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A deformation measurement system for geotechnical testing based on digital imaging, close-range photogrammetry, and PIV image analysis

Système de mesure de déformation pour l’expérimentation géotechnique basé sur l’imagerie numérique, photogrammetrie , et l’analyse d’image par PIV.

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ABSTRACT: A new technique for non-contact measurement of soil deformation in physical models and element tests is presented. This system combines digital photography, close-range photogrammetry and image analysis by Particle Image Velocimetry (PIV) to allow soil displacements to be detected to a precision of 1/15000th of the field of view. This is achieved without installing intrusive target markers in the observed soil. The precision of the PIV method and the photogrammetric reconstruction a demonstrated by a series of validation experiments, and the performance of the combined system is illustrated by three example applications.

RÉSUMÉ: Une nouvelle technique de mesure de déformation de sol sur model physique et essais en laboratoire est présentée. Ce système de mesure qui combine la photographie numérique, la photogrammetrie et l’analyse d’image par PIV (Particule Image Velocimetry) permet la détection de déplacements de sol avec une précision de 1/15000^{ième} du champ de vue. Ceci est réalisé sans l’installation de marqueurs cibles intrusifs dans le sol observé. La précision de la méthode PIV et de la reconstruction photogrammétrique est démontrée par une série d’expériences de validation. La performance du système est illustrée par trois exemples d’application.

1 INTRODUCTION

Reliable assessment of soil behaviour in element tests or physical models requires accurate measurement of deformations and strains. Figure 1 presents the strain ranges typically experienced during a variety of geotechnical processes. If element tests and physical models are to capture the relevant behaviour, they must be equipped with a deformation measurement system which can detect pre-failure strains of the order of 0.01%. In a typical element test, this strain level corresponds to a displacement of 5 μm.

The measurement of pre-failure strains in a physical model remains a difficult task. Displacement transducers can be placed at the boundary of a physical model, but these do not reveal the deformation pattern within the deforming soil. This goal is usually achieved by observing the movement of discrete target markers embedded in a plane of soil exposed by a transparent window. However, deformation measurements taken from target markers suffer significant limitations.

This paper describes an inexpensive, flexible system for physical models and element tests that provides non-contact measurement of soil deformation at pre-failure strain levels without recourse to target markers. The system combines three technologies: digital still photography, Particle Image Velocimetry (PIV) and close-range photogrammetry. The system is illustrated with three example applications.

2 IMAGE CAPTURE USING DIGITAL PHOTOGRAPHY

2.1 *Conventional image capture methods*

Photographic methods have long been used to measure soil deformation. Conventional film photography has been widely used to monitor the movement of target markers in reduced-scale geotechnical models (eg. Phillips, 1991; Mair, 1979). The deformation field is constructed by manual or semi-automatic measurement of the position of each target on the exposed film.

More recently, video capture has been used to monitor deformations in centrifuge tests (eg Allersma *et al*, 1994) and attempts have been made to measure triaxial test deformation by analyzing video footage (Obaidat & Attom, 1998).

The resolution of any measurement taken from a digital image is proportional to the object-space pixel size. Video capture in the European PAL format produces a nominal resolution of 732 x 549 pixels, although the number of photo-sensitive elements within a typical camera CCD is often considerably less. ‘Line jitter’ and the transmission of the analogue video signal through centrifuge sliprings can further reduce image quality.

2.2 *Digital still photography*

Digital still cameras allow the low-resolution and poor image quality of video capture to be overcome. An inexpensive digital still camera provides significantly improved resolution, without the disadvantages of analogue signal transmission. The images presented in this paper were captured using a Kodak DC280 digital camera, which offers a pixel resolution of 1760 x 1212.

