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Measuring soil deformation in geotechnical models using digital images and PIV analysis

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ABSTRACT: Accurate measurement of soil deformation is fundamental to the success of geotechnical modelling. Current practice is to track the movement of a grid of target markers embedded in an exposed plane of soil through a sequence of video images. A new system of deformation measurement is presented which provides improved precision and reliability whilst removing the need for intrusive target markers. Image capture using an inexpensive 2-megapixel digital camera provides a significant increase in resolution and image stability compared to video. Particle Image Velocimetry (PIV) is a velocity-measuring technique in which patches of texture are tracked through an image sequence. Image processing algorithms have been written to apply the PIV principle to images of soil. The resulting software has a precision of 1/15th of a pixel when tracking the movement of natural sand or textured clay. This system allows displacements to be measured to a precision greater than has been previously achieved, without recourse to target markers.

1 INTRODUCTION

Physical modelling of geotechnical events is used to observe soil behaviour, allowing predictive methods to be verified and real constructions to be simulated. To carry out quantitative analysis of the observed behaviour, measurements of deformation must be made. Whilst displacement probes may be placed at the model boundaries to measure the movement of a single point, this paper is concerned with the more valuable measurement of ground movements in the entire model.

The measurement of gross deformations is key to understanding the ultimate failure mechanism of a geotechnical structure. It is through the observation of failure mechanisms that design solutions for ultimate load are verified. Gross, or ultimate, displacements can usually be observed through post-test excavation of a geotechnical model. Such measurements form a ‘before’ and ‘after’ snapshot of the model, allowing the failure mode to be estimated.

In contrast to the gross deformations present at the ultimate state, serviceability state design requires an understanding of settlements and ground movements at much lower strains. To achieve this aim, the measurement resolution must be reduced by at least an order of magnitude. Coupled with the reduced scale of geotechnical models, and hence a corresponding reduction in the size of the relevant movements, the measurement of pre-failure deformations remains a difficult task.

Figure 1 presents the strain ranges experienced during various geotechnical processes. The range 0.01% - 1% strain encompasses serviceability and pre-failure deformations. It is the measurement of these movements which is a challenge in small-scale geotechnical modelling. Larger deformations which can be of interest to geotechnical modellers are also shown. Some are associated with catastrophic events (eg landslides, lateral spreading, tunnel collapse) and others with construction processes (eg. CPT/pile penetration).

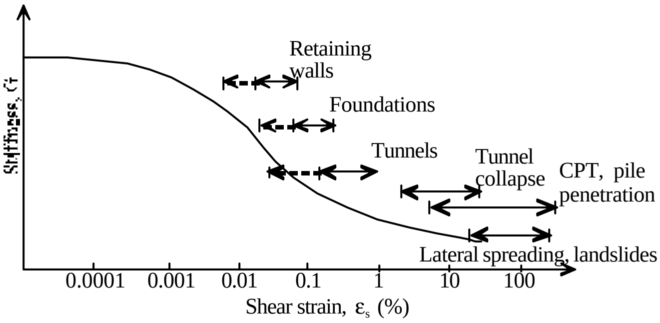

Figure 1. Typical strain ranges experienced in geotechnical engineering (after Mair, 1993).

A successful deformation measurement technique must have sufficient precision to capture the lowest relevant strain throughout the field of interest. A typical centrifuge model might have a 300 mm × 200 mm area of interest. To measure a pre-failure deformation of 0.01% strain in a zone of 10% of the model requires the detection of a movement of 2 µm.

2 BACKGROUND

The first measurements of displacements within a soil mass were carried out by Gerber (1929) using an X-ray method. Lead shots are embedded in the soil model, and successive radiographs are taken to follow the movement of these markers. This system has been widely used to detect incremental strain patterns in large sand models and shear apparatus (Roscoe, Arthur & James, 1963). The technique was successfully used to produce contours of shear and volumetric strain with a precision of 0.1% through large (2.0 m × 0.5 m) models (James, 1965).

Geotechnical centrifuge modelling does not permit the exposure of radiographs in-flight. Instead, modellers adapted the above technique by providing a transparent window exposing a plane of the model into which target markers are placed. Conventional photography is used to record the movement of these markers. The reduced size of centrifuge models compared to the previous large-scale testing coupled with the reduction in scale from model-space to film-space lead to a decrease in precision. Beasley (1973) and Mair (1979) present in-flight strain data to a resolution of 1%, from a measurement precision of 100 µm.

