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Measuring the in situ deformation of retaining walls by the digital image correlation method

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ABSTRACT

In this study, the digital image correlation (DIC) method was used to monitor the full-field deformation of a retaining wall. Two retaining walls located in mountainous areas of Taiwan were investigated. The first, Fushan slope, was characterized by substantial long-term deformation, and the second, Bulao slope, was located beneath an expressway and was severely damaged by Typhoon Morakot. This paper first describes the preparation procedures for in situ applications of the DIC method. Various environmental factors such as fog, rain, light direction, and spot mark clarity affected measurement precision, and consequently produced monitoring images that were unsuitable for further analysis. The DIC analysis results clearly indicate the deformation pattern of the retaining walls. The proposed method is accurate and effective for performing long-term monitoring of retaining walls, and the results can be used to accurately predict the tendency, location, and quantity of retaining wall displacement. Therefore, the proposed DIC method can be implemented to prevent disasters caused by landslide.

1. Introduction

Located in a sub-tropical area, Taiwan experiences typhoons during the summer and a mean precipitation of 2500 mm per year, and up to 3000 mm per year in mountainous areas. The high amount of rainfall accompanying typhoons frequently causes slope failures, such as landslides and debris flows. The dynamic effects of earthquakes also degrade slope stability because the island is located in the circum-Pacific seismic belt—an active mountain-building region. Therefore, slope disasters are a major natural hazard, and threaten human lives and the environmental ecology of Taiwan (Lin et al., 2004, 2011; Lee et al., 2008a, 2008b).

To protect communities and transport routes located in mountainous areas from slope disasters, retaining structures are commonly constructed where landslides are likely to occur. However, these retaining structures often deform, subside, slide, overturn, creep, and crack because of disruptive slope processes that occur during or after heavy rainfall. Therefore, monitoring the long-term deformation of a retaining wall is paramount to landslide hazard and risk assessment. Recently, various slope-monitoring techniques were developed to provide deformation information on a determined number of points within a landslide area (Keaton and DeGraff, 1996; Mikkelsen, 1996; Angeli et al., 2000; Coe et al., 2000; Corominas et al., 2000; Gili et al., 2000; Hervas et al., 2003; Tarchi et al., 2003). Two main approaches used to acquire the information are point-based (global positioning systems, total stations, extensometers, crack gauges, inclinometers, and tiltmeters) and area-based techniques (cameras, video recorders, laser scanning, and interferometric synthetic aperture radar). Compared with area-based methods, point-based techniques provide more precise information on the specific locations of displacement or deformation during active landslides. However, to obtain the overall deformation pattern of a landslide, numerous instruments that apply point-based measurement are required, the measuring procedures of which are usually time consuming. To achieve the low cost of equipment and highly precise measurements, the digital image correlation (DIC) method was used in this study to monitor the full-field deformation of a retaining wall.

The DIC method is a well-developed optical measuring technique used for obtaining the high-precision deformation distribution of a field. This measuring technique is based on research conducted by Chu et al. (1985) and was developed by combining deformation theory and digital images. To measure surface deformation from digital images, the DIC method is used to analyze random structural speckles on a surface, and subsequently produce a random grayscale distribution of the image surface. The characteristics of non-deformed and deformed images photographed at various times are compared based on the grayscale distribution, and the relative image positions are inferred accordingly. The displacement vectors of various image points are then calculated, and other physical values, such as strain, can also be inferred.

The DIC method was modified (Bruck et al., 1989; James et al., 1990; Chen et al., 1993; Vendroux and Knauss, 1998; Brillaud and Lagattu, 2006) to improve acquired image quality, algorithms, and image correlation processing to produce reliable and accurate strain mapping results. According to Sutton et al. (1991), the accuracy of the DIC method can be less than 0.01 pixels. The DIC method is being increasingly used in whole-field surface strain mapping applications that analyze various materials, including rock (Louis et al., 2007; Weng et al.,

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2009), granular material (Rechenmacher and Finno, 2004), metal (Melrose et al., 2004), concrete (Choi and Shah, 1997), and other materials (Mott et al., 1996; Muszyñski et al., 2002; Tung et al., 2008). In contrast with previous laboratory studies, this study adopted the DIC method to measure the in situ deformation of retaining walls. To obtain appropriate digital images for DIC analysis, the preparation procedures in the field were developed first. The acquired digital images were then analyzed to identify the deformation patterns in the monitoring area. Finally, the environmental factors that affected the in situ measuring precision of DIC were explored.

2. The DIC method

2.1. Theoretical basis of the DIC method

The theoretical basis of DIC is described as follows:The non-deformed image is referred to as Image *A* and the deformed image is referred to as Image *B*, as exhibited in Fig. 1. The coordinates (x, y) and (x^*, y^*) are related by the displacement function between the two images. If the motion of the object relative to the camera is parallel to the image plane, then the relationship between two points can be expressed as (Russell and Sutton, 1989)

$$x^* = x + u(x, y) \quad (1)$$

$$y^* = y + v(x, y), \quad (2)$$

where $u(x,y)$ and $v(x,y)$ are the displacement functions.