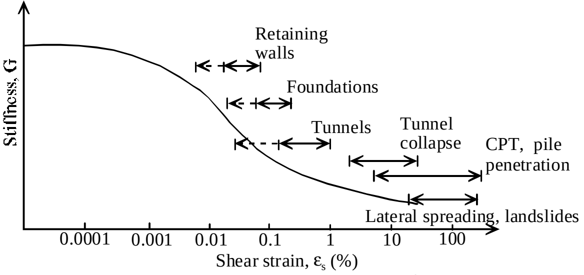


Figure 1. Typical strain ranges in geotechnics (after Mair, 1993)

3 DEFORMATION MEASUREMENT USING PIV

3.1 *Image space deformation measurement*

Having obtained a series of images depicting the element test or physical modeling event, the experimentalist must identify and measure some relevant deformations. In the case of film photography, this is achieved by physically measuring the exposed film (eg. Phillips, 1991), or by manually digitizing the pixel coordinates from the captured video image (eg. Saada *et al*, 1999). Manual measurement can only be used to track easily-identifiable features, and is subject to user errors. Manual digitizing limits precision to a single pixel.

The image processing technique of ‘blob tracking’ offers a less laborious approach when examining a grid of target markers. The centroid of the intensity peak created by a coloured target on a contrasting background is used to identify the location of that target. Chen *et al* (1996) found that under the test conditions of a typical centrifuge model, the RMS location error when locating target markers by centroiding can be 0.3 pixels.

Centroiding methods can only be used to track discrete targets markers. These do not provide detail in areas of high strain gradient, they can become obscured by soil leading to false measurements, and the location at which deformations are to be measured must be determined prior to the modeling event.

3.2 *Particle Image Velocimetry (PIV)*

An alternative technique for measuring the deformation of soil through a series of digitally captured images is Particle Image Velocimetry (PIV). PIV is a velocity-measuring technique that was originally developed in the field of experimental fluid mechanics (Adrian, 1991). By seeding the flow with texture in the form of polystyrene balls or powder, the velocity field is deduced by tracking small patches within a larger image.

The movement of soil within a physical model or element test can be treated as a low-velocity flow process. Image processing algorithms based on PIV have been written to track the movement of small patches of soil (typically 2-4mm in size) through a series of digital images (White *et al*, 2001).

3.3 *Precision of PIV*

It has been demonstrated that the planar movement of sand can be detected using PIV to a precision of 1/15th of a pixel (White *et al*, 2001). Using a Kodak DC280 camera this corresponds to a precision of 1/26400th of the field of view. This precision represents a displacement of 11µm in a typical centrifuge model (300 x 200 mm) and a displacement of 1.9µm over a typical 50mm gauge length in an element test.

Whilst the PIV technique eliminates the need for target markers to be placed within the deforming soil, some stationary reference markers should be placed in the image to allow soil movement to be isolated from movement of the camera. These reference markers can also be tracked by PIV.

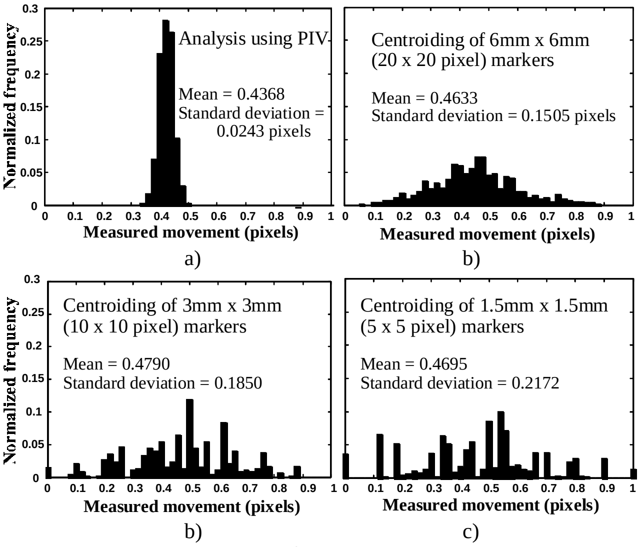
A validation experiment was used to assess the relative precisions of centroiding and PIV for detecting the movement of reference targets. A 150mm x 150mm calibrated photogrammetric target consisting of three grids of 1.5mm, 3mm and 6mm diameter reference dots was obtained from Edmund Industrial Optics, USA (figure 3d). The target was attached to a translating table below a fixed camera. A pair of images was obtained between which the table was translated by 0.4 pixels (≈50µm). The performance of the PIV method in measuring this small displacement of each reference dot was compared with area-based centroiding. Figure 2 shows the distribution of measured movements. These demonstrate that the PIV method can measure target movement to a precision of 1/40th of a pixel, which represents 1/70000th of the field of view. This is almost an order of magnitude better than was achieved by centroiding.

