Stereo Photogrammetry in Geotechnical Engineering Research

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ABSTRACT: A photogrammetry technique, in which a stationary camera photographs displaced objects, was used to investigate disturbance during penetration testing in sand. Two different penetration probes were cut longitudinally in half. These were then pushed into a container of sand, with their flat cut faces against a glass wall, and photographed using a fixed camera. Pairs of photographs were then viewed in a stereo-plotter and parallax was measured at grid points scored on the glass, using the floating dot technique. Displacement of the sand grain originally at a grid point, in the direction of the projectors, could then be calculated. Rotation of the photographs by 90 degrees provided the orthogonal displacement component. Plots were made of node point displacements and volumetric and shear strains. These showed that the dilatometer, with its measuring device on the flat surface, appears to test a much less disturbed soil than do the cone shaped instruments.

INTRODUCTION

GEOTECHNICAL ENGINEERING is the branch of civil engineering involved with the design, analysis, and construction of structures to be either founded on or constructed of geological materials, i.e., soil and rock. In any such undertaking three geotechnical parameters are required: shear strength for bearing capacity, modulus for settlement computation, and the *in situ* stress state and history.

Traditionally, these properties have been determined by obtaining soil samples from the site and performing laboratory tests. However, the profession is increasingly recognizing the deficiencies in this approach. Stress release and disturbance of the samples can result in laboratory determined parameters which are quite different from those existing in the ground. Over the past decade the use of *in situ* testing has grown rapidly. *In situ* testing simply means testing the geological material in place in the ground, rather than sampling and performing laboratory tests. There is a wide variety of such equipment, ranging from the simple hammering of a rod into the ground and counting the blows, to the most sophisticated, electronic self-boring pressuremeter devices, with transducer and strain gauge data recorded on tape ready for computer reduction.

The research described in this paper involves two *in situ* testing devices—the cone penetrometer and the dilatometer. These are very briefly described. The cone penetration test in its simplest form has been in use for many years, especially in Europe. The test consists of pushing a solid metal tip or cone, on a string of drill rods, vertically into the ground. This is usually accomplished by hydraulic rams mounted in a special heavy truck. The pressure required to maintain a slow constant penetration rate is recorded. Literally hundreds of different shaped cones have been developed throughout the world. In 1977 an international committee on standardization of penetration testing (ISSMFE, 1977) adopted as a standard the cone shape illustrated in Figure 1a. Such a cone is shown on the left in the photograph in Figure 2.

The second device, the flat plate dilatometer, is a more recently introduced piece of equipment (Marchetti, 1980). The shape of the blade is shown in Figure 1b and a photograph is included in Figure 2. The dilatometer blade, on a string of drill rods, is pushed vertically into the ground using the same equipment as in the cone test. Penetration is stopped at 20-cm intervals and the gas pressure necessary to expand the thin circular steel membrane a fixed distance into the soil is recorded. In both tests geotechnical parameters are determined from the field results by a variety of empirical and quasi-theoretical correlations.

One of the most serious shortcomings in geotechnical engineering is the absence of a reliable method for predicting the performance of structures founded on sand. Because both the cone penetration and dilatometer devices are very suited to testing in sand, they represent a possible solution to the above problem. However, because both tests consist of penetrating a solid probe into the ground, a certain disturbance of the soil results. The magnitude, location, and type of disturbance are all important in evaluating the usefulness and reliability of the test.

This paper describes a laboratory photogrammetric testing technique which allows a determination of the displacements and strains around a penetrating probe. Results from the two different

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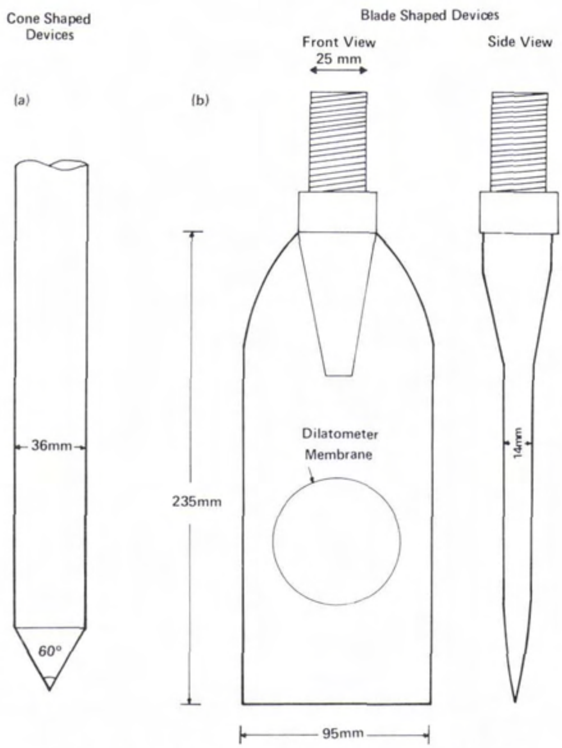

