A DIGITAL IMAGING SYSTEM FOR THE PRECISE 3D MEASUREMENT OF SURFACE DISPLACEMENT IN GEOTECHNICAL CENTRIFUGE MODELS

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ABSTRACT

The application of digital imaging to the two dimensional measurement of deformations in soil models undergoing experimentation in a geotechnical centrifuge is increasing. Typically a single camera is used to image, through a window, targets located in the side of a soil sample. Digital image measurement and analysis techniques of varying sophistication and geometric fidelity are then used to compute displacement information from the sequence of images. A number of discrete displacement transducers are also used to provide information concerning changes in shape of the soil surface during the experiment. This paper describes a new complementary system incorporating multiple CCD cameras that can be used to measure many hundreds of 3D locations on the upper surface of the soil. The paper focuses on the imaging system, calibration procedures and 3D target co-ordination and registration algorithms necessary to compute reliable surface information in the harsh centrifuge environment.

1. INTRODUCTION

In order to understand the detailed behaviour of geotechnical events and processes it is important to be able to observe how soils respond to load. Single element testing apparatus can be used to investigate the stress-strain behaviour of soil when subjected to particular stress paths. However, the response of geotechnical structures is the integrated effect of a large number of soil elements each following their own particular stress path. It is therefore of major importance to be able to measure displacements and hence strains during real geotechnical events. Instrumentation of prototype structures can yield valuable results, but much more can be learned from comprehensive test series on small-scale geotechnical models.

The behaviour of geotechnical structures can be studied using physical models, the main requirement being to create in the model stress profiles corresponding to those in the prototype. This can be achieved by accelerating small-scale (1:n) models to n times earth's gravity using a geotechnical centrifuge. Thus a 10 m layer of soil can be represented by a 10 cm deep model of the same soil accelerated to 100g because the reality and the model will then experience the same self weight stresses at homologous points.

Centrifuge testing allows the study of geotechnical processes in scaled models with properly established scaling laws relating the model to the corresponding prototype. Particularly valuable are measured movements in vertical sections of plane models that can be observed through a perspex window in the sidewall of a model container. These subsurface deformations can be compared directly with those from finite element predictions and can be used to test and improve constitutive models of soil behaviour.

In order to monitor such movements, the technique commonly adopted is to place markers or targets in the soil face that is in contact with the window. A single CCD camera vision metrology system allows these targets to be viewed during centrifuge flight (Figure 1). Thus, by measuring the position of these targets in the resultant sequence of calibrated digital images, displacements in the model can be determined. Such measurements of 2D soil movements are accepted as an appropriate technique (Allersma, 1991; Ethrog, 1994). A model width is typically of the order of 500 mm which in an experiment at 100 g represents a prototype distance of 50 m. The most useful measurements of displacement will need to have an accuracy of 0.01 - 0.1 mm. i.e. 1 - 10 mm. prototype scale.

Whilst measurements in image space are straightforward, utilising established circular target recognition techniques such as dynamic thresholding and subsequent centroiding (Shortis et al 1995), their transformation into object space defined by the plane of the soil is undertaken using a variety of techniques. Methods range from precise opto-mechanical alignment of the camera and soil plane, through deterministic mathematical transformations, to complete photogrammetric solutions employing camera calibration, dynamic computation of camera location, and a refractive model to account for the optical effects of the window between the camera and soil. Measurement precisions, in the soil plane, of between 0.05 and 0.08 mm are typically achieved at City University (Taylor et al, 1998) using a mathematical model based on established photogrammetric procedures.