4 IMAGE CALIBRATION

Having measured the image-space coordinates of the deforming soil, these must be converted into model-space coordinates. This process is known as camera calibration. This has conventionally been achieved by linearly scaling the coordinates (eg. Saada *et al*, 1999, Obiadat & Attom, 1998, Allersma *et al*, 1994).

However, this is not a robust approach since: 1) the camera may not be perpendicular to the model plane and 2) the camera will not produce a perfect perspective projection. Also, the experiment may include a window through which the rays are refracted, or in a centrifuge test the camera lens may tilt under the increased g-level, leading to an apparent movement from which the true deformation must be isolated. Close-range photogrammetry allows these effects to be included in the image calibration.

To carry out camera calibration, the experimental apparatus must include a set of control targets whose model-space coordinates are accurately known. By measuring the image-space positions of these targets, the parameters which describe the image-space to model-space transformation can be deduced. The calibration routine developed in this research uses a total of 18 parameters to describe the model-space to image-space transformation. These parameters describe the position of the camera relative to the model-space coordinate system, the intrinsic camera parameters which define the linear perspective projection and the non-linear radial and tangential lens distortion. Refraction through a double layer window is modeled using Snell's Law.



a) b)

b) c)

Figure 2. Comparative precision of PIV and centroiding methods

During centrifuge testing, it was found that the intrinsic camera parameters of the digital still camera varied with g-level. It has been reported that the intrinsic parameters of a solid-state miniature video camera do not vary under centrifuge acceleration (Taylor *et al*, 1998), but this research has found that the more compliant arrangement of mechanical lenses in a digital still camera leads to some variation of the intrinsic parameters with g-level. To eliminate this effect, all camera calibration parameters are re-evaluated for each image within the sequence.

The precision of the calibration routine was evaluated using the calibrated photogrammetric target. The grid of target dots was photographed directly, and through a 50mm piece of Perspex, using a camera positioned perpendicular to the plane of the target. The measured image coordinates of these target dots were used to solve for the camera calibration parameters. Using these parameters, the target dots were reconstructed, and the deduced model-space coordinates compared with the known values.

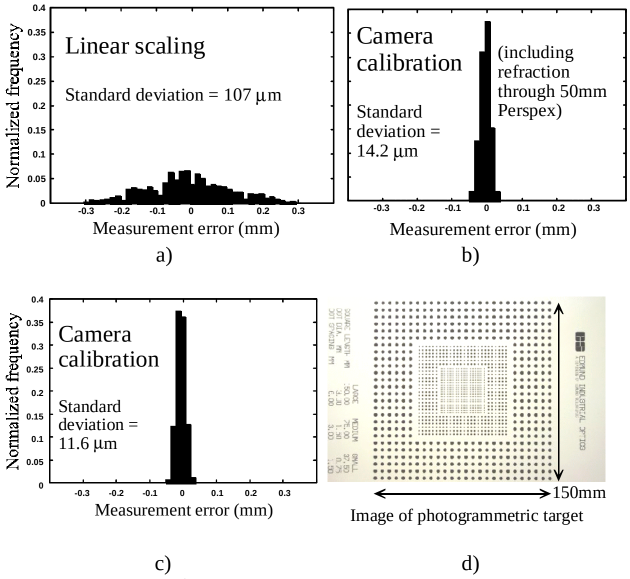
Figure 3 shows the distribution of model-space errors following reconstruction using linear scaling (figure 3a) and using camera calibration (figures 3b, 3c). The use of linear scaling produces errors of 108µm, which are reduced by an order of magnitude through camera calibration. Precision is reduced by 2µm when viewing through a thick layer of Perspex. Further calibrations using a smaller number of control points, which is more representative of a typical experiment, show that precisions of 13µm and 14µm are achieved using 12 control points with and without refraction respectively. This precision is equal to 1/18500th of the field of view.