FIG. 1. Sketches of the cone and blade shapes.

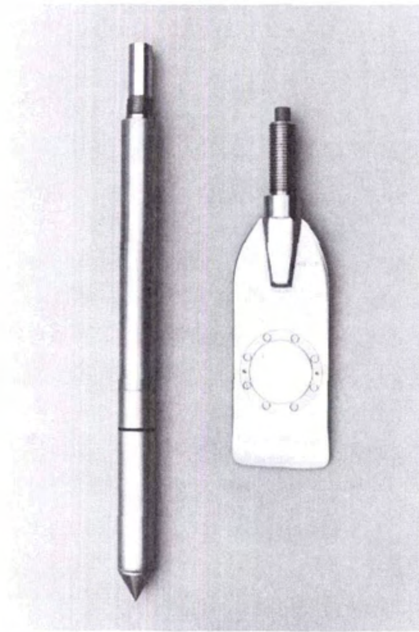

FIG. 2. *An electric cone tip and a Marchetti dilatometer.*

shaped devices will be shown to illustrate the testing and data reduction procedures.

THE STEREOSCOPY TECHNIQUE

In conventional stereophotogrammetric methods, two photographs of an object are taken from slightly different camera positions. These photographic plates are then positioned in a stereo projector and a stereoscopic image is obtained. Figure 3 illustrates such photographs being taken and the corresponding stereo image which is obtained by a simultaneous projection of the plates. The height of a point in the stereo model is due to the difference in locations of the corresponding image points in the two photographs, called x-parallax. This is the basic principle of stereophotography.

Parallax can also be produced by keeping the camera position stationary and photographing the displacement of an object. Figure 4 illustrates a fixed camera photographing a translated object and the stereo model which is obtained by a simultaneous projection of these images. The heights of points in the stereo model depend on the magnitude of the x-movement.

If the object undergoes a general planar displace-

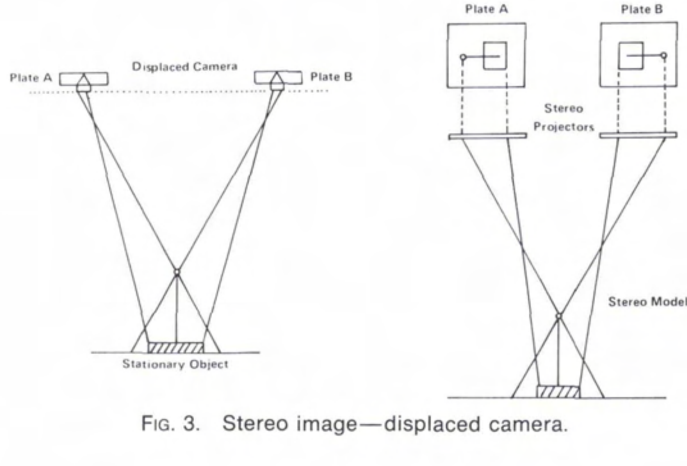

FIG. 3. Stereo image—displaced camera.