It has become apparent during such experiments that some means of determining to what extent the measurements made in the soil plane at the window surface are representative of the movements throughout the depth of the soil. One means of at least partial verification is to make measurements of the soil surface

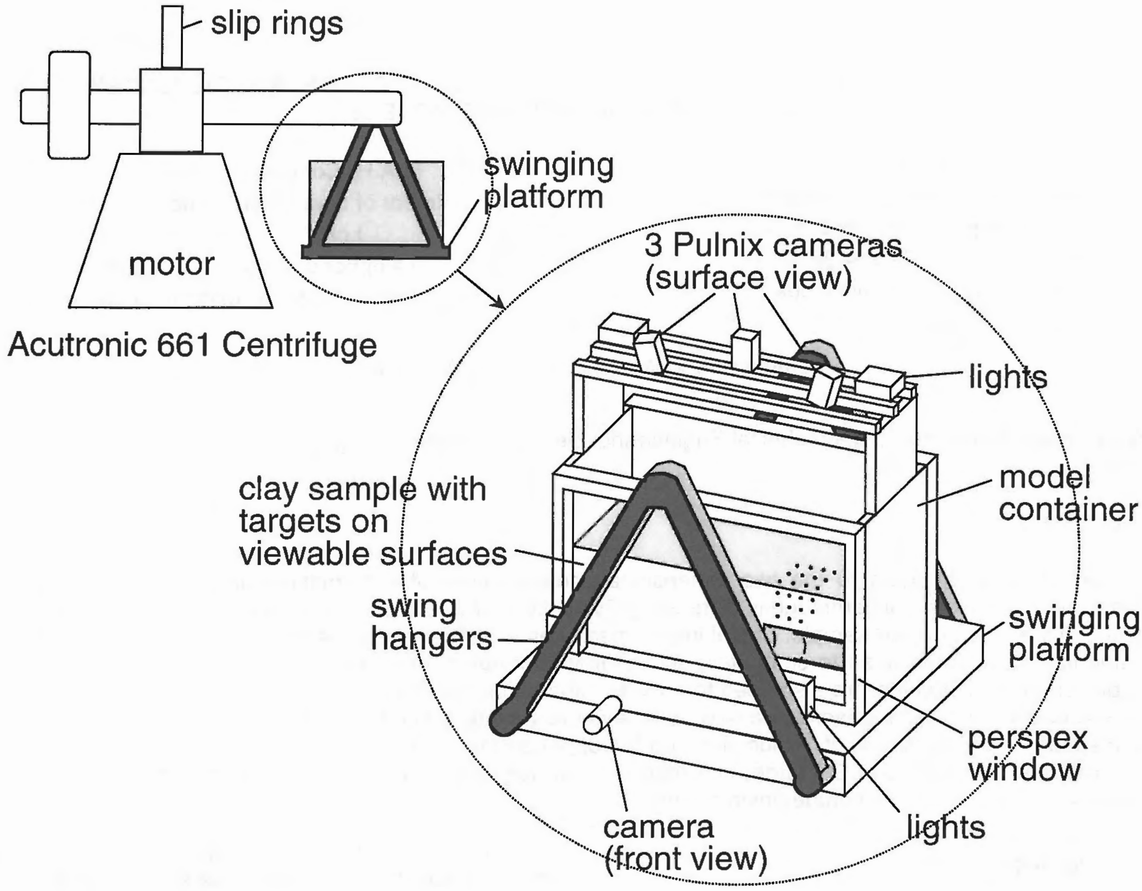

Figure 1. The arrangement of the geotechnical centrifuge, detailing the camera configuration used.

as the geotechnical experiment progresses. The conventional method is to use linear displacement transducers to measure change at discrete locations on the soil surface. Whilst these can provide very precise measurement (better than 0.025mm) of the soil surface at each discrete point, it is not feasible to measure sufficient points to define the soil surface. This paper describes an alternative method, which uses an image based measurement solution to measure the 3D movements of several hundred targets located at the soil surface.

2. ELEMENTS OF THE VISION METROLOGY SYSTEM

The 3D measurement procedures used to determine initial soil surface shape and its subsequent change are founded upon the capture of image sequences from three synchronised CCD cameras to provide overlapping views of the targeted surface of the soil sample. Common target images in the three sets of image measurements obtained are identified and measured before use within a photogrammetric procedure to compute the 3D co-ordinates of the targets at the soil surface. These co-ordinate data can then be triangulated to determine the shape of the soil surface for each set of images.