5 SYSTEM APPLICATIONS

5.1 *System performance*

The overall precision of the system is found by combining the errors, expressed as a fraction of the field of view, accrued during the image measurement and calibration stages. The PIV measurement precisions have been shown to be 1/26400 and 1/70000 for tracking the soil and control points respectively, and calibration using 12 control points has a precision of 1/18500. Summation of these errors produces a precision for measuring planar deformation which is slightly better than 1/15000.

This precision compares favourably with other published photographic measurement techniques. The values of precision quoted in table 1 are those of the original authors. To allow each system to be compared, these have been normalized by the field of view used in the original reference.



a) b) c) d)

Figure 3. Precision of calibration routine

Table 1. Comparative system performance.

System	Reference	Capture	Analysis
1	This paper	Digital still	Auto PIV texture tracking
2	Taylor *et al* (1998)	Video	Auto target recognition
3	Allersma *et al* (1994)	Video	Manual ‘blob’ digitizing
4	Phillips (1991)	Film	Auto target recognition
5	Obaidat *et al* (1998)	Video	Manual feature digitizing
6	Saada *et al* (1999)	Video	Manual feature digitizing
7	Andrawes *et al* (1973)	Film	Hand measurement

System	Image calibration	Quoted precision	Normalised precision[1]
1	Photogrammetry	20 μm [2]	1/15000
2	Photogrammetry	60 μm	1/5600
3	Linear scaling	200 μm	1/500
4	Linear scaling	10 μm	1/5000
5	Linear scaling	150-230 μm	1/1300-1/2000
6	Linear scaling	130 μm	1/1400
7	Photogrammetry	5 μm	1/12000

[1] Normalised precision = quoted precision / width of field of view
[2] Over field of view of 300 mm x 200 mm

5.2 *Application: pile penetration in a calibration chamber*

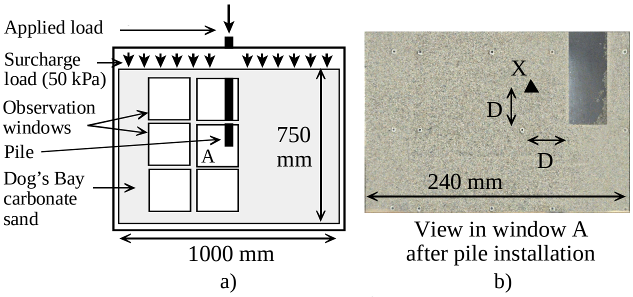
The strength of piles driven into sand is arguably the topic of greatest uncertainty in foundation design (Randolph *et al*, 1994). There is no accepted consensus for the mechanism by which a pile penetrates soil (i.e. the soil displacement and strain fields).

To address this uncertainty, a plane strain calibration chamber (1000 x 850mm) with transparent observation windows has been constructed (figure 4a). A model pile (D=32 mm) is jacked into the chamber whilst the resulting soil displacement is captured by digital photography. The deformation system described in this paper is demonstrated using a test on carbonate sand.

A sequence of 250 images was captured as the pile was jacked to a depth of 360 mm. Figure 4b shows the final image. To demonstrate this measurement system, three patches of soil that form the nodes of a triangular element located at point X in the final image have been tracked throughout the penetration.