The use of video photography can eliminate the need for time-consuming measurement of exposed film. The image processing technique of centroiding can be used to estimate the location of the array of target markers. Under the conditions of a typical geotechnical model, centroiding is reported to locate target markers to an accuracy of 0.1 pixel (Chen et al, 1996). Taylor et al (1998) report a centroiding-based measurement system which can track movements of 3 mm diameter target markers embedded in clay with a precision of 60-105 µm over a 300 × 200 mm field of view. An example of the resulting displacement measurements are presented by Grant (1998) as contours of strain with a resolution of 1%.

Whilst the technology of the systems described above has evolved considerably in the previous 70 years, the continuing reliance on discrete target markers is a significant drawback. The influence of a dense grid of inclusions in the soil model is not easily quantified. The detail in areas of high strain gradient is unsatisfactory, measurement reliability breaks down when targets become partially obscured by soil, and the points at which observations are made must be determined prior to the modelling event.

This paper presents a new system based on digital photography and PIV image processing, which eliminates the reliance on target markers, and provides displacement measurements to a precision higher than described above. These measurements can be at locations within the model determined by the user after the modelling event has been recorded.

3 IMAGE ACQUISITION

Image frames acquired from a European standard (PAL) video signal have a nominal resolution of 732 × 549 pixels, although the number of photosensitive elements on a typical CCD are considerably less due to the use of interlaced scanning. The precision of any image measurement is inversely proportional to the object-space pixel size. In other words, a twofold increase in pixel resolution corresponds to a doubling of the measurement precision.

The decreasing cost and increasing sophistication of digital still cameras has provided an alternative to video capture in applications where a high frame rate is not required. The images presented in this paper were captured using an inexpensive (.$400) Kodak DC280 digital still camera which provides a pixel resolution of 1760 × 1168. This represents a fourfold reduction in object space pixel size compared to that of PAL video.

There are other significant differences between a video capture system and a digital still camera. The analogue transfer of video signals through centrifuge slip rings leads to image deterioration, and storage on analogue tape creates line jitter. In contrast, digital still images are stored onboard the camera and transmitted digitally through the sliprings. This prevents the addition of noise during the transfer and storage stages.

Most digital cameras have native control software which can be tailored to suit the experimental application. Remote adjustment of camera settings, image tagging and event logging can all be achieved whilst the camera is operating onboard a centrifuge. The Kodak DC280 and DC215 cameras have both been successfully proof tested on the Cambridge beam centrifuge to 100 g without loss of functionality.

The duration of a typical triaxial or non-dynamic centrifuge test is such that the 10-20 second interval required for image capture and download leads to only a small deformation increment between successive images.

4 PIV IMAGE ANALYSIS

Particle Image Velocimetry (PIV) is a velocity-measuring technique which was originally developed in the field of fluid mechanics. The flow field of a fluid can be examined by seeding the flow with marker particles and tracking the movement of small patches within a larger image (Adrian, 1991).

The deformation of soil can be considered as a low-velocity flow process. In fluid mechanics experiments, polystyrene balls or coloured powder are added to the flow field to provide identifiable texture on which the image processing can operate. In contrast, natural sand has its own texture in the form of different coloured grains, and the light and shadow formed between adjacent grains when illuminating a plane of granular material. Texture can be added to an exposed plane of clay by the addition of coloured 'flock' material or fine sand.

Image processing algorithms have been written to implement the patch-matching PIV principle through a sequence of digitally-captured images of soil. Firstly, a grid of patches is laid out over the area of interest at the locations for which a displacement vector is to be found (Fig. 2). Each patch is then translated at 1-pixel intervals over a pre-defined search zone. At each position, the degree of match between the sample patch and an interrogation patch taken from the same location in the subsequent image is assessed.

This comparison process produces a map of 'degree of match' over the entire search zone. Spline interpolation in the zone of best match allows the patch displacement to be assessed to sub-pixel precision.