2.1 Image sequence acquisition

A gantry structure has been designed to support three low cost 2/3" monochrome CCD cameras at accelerations of up to 100 g. The cameras employed in this case are a single Pulnix TM6CN and a pair of Pulnix TM6EX cameras (Robson et al, 1993). Each is fitted with a fixed focus 'C' mount lens of 4.8mm focal length. The analogue image data from the three cameras monitoring the soil surface are passed out of the centrifuge environment to a host computer by means of slip rings. Whilst the Pulnix cameras have not been designed to operate at 100 gravities, the applied forces can be simply regarded as a self-weight problem. As such the camera mountings are designed to securely support the heavier lens and "C" mount assembly with the cameras being operated within 20 degrees of verticality. To date no problems arising from the high gravity environment have been experienced, although they were expected and procedures were adopted to detect them.

To monitor effectively dynamic change in the soil surface the cameras must be synchronised. To achieve this the first camera provides a set of master image control signals that are then used to drive the second and third cameras. In this way the set of three monochrome images can be sent to a colour frame grabber as if they were the red, green and blue image planes from an RGB colour camera. In-house image capture software then treats the resultant colour image as three colour bit planes and splits these back into three monochrome TIFF images for subsequent storage to disk. Based on a Matrox Meteor PCI frame grabber, running under Microsoft Windows NT, the system is able to store images to hard disk at a rate of up to one set of three frames every two seconds. This method allows sufficient image storage for all typical geotechnical tests which may run for anything up to 24 hours. In this system hard disk transfer provides the bottleneck, however the frame rate achieved is sufficient for the purposes of most geotechnical events.

2.2 Datum definition

To ensure correct scale and orientation of the computed soil surfaces it is necessary to establish a datum. To this

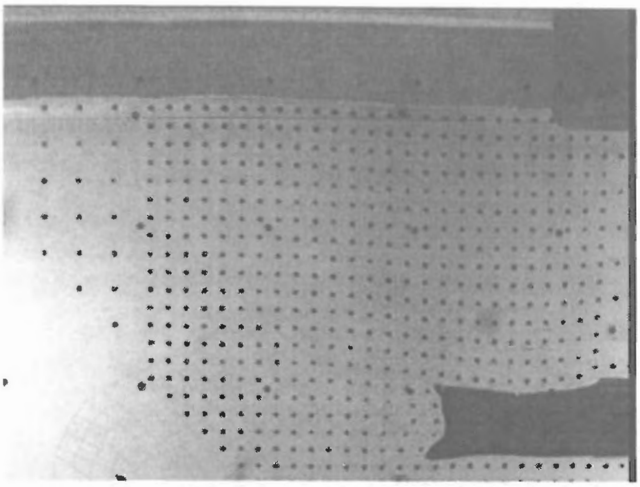

Figure 2. Soil model front view showing a tunnel section during collapse.

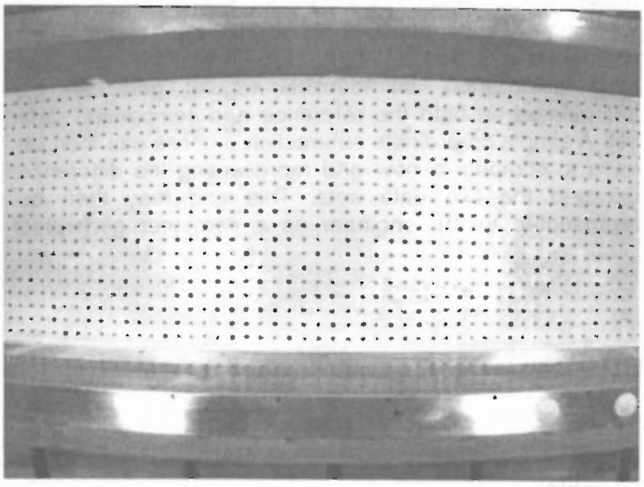

Figure 3. View from the central camera (of three) monitoring targets on the soil surface.

end, pre co-ordinated circular black control targets are used. These are defined by attaching pre-targeted aluminium rails to the sides of the soil model enclosure. Both targets and rails are attached at machined locations to provide an array of about twenty points co-ordinated with respect to one corner of the model enclosure. Not only do these provide an appropriate datum, which is assumed to be stable during centrifuge testing, but they also provide preliminary values for the exterior orientation of each of the three cameras to be computed by means of a least squares resection process (Cooper and Robson, 1997). Illumination of both the targets and the soil model is provided by two 10W fluorescent tubes with a total output of approximately 1klm.