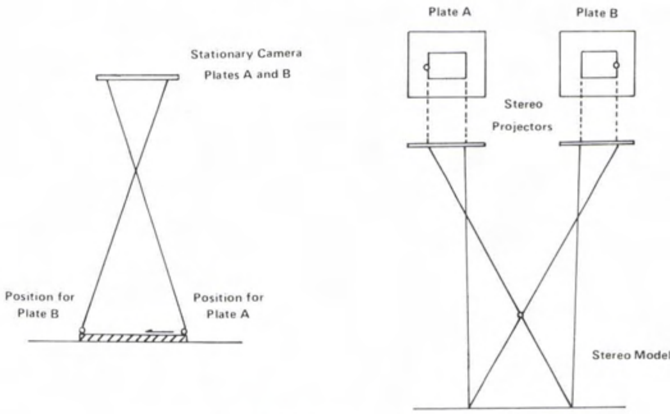

FIG. 4. Stereo image—displaced object.

ment, i.e., movement components in two directions, only the component of displacement along the line joining the projectors contributes to the elevations in the stereo model. In order to completely define an actual displacement, two measurements must be made. The component of the displacement is first measured in any particular direction by positioning the photographic plates in the projector so that the line connecting the two plates is parallel to that direction. The plates are then rotated 90° in order to determine the perpendicular component of the movement. The actual magnitude and direction of the displacement is then obtained by a vector sum of these normal components.

The use of this technique was pioneered at the University of Southampton, United Kingdom (Butterfield *et al.*, 1970; Andrawes and Butterfield, 1973). Wong and Vonderohe (1981) described its use in a tunneling application.

TEST EQUIPMENT AND PROCEDURE

In order to photograph the probe and the surrounding sand during penetration, the system must be cut along a plane of symmetry, as shown in Figure 5. In the case of the cone (Figure 5a) the problem is one of axisymmetry. Whatever occurs in the place o a b c, likewise occurs in o a_1 b_1 c, o a_2 b_2 c, . . . , o a_n b_n c—like pages in a book. In the case of the dilatometer (Figure 5b) the problem is assumed to be one of plane strain. Whatever occurs in the plane o a b c likewise occurs in the parallel planes o_1 a_1 b_1 c_1, o_2 a_2 b_2 c_2, etc., and by symmetry in planes o e d c, o_1 e_1 d_1 c_1, etc. The assumption of plane strain can be made because of the plate shape of the dilatometer blade, with the width being sufficiently greater than the thickness.

Figure 6 shows the dummy probes used in the research. These were machined from stainless steel to exactly the same size and shape as the actual probes, then cut longitudinally in half. To contain the sand a wooden box was built with one glass wall. Inside dimensions were length 100 cm, width 50 cm, and height 65 cm. A square grid or static datum plane was scored on the inside face of the glass. The middle third of the glass length had a 15-mm by 15-mm square grid, while the two outer thirds had 30-mm by 30-mm grids. Before each test the grid was darkened with a black marker so that it could be more easily seen on the photographs and in the stereo image. Such a grid, which was not employed by Wong and Vonderohe (1981), allows the displacement of the soil at each grid corner point to be determined relative to this datum plane. It also permits the simple computation of soil strains using the techniques of the finite element method. Considerations can then be made for axisymmetrical displacements as well as for the usually assumed plane strain conditions.

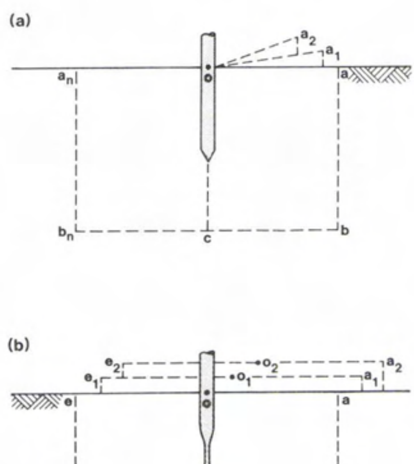

FIG. 5. Probe planes of symmetry.

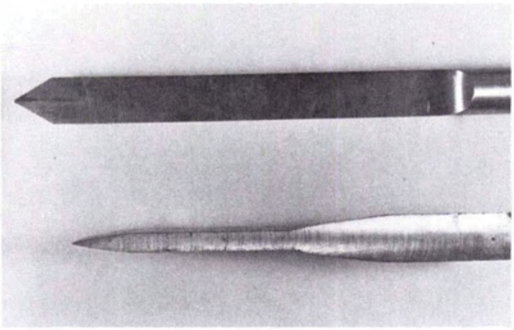

FIG. 6. Dummy cone and blade probes.