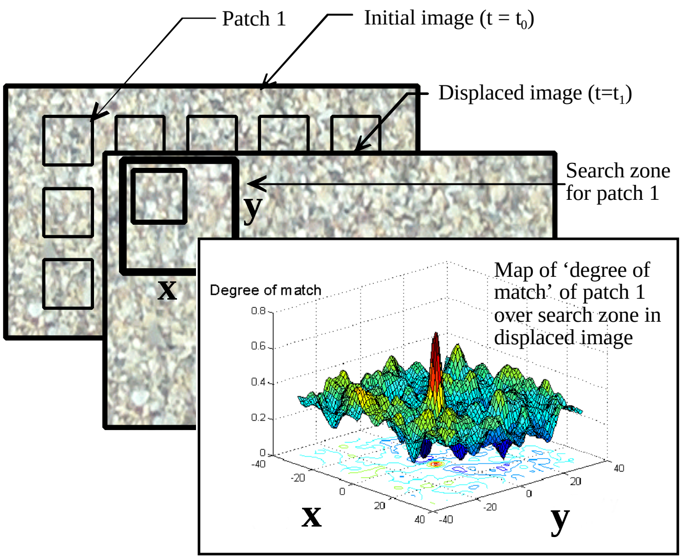

Figure 2. PIV image analysis technique.

A suitable patch size corresponds to a couple of particle diameters. This derives from the requirement that the patch contains sufficient texture to be identifiable in the subsequent image. Figure 3a shows part of a 1760 × 1168 pixel image of Dog's Bay carbonate sand (D_{50} = 0.3 mm) photographed at an image scale of 10 pixels per mm. Patches of size 10 x 10 pixels contain sufficient texture to produce successful PIV analysis, allowing a full image to consist of 176 × 116 measurement points, each of object-space size of 1 mm × 1 mm. This method of obtaining over 20,000 displacement measurements is significantly more practical than embedding a similar number of target markers in a soil model.

To be sure to detect the displaced patch, the search zone should have a width equal to twice the maximum possible soil displacement between each image pair. However, this can increase the computational requirement unnecessarily. In a typical geotechnical model, strain rate, and hence patch velocity, will vary gradually across the model. A more efficient technique of selecting the search zone is to shift the zone from the sample location by the displacement vector of nearby previously-evaluated patches. The size of the search zone can then be reduced to a fraction of the expected displacement.

Having obtained the displacement field using PIV analysis, a calibration procedure for the image-space to object-space transformation is essential when large displacements are under consideration. The non-coplanarity of the CCD and the soil plane, coupled with the radial and tangential lens distortion present in short focal-length optics, leads to a variation in image-object space scale factor across the image.

5 VALIDATION EXPERIMENTS

A series of bench-scale experiments have been conducted to assess the precision and reliability of the PIV technique to measure deformations in soils. The experimental apparatus consists of a rigid soil container which is driven by a micrometer along track in an aluminum base plate with PTFE guides. This apparatus allows a plane of soil to be translated horizontally beneath a rigidly fixed camera. Small known increments of movement are applied to the soil container via a micrometer and the resulting sequence of photos are analysed using PIV. All digital images were acquired using a Kodak DC280 camera. The field of view of the entire 1760 × 1168 pixel image was 176 mm × 117 mm which corresponds to an object-space pixel size of 0.101 mm.

5.1 *Deformations in sand*

A grid of 420 patches of sand was selected from digital images of the translating soil. Each of these patches contains 100 pixels and corresponds to 1 mm^2 of sand (Fig. 3a). To validate the PIV technique, each of these patches was tracked through a series of ten 0.1 mm translation steps. Since the body of sand was translating uniformly, the variation in the detected displacement of each patch indicates the precision of the PIV analysis. In the interests of brevity, only the 0.1 and 1 mm deformations will be examined in this paper. In image space, these displacements correspond to values of 1 and 10 pixels respectively.