2.3 Camera calibration

If change in the soil surface is to be determined precisely it is necessary to calibrate each of the cameras. Due to geometrical limitations it is not an easy matter to calibrate the cameras during a geotechnical centrifuge test (Fraser et al, 1995). Instead a purpose built calibration object consisting of a 3D array of black targets on a white supporting structure is positioned on top of the soil model immediately before spin up. The object is located in the centre of and at each end of the soil model and rotated about its centre in 90-degree increments, and randomly angled with respect to the soil surface, at each location. In this way a network of twelve images is captured with each camera. The imaged targets are then measured using a centroid procedure, preliminary camera orientations determined and a self calibrating bundle adjustment computed to provide a simultaneous calibration for each camera. The target array is then removed from the soil box to allow the geotechnical test to commence. The calibration procedure is repeated at the end of the experiment to determine if any irreversible geometric change has occurred in the cameras during the experiment.

2.4 V.M. system setting up and evaluation of starting data

Three-dimensional measurement requires that each target is imaged on at least two, but preferably on all three, images in each sequence. Since the targets used are commonly about 900 simple black plastic pins pressed into the soil, target image quality is of paramount importance. In a set-up procedure, which is currently only partially automated, corresponding targets are identified in each of two images using a centroiding procedure with dynamic thresholding. Three-dimensional co-ordinates of the targets in the soil are then computed by intersection. Given such a set of initial target co-ordinates the imaged location of each target in the third camera can be automatically determined by reprojection. Whilst this procedure could be fully automated, by means of target image searches and an correspondence solution, interactive setting up gives the geotechnical engineer greater confidence that the images are of appropriate quality before commencement of the test and that no configurational changes are necessary. The final stage in the process is to refine the solution by computing a bundle adjustment. This process also allows a rigorous statistical analysis of the measurement data and is integrated within a visualisation tool enabling direct assessment of system quality parameters.

2.5 Image sequence measurement and target tracking

Given that the orientations and initial 3D target co-ordinates have been determined, the processing of image sequence data is straightforward. At the time of writing there has been no need to process image measurement data during the experiment, so all data are post processed from the stored images that provide a permanent archive of the experiment. The initial XYZ co-ordinates, and when available the last three locations, of each target are used in a tracking procedure to identify imaged targets in each subsequent image set in the sequence by means of a back driving procedure (Robson and Shortis, 1997). The algorithm, which includes centroiding with a dynamic threshold is very efficient and proceeds on an image by image basis. Since the exterior orientation of each camera cannot be assumed to be stable during the test a bundle adjustment, following a partitioned design to maximise speed, is run for each image set.

2.6 Visualisation of computed soil surfaces

The resultant sets of 3D co-ordinates and their associated stochastic properties are of limited immediate use to the geotechnical engineer unless they can be visualised. The current aim of the visualisation process is to provide surfaces of difference between any pair of computed co-ordinate sets. Since all data are based on the datum provided by the control targets, attached to the sides of the soil model enclosure, the process is much simplified.

A first step is to triangulate the data; this is carried out by the established method of Delaunay triangulation (Preparata & Shamos, 1985). Once a triangle mesh has been established, an identical regular grid can be interpolated on both the reference and comparison data set. A simple co-ordinate subtraction process can then be used to compute a new grid representing the difference between the two data sets. This grid may then be represented to the engineer as a computer generated surface or in the form of a contour plot for example. Whilst all these data processing steps are currently only semi-automated, existing PC based computing facilities are able to provide sufficient processing power for complete automation and data processing during the experiment if required.