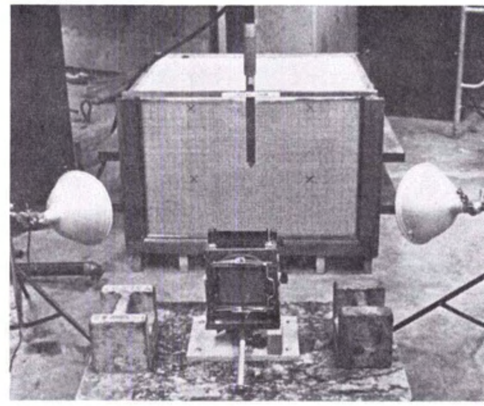

FIG. 8. Test set-up.

The sand used in the research was a blend of four commercially available graded sands. It was placed in the box and tests were performed at different densities which had been obtained by using different filling and mechanical compaction procedures. In a few tests heavy loads were placed on the sand surface, such that the penetration might simulate tests at great depth.

The test procedure consisted of penetrating the probe into the sand with the flat, cut face against the glass (Figure 7). A small hydraulic jack was used for the penetration. A series of six or eight photographs were taken—one prior to penetration and the rest during penetration—from a rigidly fixed camera. Figure 8 shows a test set-up.

The three-dimensional problem is thus studied by physically cutting the probes and viewing a two-dimensional plane—a radial plane in the case of the axisymmetrical cone and a plane strain plane in the case of the dilatometer. Tests were performed to measure the friction between the sand and the glass of the container wall. For a dense sand, a coefficient of friction of 0.25 was found for smooth glass and 0.30 for a plate scored with the 15-mm grid.

To avoid possible distortion of parallax due to quality of photographic paper or the enlargement process, film diapositives were used rather than prints. The diapositives were sandwiched between thin, clear photographic glass plates and used directly in the stereo plotter. The camera was fixed in position relative to the model, with its optical axis normal to the displacement plane. The camera used was a B & J orbit view camera with a 4-inch by 5-inch plate holder. Ektachrome 50 Professional Tungsten Film was used.

To analyze each pair of test photographs, a Fotocartografo Nistri Model VI double-projection anaglyphic plotter was used (Figure 9). A floating dot was used to measure the parallax.

Figure 10 shows two pairs of stereophotographs. Two readings are taken at each grid point. The floating dot is first placed on the grid and a reading from the platen dial recorded. The dot is then placed on the sand, which may appear above or below the stationary datum grid, and a second reading is taken. The difference in these readings is a measure of how far the sand moved at that point,

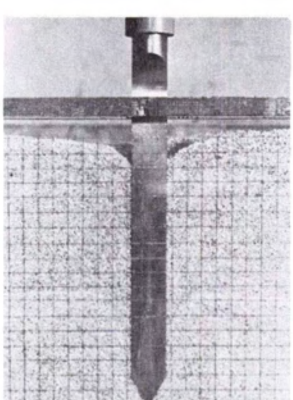

FIG. 7. Cone probe penetrated into sand.

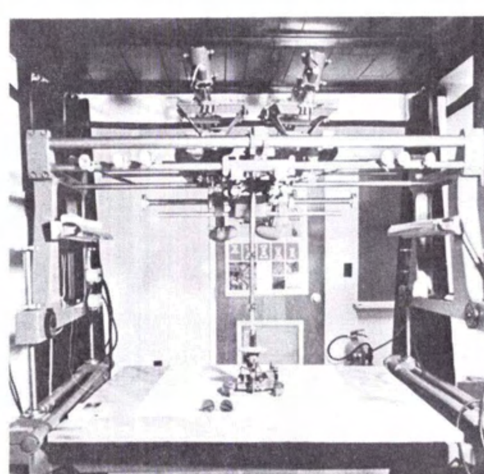

FIG. 9. Double projection anaglyphic plotter.