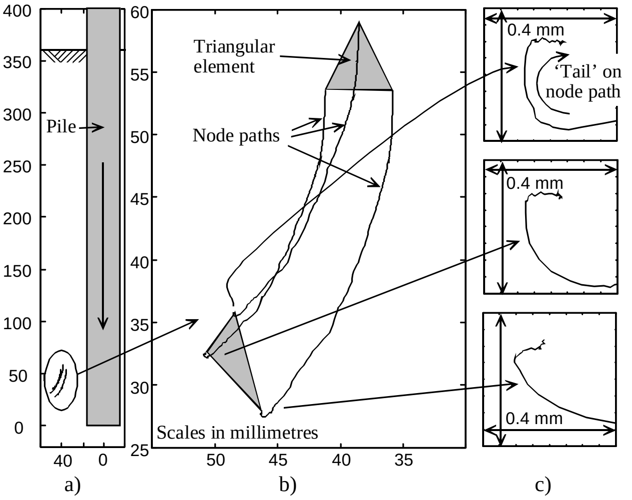
The paths of the three nodes of element X relative to the advancing pile are shown in figure 5a, and enlarged in figure 5b. The nodes travel a total distance of approximately 30mm, with large shear distortion and rotation clearly evident. The precision of the PIV technique is demonstrated by the detection of a small ‘tail’ on each trajectory after the pile passes. Each node moves towards the pile by a distance of approximately 100 μm (approximately 1/3 of the D_{50} grain size).

Enlargement of these ‘tails’ (figure 5c) reveals noise of the order of 10μm; slightly above the calculated precision quoted in section 5.1. These node paths show that PIV is both precise enough to resolve very small increments of movement and robust enough to track deforming soil through very large strains and rotations.



a) b)

Figure 4. Plane strain calibration chamber for pile testing



a) b) c)

Figure 5. Selected node paths during pile penetration

5.3 *Application: embankment settlement in a centrifuge test*

The progressive failure of clay embankments due to consolidation and swelling during climatic cycles cannot easily be modeled numerically and requires many years of field observation if useful data is to be acquired. To provide an inexpensive alternative, which yields useful data in a short time frame, centrifuge modeling in a plane strain strongbox has been carried out.

Figure 6 shows the crest of the model embankment with the black control points on the Perspex window clearly visible. During swing-up to a centrifuge acceleration of 60g, the image changes due to two effects. Firstly, the embankment settles due to the increasing self-weight, moving downwards through the image. Secondly, the camera lens is pulled downwards due to the centrifuge acceleration, causing an apparent upward movement.

Figure 7 shows the apparent movement of the embankment, due to the superposition of these two effects. The apparent movement of the control points due to deflection of the camera is shown in figure 6 to be around 70 pixels (≈10 mm). This movement is eliminated by the camera calibration routine (figure 8). Despite being dwarfed by the apparent movement due to camera deflection, settlement of 1.3 mm (≈10 pixels) is evident.

The displacement field shown in figure 8 consists of over 900 vectors. This is significantly more measurements than have been made in previous similar tests using target markers (eg. Sharma, 1994). Installing 900 targets is impractical and the resulting dense grid of inclusions may influence the observed behaviour. In contrast, the PIV technique allows many more measurements to be made, without recourse to target markers.