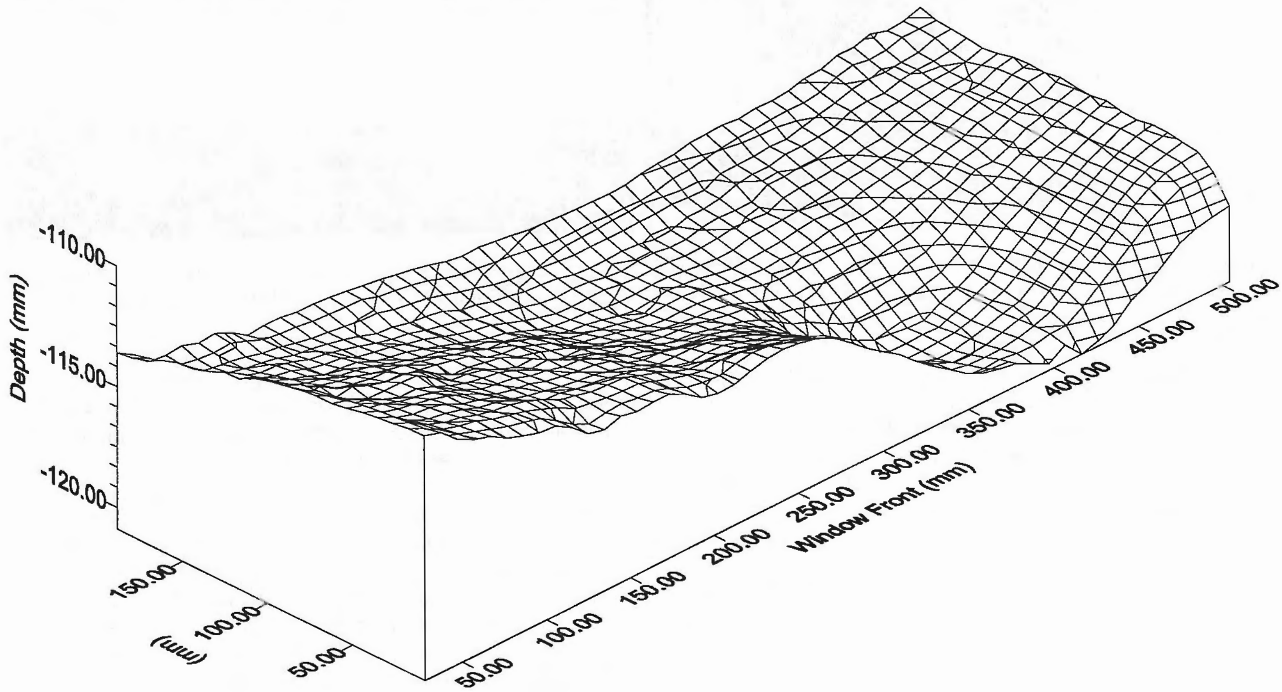

Figure 4. Soil surface computed after collapse.