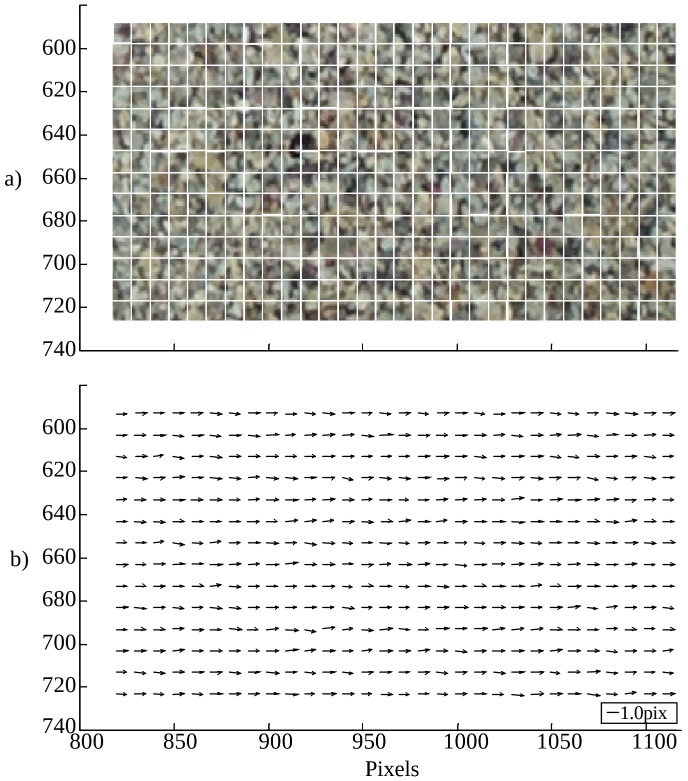

Figure 3. Sand image patches (a), with measured movements during 1 pixel translation (b).

The measured displacement vectors for each patch during the first 0.1 mm (1 pixel) translation step are presented in Figure 3b. The distribution of these vectors is shown as a histogram in Figure 4. The PIV analysis of these patches exhibits excellent internal consistency with the standard deviation of the measured 1 pixel displacements being 0.043 pixels. The mean standard deviation of the incremental patch displacements for the remaining nine image pairs was 0.050 pixels.

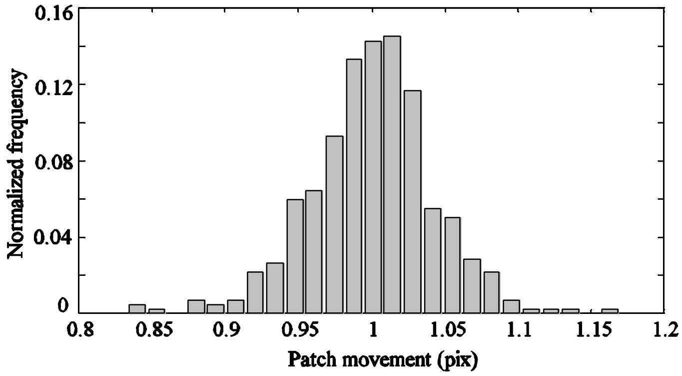

Figure 4. Image-space distribution of measured sand movement at 1 pixel translation.

To further validate the technique against known movement, the sand was translated a full 1 mm using the micrometer. This larger distance was used as a basis for comparison to reduce the significance of operator errors in the micrometer movement. The distribution of measured object-space patch displacements is shown in Figure 5. As can be seen in this figure, the PIV analysis displays an excellent agreement with the applied movement, exhibiting a standard deviation of 6 µm (0.061 pixels in image space).

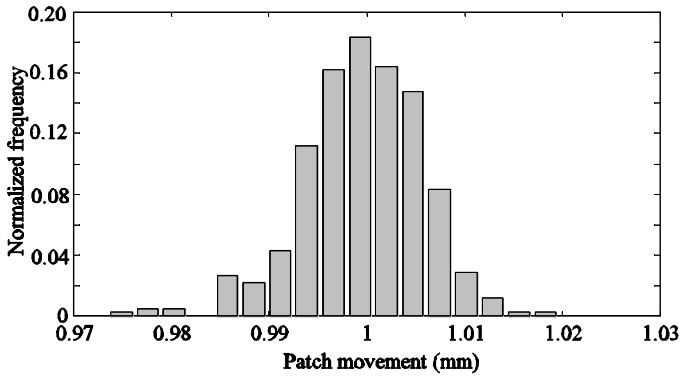

Figure 5. Object-space distribution of measured sand movement at 1 mm translation.

5.2 *Deformations in clay*

Unlike images of sand which have an inherent texture, the particle size distribution of clays dictates that texture must be imparted to the uniformly-coloured clay soil. In the present study, a flock material was lightly dusted onto the clay surface. The density of the flock dusting was purposefully made lower than that required for complete coverage of each of the 420 patches of 10 × 10 pixels to illustrate the issues of applying the PIV technique to clay soils.