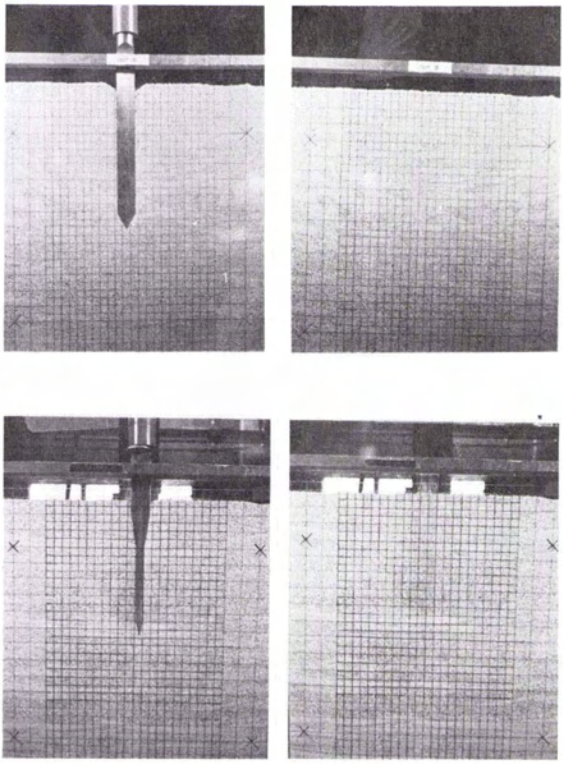

FIG. 10. Two stereo pairs.

in the direction parallel to the line of the projectors, during the time between photographs.

Each pair of photographs was viewed twice to provide orthogonal displacements which could be summed to give the actual movement vector.

DATA REDUCTION

The grid scored on the glass was numbered in finite element terminology with 1234 node points and 1213 elements. At each node point where sand movement had occurred, the two floating dot readings were recorded and subsequently entered as data in the computer reduction program.

Displacements were determined by

$$U \text{ or } W = C \cdot \Delta h$$

where

- U = horizontal displacement in millimetres,
- W = vertical displacement in millimetres,
- Δh = difference in floating dot grid and sand readings, and
- C = constant which is a function of the stereo plotter set-up.
- C = 0.012958 for the cone study.
- C = 0.016402 for the blade study

$$D = \sqrt{(U^2 + W^2)}$$
$$\theta = \tan^{-1} (W/U)$$

where

- D = actual displacement in millimetres, and
- θ = angle of displacement from horizontal.

Volumetric strains were defined for each element by

$$\epsilon_v = \frac{\Delta V}{V}$$

where

- ϵ_v = volumetric strain,
- ΔV = change in volume, and
- V = original volume.

In the case of the blade shaped device, plane strain conditions were assumed to apply. The volumetric strain was therefore calculated as

$$\epsilon_v = \frac{A - A_0}{A_0}$$

where

- A_0 = original area of grid element, and
- A = deformed area of an element defined by the ends of the four corner node point displacements, D.

For the case of the axisymmetrical cone the effect of the tangential strains must be included. The volumetric strain was therefore calculated using the equation

$$\epsilon_v = \frac{V - V_0}{V_0}$$

where

- V_0 = the volume found by revolving the original undeformed square grid element around the axis of symmetry, and
- V = the volume found by revolving the deformed quadrilateral element around the same axis.

A decrease in area or volume, i.e., compression, was defined as a positive volumetric strain, while an increase was defined as negative.

Shear strains were determined at each node point by

$$\gamma_{xz} = (\gamma_{xy_2} + \gamma_{xz_4})/2$$

where

- γ_{xz_2} = shear strain in the 2nd quadrant grid element, node at the origin, and
- γ_{xz_4} = shear strain in the 4th quadrant grid element, node at the origin

$$\gamma_{xz_i} = \alpha_i + \beta_i$$

where

- i = 2 or 4,
- α = the change in direction of the horizontal side of the element at the node point, in radians, and