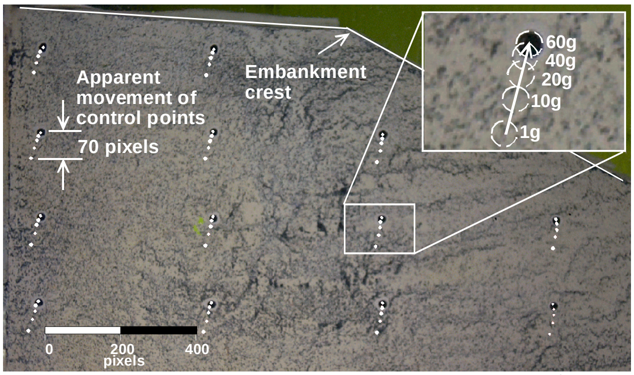


Figure 6. Image-space control point movement due to camera deflection

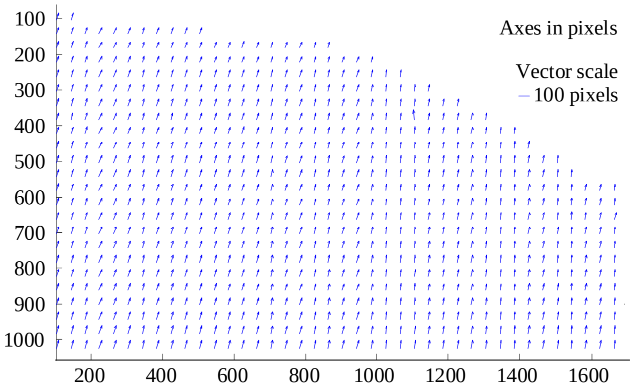


Figure 7. Displacement vectors deduced without camera calibration

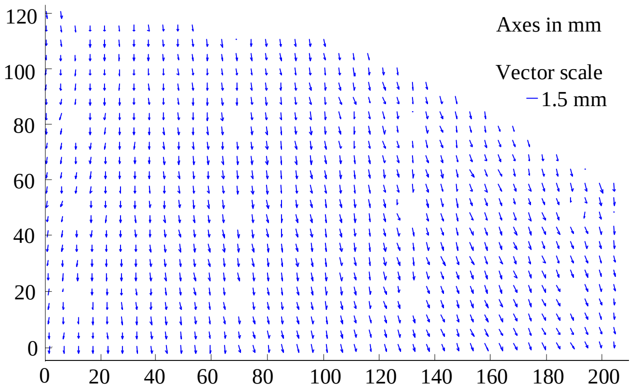


Figure 8. Displacement vectors following camera calibration

5.4 *Application: deformation in a triaxial test*

This measurement technique can be used to measure local strain in triaxial testing without the need for on-sample instrumentation. Since the system can obtain displacement measurements at multiple locations, it can be used to examine the onset and evolution of non-homogenous deformations.

Figure 9 shows a typical image of a 40mm 'gauge length' of triaxial sample within a textured membrane, obtained during a compression test on a dry sample under vacuum. The vector field in figure 9 shows 1100 uncalibrated displacement measurements and was obtained during a top platten movement of 50µm. This boundary displacement matches closely with the vertical component of the displacement vectors at sample mid-height, which measure a nominal 24µm. Measurement noise of around 3µm is evident, which corresponds to a strain of 0.01%, and is in agreement with the quoted system precision.

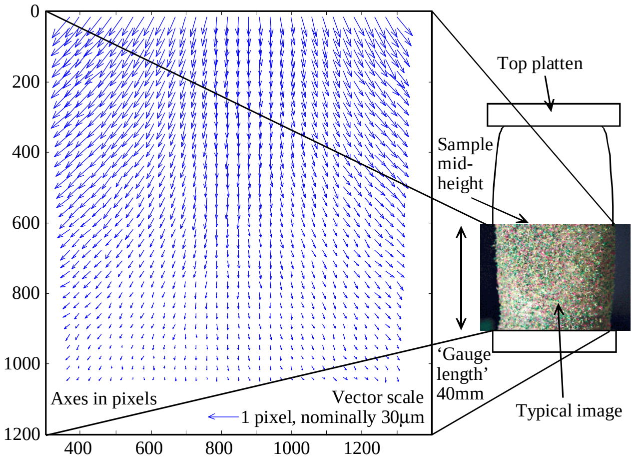


Figure 9. The measurement of deformation in a triaxial test

6 CONCLUSIONS

The three technologies of digital still photography, Particle Image Velocimetry and close range photogrammetry have been combined to form a deformation measurement system for physical modeling and element testing. It has been demonstrated that planar deformation in a physical model can be detected and calibrated to a precision of 1/15000th of the field of view.

The technique is equally applicable to triaxial testing, and has been shown to offer a resolution sufficient to measure pre-failure strains and the flexibility to capture non-homogenous deformations, which are invisible to conventional transducers.

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