The distribution of measured patch movements using each of the 420 soil patches for the first 0.1 mm (1 pixel) translation step is presented in Figure 6. Although there exists a considerable number of patches moving the expected distance of 0.1 mm, a significant number of patches are incorrectly recorded as undergoing large displacements. These 'wild vectors' derive from patches being incorrectly identified in the subsequent image due to insufficient image texture.

As a comparison, the intensity histograms for patches containing sand, pure kaolin clay, and clay with flock are presented in Figures 7a to 7c, respectively. To eliminate the wild vectors, each patch was evaluated for texture content according to the following criteria. If a patch of clay contained at least 10% by area of pixels significantly darker than the background it was accepted. The 124 patches which passed this criterion are shown in Figure 8a.

The measured patch movement for the first 0.1 mm (1 pixel) translation step using the filtered patches is presented in Figure 8b and as a histogram in Figure 9. The PIV analysis of these patches exhibits excellent internal consistency with a standard deviation of 0.076 pixels. This demonstrates that the addition of flock material to uniformly-coloured clay allows successful texture-based PIV analysis.

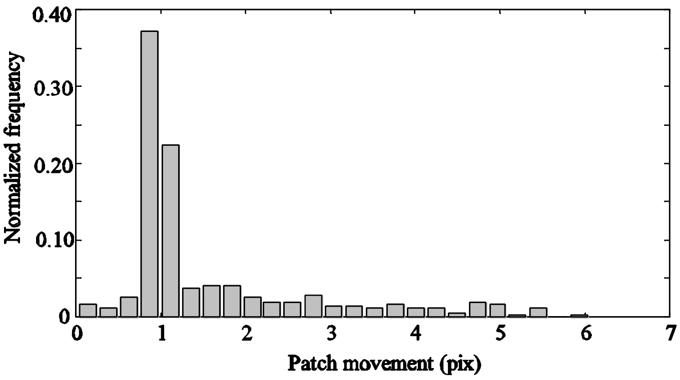

Figure 6. Image-space distribution of measured movement of all clay patches at 1 pixel translation.

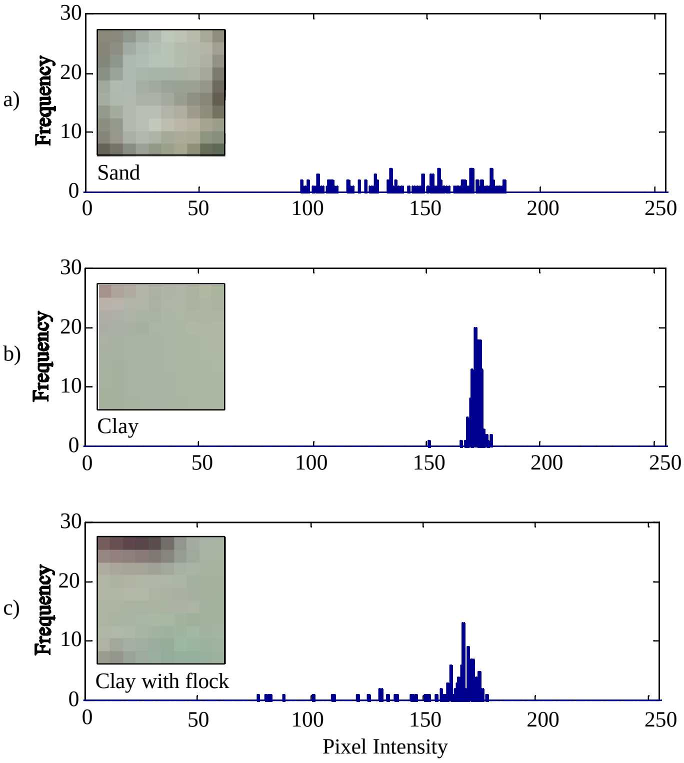

Figure 7. Pixel intensity of patches of sand (a), clay (b) and clay with flock.

