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Measurement of deflections in buried flexible pipes by close range digital photogrammetry

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ABSTRACT

In this study, the monitoring of the load–deflection behavior of buried flexible pipes by digital close range photogrammetry was described. Experimental investigations were performed in a test box made of steel, with a Plexiglas front wall. An online vision system with three CCD cameras was developed to measure automatically the deflections of pipes during load tests. The system can also correct image distortions caused by refraction of light rays passing through different medias. The computational approach involves first determining camera calibration parameters, then calculating of object coordinates of targets placed on pipe wall section after each load step using the results of the calibration process. In loading tests, LVDTs were also used to measure the changes in vertical diameters of the pipes. The comparison of results obtained from both measurement systems indicated that photogrammetric system is reliable and accurate to monitor deflection behavior of pipes under loading conditions.

1. Introduction

The testing of buried flexible pipes under different loading conditions is a standard engineering application. Geometrical measurements are performed for the examination of the behavior of pipes and for the verification of theories or mechanical models. This is often realized by static, quasi-static, or dynamic short and long time load experiments on pipes. In these tests, it is desired to determine parameters and effects such as the change in shape, displacement, load and strain. Displacement measurements are commonly performed with wire strain gauges or inductive displacement transducers. Although these devices provide online results with a high geometric precision and reliability it has some serious disadvantages, such as only point wise and one-dimensional measurement capability [1–4].

In order to remove these disadvantages, digital photogrammetric techniques may provide a good alternative. The use of photogrammetry in pipe testing experiments allows the simultaneous measurement of displacements at an arbitrary number of locations. In order to be non-contact a measurement system, test object is not affected by measurement device or measurement device is not damaged during load tests. The precision potential of the method is high as compared to conventional techniques under suitable circumstances.

Photogrammetric techniques have been successfully used in a similar large number of metrology tasks such as testing of concrete slabs and columns [4], thermal deformation of steel beams [5], textile reinforced concrete probes in load tests [2], pavement deformation under rolling load [6] and beam deflections in load tests [3].

In this work, the use of digital photogrammetry for measurement of deflections in buried flexible pipes during load tests is described. A digital photogrammetric system, which can correct image distortions caused by refraction of light rays passing through different medias such as Plexiglas and air prior to entering the camera lens and can provide near real time measurement results, was developed and used to measure the deflections in buried flexible pipes during load tests. The system consists of two basic

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components: hardware and software. Briefly, hardware component comprise of image acquisition system and the software which was developed by using Borland C++ builder programming language contain photogrammetric processing of obtained image data. Twenty-six load experiments for three pipes with different diameters (300, 212, 100 mm) were carried out. The mean object point precision at the sub-millimeter level was achieved at each measurement epoch for these tests with the photogrammetric system. Furthermore, LVDTs were also used to determine the shortening in the vertical direction of flexible pipes in experiments. Measurement results obtained from both measurement systems were compared and it was demonstrated that the developed photogrammetric system is accurate and reliable to determine near real time load–deflection behavior of test objects.

In the following, the design of the photogrammetric measurement system is described. Hardware component and the used algorithms are given, and it is explained how measurement process of the system is carried out. Then, load experiments of buried flexible pipes performed by using photogrammetric system are depicted and finally, results of the project are summarized.

2. Data acquisition and calibration

Fig. 1 shows the setup of the used image acquisition system. The system consists of three progressive scan CCD cameras (Basler a302fc) with a resolution of 780×582 pixels and a pixel size of 8.3 μm^2. The CCD cameras mounted on a tripod that can move vertically and rotate around its vertical axis. The two outer cameras were fitted with 16 mm lenses, whereas the centre camera equipped with a Computar TV zoom lens with 12–70 mm focal length. The cameras were connected to a PC via the IEEE-1394 port allowing digital transmission of images.

Camera calibration and orientation procedures are a necessary precondition to obtain precise and reliable 3D metric information from images. For this reason, before each load test, the multiple camera system was calibrated by self-calibrating bundle adjustment method which is the most versatile and accurate photogrammetric positioning and calibration method. The mathematical model of the method is based on the collinearity condition which is implicit in the perspective transformation between image and object space:

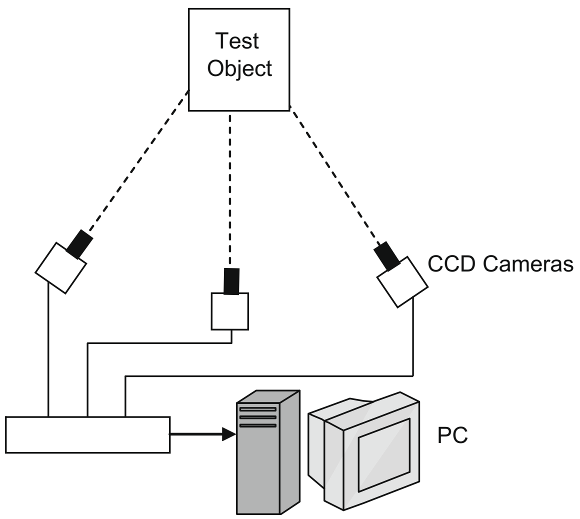

Fig. 1. The image acquisition system.

$$
\begin{aligned}
x - x_0 + \Delta x &= -c\frac{R_1}{R_3} \\
y - y_0 + \Delta y &= -c\frac{R_2}{R_3}
\end{aligned} \tag{1}
$$

with

$$
\begin{bmatrix} R_1 \\ R_2 \\ R_3 \end{bmatrix} = R \begin{bmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{bmatrix}
$$

where

x, y	Image coordinates of point
x_0, y_0, c	The interior orientation (IO) parameters
X, Y, Z	Object coordinates of point
X_0, Y_0, Z_0	Object coordinates of the perspective center
R	Orthogonal rotation matrix built up with the three rotation angles (ω, φ, κ) of the camera
$\Delta x, \Delta y$	Correction term of additional parameter set

The image coordinate correction terms Δx and Δy, which are functions of a set of additional parameters (AP) account for the departures from collinearity due to lens distortion and focal plane distortions. In our study, standard 10-term, 'physical' calibration model comprising interior orientation elements (x_0, y_0, c), lens distortion coefficients (k_1, k_2, k_3, p_1 and p_2) and terms for differential scaling and non-orthogonality of the image coordinate axes (b_1, b_2) as described by Fraser [7] were used.

$$
\begin{aligned}
\Delta x &= -x_0 - \frac{\bar{x}}{c}\Delta c + \bar{x}r^2k_1 + \bar{x}r^4k_2 + \bar{x}r^6k_3 + (r^2 + 2\bar{x}r^2)p_1 \\
&\quad + 2p_2\bar{x}\bar{y} + b_1\bar{x}b_2 + \bar{y} \\
\Delta y &= -y_0 - \frac{\bar{y}}{c}\Delta c + \bar{y}r^2k_1 + \bar{y}r^4k_2 + \bar{y}r^6k_3 + +2p_1\bar{x}\bar{y} \\
&\quad + (r^2 + 2\bar{y}^2)p_2
\end{aligned} \tag{2}
$$

with

$$
\begin{aligned}
r &= \sqrt{\bar{x}^2 + \bar{y}^2} \\
\bar{x} &= x - x_0 \\
\bar{y} &= y - y_0
\end{aligned}
$$

where

k_1, k_2, k_3	First three parameters of radial symmetric distortion
p_1, p_2	First two parameters of decentering distortion
b_1	Affinity
b_2	Non-orthogonality