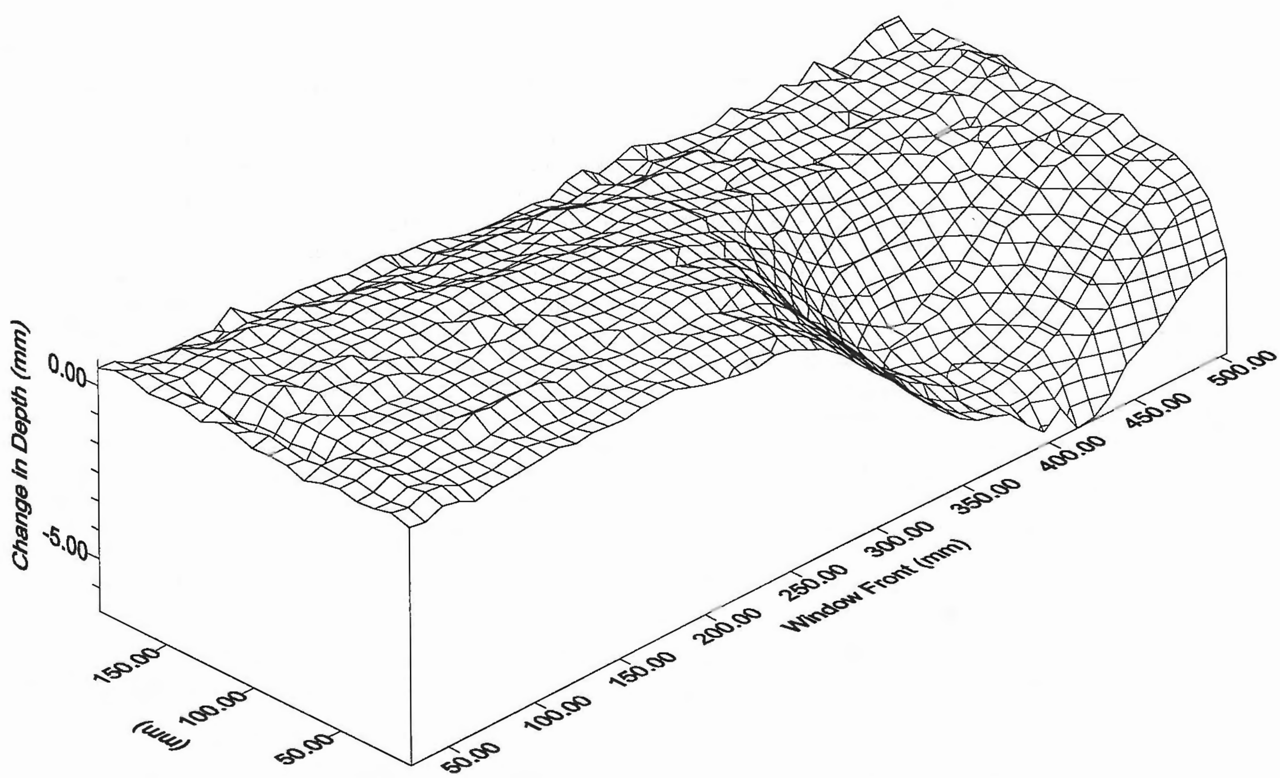

Figure 5. Difference between the original soil surface and that computed after collapse.

3 EXPERIMENTAL RESULTS

Currently two geotechnical tests have been conducted using the described system to monitor soil surface change. In both cases these have been successfully carried out in conjunction with a conventional single camera system measuring displacements in the plane of the window. A typical image from the 2D system monitoring the front face of a model is shown in figure 2. Figure 3 is a typical image from the middle camera, of the set of three, viewing the top of the soil model.

3.1 Computed target locations and precisions

Since a bundle adjustment procedure has been employed, all computations include an in-built statistical analysis of the quality of all estimated parameters. For the each of the 3D tests thus far carried out about 940 targets were located in the soil surface. Of these about 90% were imaged by all three cameras. Typical rms standard deviations for the co-ordinated targets are 0.057mm, 0.042mm and 0.098mm in X, Y and Z axes respectively. The lower precision in the Z direction is expected since the camera configuration was limited by mechanical constraints within the centrifuge such that all optical axes were parallel to the Z axis to within about 20 degrees. Whilst the quality of these results is not as good as that obtained with displacement transducers, the large number of target points provides a set of dense information spaced evenly over the soil surface. Unfortunately displacement transducers could not be used to provide an independent check as their use would have obscured the soil surface.

3.2 Surfaces of change

Figure 4 shows the soil surface computed from the set of images corresponding to figures 2 and 3 where the model has all but collapsed. It should be noted that the depth axis (Z) has been exaggerated in this figure. Figure 5 has been computed by simple differencing of the grid generated from images at the beginning of the experiment and that from figure 4. These data, and others from the sequence, are currently being analysed in conjunction with 2D movements computed from images taken with the single camera viewing the front of the sample. Of particular interest are any discrepancies between the movements in the soil surface close to the window and those measured at the window by the conventional 2D system.

4 CONCLUSIONS

a). A 3D-measurement system able to monitor change in surfaces of geotechnical models tested on a centrifuge has been successfully designed, constructed, calibrated and tested.

b). Initial results appear promising and will undoubtedly enhance understanding of geotechnical events.

c). With the availability of low cost computing and imaging hardware, there is considerable scope to further develop and automate the technique.

d). It is expected that on-going developments in both automation and visualisation of information will allow both 2D and 3D monitoring to take place on-line when real-time feedback is required by the engineer.

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