The non-deformed image is divided into discrete elements using the finite element method, displayed as the rectangular element, *a*, in Image *A* in Fig. 1. The pixel in the *i*th row and the *j*th column at the local coordinate is referred to as the (i, j) pixel. After deformation (Image *B*), Element *a* becomes Element *b*, and Element *b* can become non-rectangular through deformation. *P* and P^* are the central points of Elements *a* and *b*, respectively.

Although deformed Element *b* is illustrated in Fig. 1, the exact location of Element *b* is unknown until DIC analysis is complete. The goal of DIC analysis is to identify the locations of the deformed element in Image *B* associated with each non-deformed element in Image *A*. To identify the location of a deformed element, the pixel grayscale values of the associated elements are calculated before and after deformation. Theoretically, the pixel grayscale values should be identical. Nevertheless, the two digitized images are compared and a local correlation function of the two images is determined by using the least squares matching method. The following image correlation function (Chu et al., 1985) is used to determine the degree of similarity between the two images:

$$COF = \frac{\sum g_{ij}\tilde{g}_{i*j*}}{\sqrt{\sum g_{ij}^2 \cdot \sum \tilde{g}_{i*j*}^2}}, \quad (3)$$

where *COF* is the image correlation function, and g_{ij} and $\tilde{g}_{i^*j^*}$ are the grayscale values of the non-deformed element at (i, j) and the deformed sub-image at (i^*, j^*), respectively. The grayscale values of all points with integer coordinates are stored in a two-dimensional matrix, allowing the grayscale values to be directly used. The grayscale values of other non-integer points are obtained by interpolating the grayscale values of the closest four integer points.

Theoretically, when $COF = 1$, the deformed sub-image corresponds exactly to the non-deformed sub-image after deformation. The coordinate of the deformed sub-image can then be determined. However, *COF* occasionally cannot reach 1 because of deformation. Therefore, an optimal procedure is conducted to identify the maximal *COF* value. The Newton–Raphson method (Bruck et al., 1989) was used as the optimal procedure in this study. If the optimization procedure recognizes the optimal function parameter for every sub-image, the nodal displacements at the four corners of each sub-image can be obtained. The displacement field in the sub-image is then interpolated by using a bilinear function. The full-field displacement information is obtained by overlapping sub-images. The described method was used to monitor the movement of retaining walls located in mountainous areas of Taiwan. Before monitoring retaining wall deformation, this study verified the precision of the DIC method when used in the field. Two retaining walls were then studied. The first retaining wall was selected because it exhibited substantial long-term deformation. The second selected retaining wall was located beneath a principal expressway and was severely damaged by Typhoon Morakot. The following section describes the monitoring details of the two retaining walls.

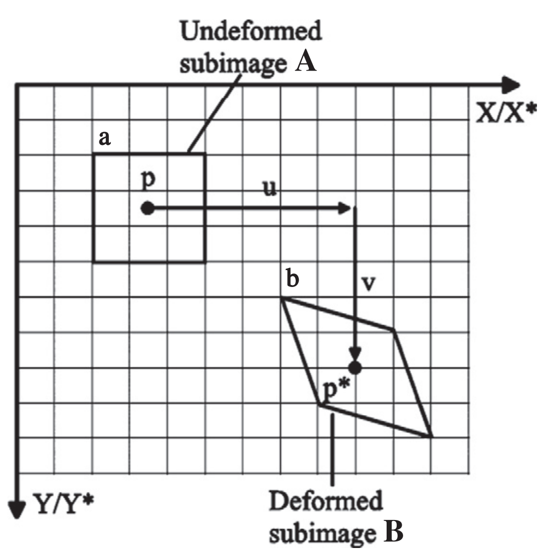

Fig. 1. Relationship between deformed and non-deformed sub-images.

2.2. Accuracy verification

A field experiment was first conducted to verify the accuracy of the DIC method when applied to an in situ experiment. An outdoor slope was chosen for the experiment to represent a real slope. The measurement accuracy of the DIC method in an environment where temperature, humidity, and sunlight were uncontrollable was then determined. The detailed experimental setup and results are described as follows.

2.2.1. Experimental setup

In this study, a Canon EOS 600D digital camera and a Canon EF 100 mm f/2.8 Macro USM lens were used. The distance between the camera and the observed target placed on the slope was approximately 115 m. The field of view of the camera was approximately 30 m × 20 m. A 60 cm × 80 cm board painted with black and white diamond-shaped blocks was used as a monitoring target. The diamond-shaped blocks had a diagonal length of 5.43 cm. The board was placed on an X–Y table located on the slope. The target arrangement is illustrated in Fig. 2.

To investigate the accuracy of the method when used to measure in-plane displacement, the target was moved in the X direction, as depicted in Fig. 2. Images for DIC analysis were photographed from − 60 mm to 60 mm.

2.2.2. Experimental results

Fig. 3 displays a typical analysis image. The figure indicates that the size of the target in the image is considerably small at approximately 120 pixels wide.

The analysis results are exhibited in Fig. 4a. These results demonstrate that a close linear relationship exists between the measured