evaluating concrete structures. Traditionally, visual inspection and non-imaging NDT approaches were employed to evaluate the condition of a concrete structure in service, offering only superficial qualitative information. Through the use of models based on image analysis techniques, NDT imaging methods can provide more accurate, quantitative concrete data. Consequently, there is an increasing need for precise and reliable methods that use NDT imaging techniques. Such tools will enable the prediction of the future performance of infrastructure in order to allocate limited funds to optimize maintenance, improve serviceability, and reduce life-cycle costs.

A variety of image processing techniques can be used to characterize the damage in concrete data; among these methods are edge-detection algorithms [5]. Edges are considered to be areas with strong intensity contrasts in an image, causing a jump in intensity from 1 pixel to the next. In image data of damaged concrete, these edges would characterize boundaries between areas of sound concrete and deterioration, such as cracks. Other approaches used for damage characterization include transform-based techniques. Wavelet transforms are powerful tools often employed in image processing applications. The main advantage of this transform remains in its ability to locally describe signal frequency content. Through the wavelet transform [6], an image is decomposed into several high-frequency images containing wavelet coefficients representing details with increasing scale and different orientations [7]. More specialized methods that may be used to detect deterioration in concrete images are statistical-based approaches. These techniques allow for the analysis of the textural content in an image. Statistical texture methods analyse the spatial distribution of grey values by computing local features at each point in the image, and deriving a set of statistics from the distributions of the local features [8].

## 3. Research data

The data used in this research consists of very high resolution acoustic imagery taken from two boreholes drilled in a 50-year old lock located in Eastern Canada. Some examples of images exhibiting various types of damages are shown in Fig. 1. The boreholes, with diameters of 77 and 96 mm were drilled for a previous seismic tomography study and the recovered cores were tested for mechanical properties. The boreholes were not washed prior to the logging and parts of the borehole wall were covered with a thin mud layer made of concrete laitance.

Optical images were taken using an OBI-40 camera from Mount Sopris Instruments. Acoustic images were taken using an ABI-40 Televiewer; basic processing was performed using the WellCAD software of Advance Logic Technology. Acoustic borehole scanner tools generate an image of the borehole wall by transmitting ultrasound pulses from a rotating sensor and recording the amplitude and travel time of the signals reflected at the interface between mud and formation, which is the borehole wall. The amplitude is mainly affected by the reflecting material, while the travel time is affected by the distance between the probe and the borehole wall. The data is displayed as an unrolled picture of the borehole wall starting at 0–360°. The up-hole mode was used at a logging speed of 2 m/min for a vertical sample rate of one sample/1.7 mm. The horizontal sample rate was fixed at 252 samples/revolution. The image resolution is <2 mm, with an acoustic calliper that can measure fractures to 0.05 mm.

## 4. Image processing

### 4.1. Edge-detection algorithms

An edge is an image contour across which the brightness of the image changes abruptly. Possible causes for an intensity edge are discontinuities in the normal surface, depth, reflectance, and illumination.

In order to identify edges within an image, edge-detection operators analyse the grey level of each pixel and its neighbour to determine which ones belong to areas with sharp contrast in grey-level intensity. The basic edge-detection operator is calculated by forming a matrix centered on a pixel chosen as the centre of the matrix area. If the value of this matrix area is above a given threshold, then the middle pixel is classified as an edge. The slope and direction of the edge, also known as the magnitude and the orientation of the gradient vector, are usually used to establish the areas of contrast.

Most edge-detection approaches may be categorized as first- or second-order methods., First-order operators, also known as gradient methods, consist of such approaches as the Roberts' Cross and Sobel operators [9,10]. A common second-order technique, also known as a Laplacian operator, is the Marr–Hildreth approach [11].

### 4.2. Gradient-based techniques

Edge-detection based on gradient methods find edges by calculating an estimate of the gradient magnitude in the first derivative, and comparing this estimate to a fixed threshold to determine edge points. A fast rate of change of intensity at some direction given by the angle of the gradient vector is observed at edge pixels. The magnitude of the gradient indicates the strength of the edge. All the gradient-based algorithms have kernel operators that calculate the strength of the slope in directions, which are orthogonal to