6 CONCLUSIONS

Conventional techniques of measuring soil deformation in geotechnical models rely on intrusive target markers and video image capture. The reported precision of such systems when viewing a typical (300 mm × 200 mm) soil model is of the order of 100 µm. Differentiation of the resulting displacement vectors has allowed contours of 1% strain to be produced. The use of target markers has a number of drawbacks, and video image capture is unstable and of low resolution.

A new system of displacement measurement based on digital image capture and PIV image analysis has allowed precision and reliability to be improved. Inexpensive digital still cameras offer over twice the resolution of video capture and provide more stable images. Although these cameras include mechanical operating parts, two models have been successfully tested in the centrifuge environment.

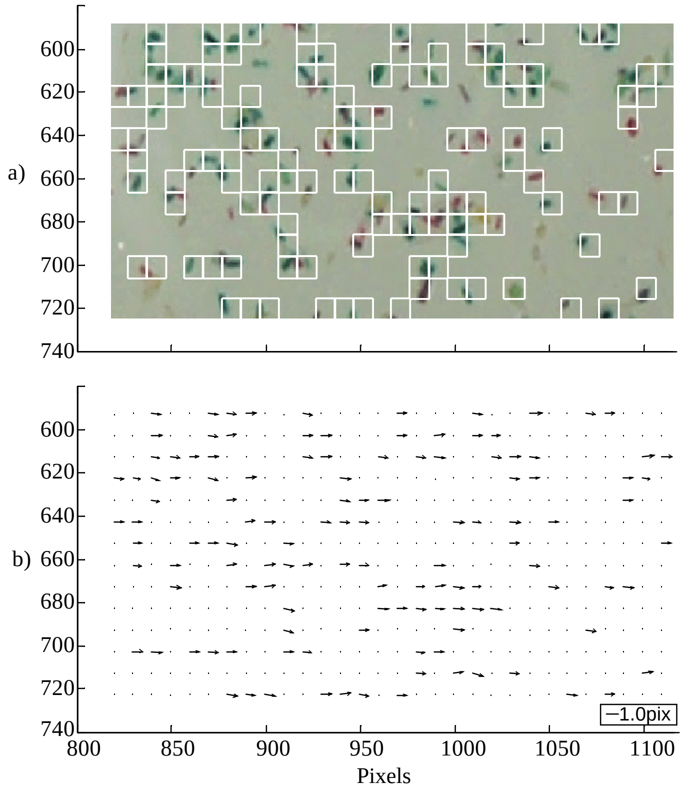

Figure 8. Filtered clay/flock image patches (a), with measured movements during 1 pixel translation (b).

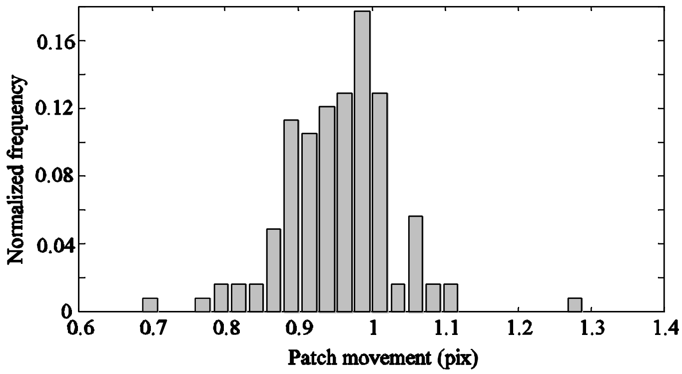

Figure 9. Image-space distribution of measured clay/flock movements during 1 pixel translation.

PIV analysis is a texture-based image processing technique which has been adapted from its fluid mechanics origins to suit geotechnical applications.

Algorithms have been written which allow displacements of small patches of sand and textured clay to be measured to a precision of 1/15th of a pixel.

The combination of digital image capture and PIV analysis allows deformation fields comprising many thousand displacement vectors to be calculated to a precision higher than is possible using centroiding methods. Since the Kodak DC280 digital camera provides 1760 × 1168 pixel images, the resulting precision when viewing a 300 mm × 200 mm soil model is 17 μm. This is a significant increase in precision and measurement density, and has been achieved whilst removing the need for target markers.

The applications of this system are wide. It has been combined with a calibration procedure based on the principles of close-range photogrammetry to allow the deformation of centrifuge and 1-g soil model to be tracked through a large (>50) sequence of images. A further application is non-contact deformation measurement of element tests.

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