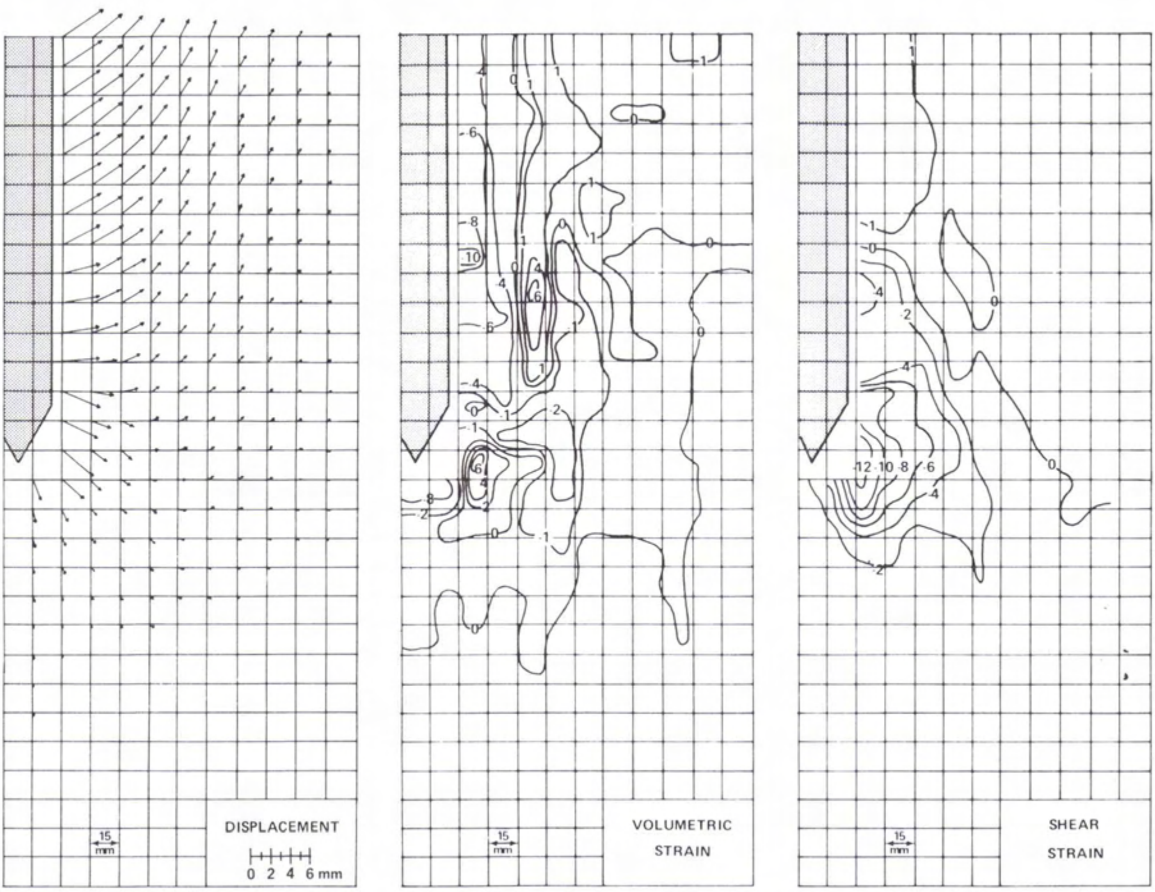

FIG. 11. (a) Cone—dense—displacements; (b) cone—dense—volumetric strain; (c) cone—dense—shear strain.

β = the change in direction of the vertical side of the element at the node point, in radians.

An increase in the original right angle was defined as a negative shear strain and a decrease in angle was defined as positive.

RESULTS

In the research program tests were performed using two different probes in five different density soils with and without surface surcharging. The results from only two tests are presented and very briefly discussed in order to demonstrate the capabilities of the procedure. Only one pair of photographs from each test is analyzed. One photograph is of the sand prior to insertion, the other is the last photograph taken, at final penetration (Figure 10).

Three figures are plotted for each of the two tests. These are node point displacement vectors, contours of volumetric strain, and contours of shear strain. Because the probes are both symmetrical, results are plotted for only half the problem, the right hand side. The displacement vectors are simply straight lines joining the first and final photograph locations of particular sand grains. They do not represent the actual paths of grain movement during probe penetration.

Figure 11 shows results from the penetration of the cone device into a dense sand with no surface surcharge. The displacement vectors for this dense sand (Figure 11a) show a downward and outward movement below the cone tip, and an upward and outward movement above the tip. There is a noticeable pattern of curved surfaces of particle movement from the probe to the sand surface. Essentially, the sand was so dense that it was easier to displace it, causing surface heaving, than to densify it.

The volumetric strain contour picture (Figure 11b) is complex. Positive contours represent areas of soil densification, and are to be expected due to sand displacement by the penetrating solid probe. However, below the tip and adjacent to the shaft are found contours of negative volumetric strain, indicating zones of loosening. These are believed to be a consequence of the shape of the cone tip and

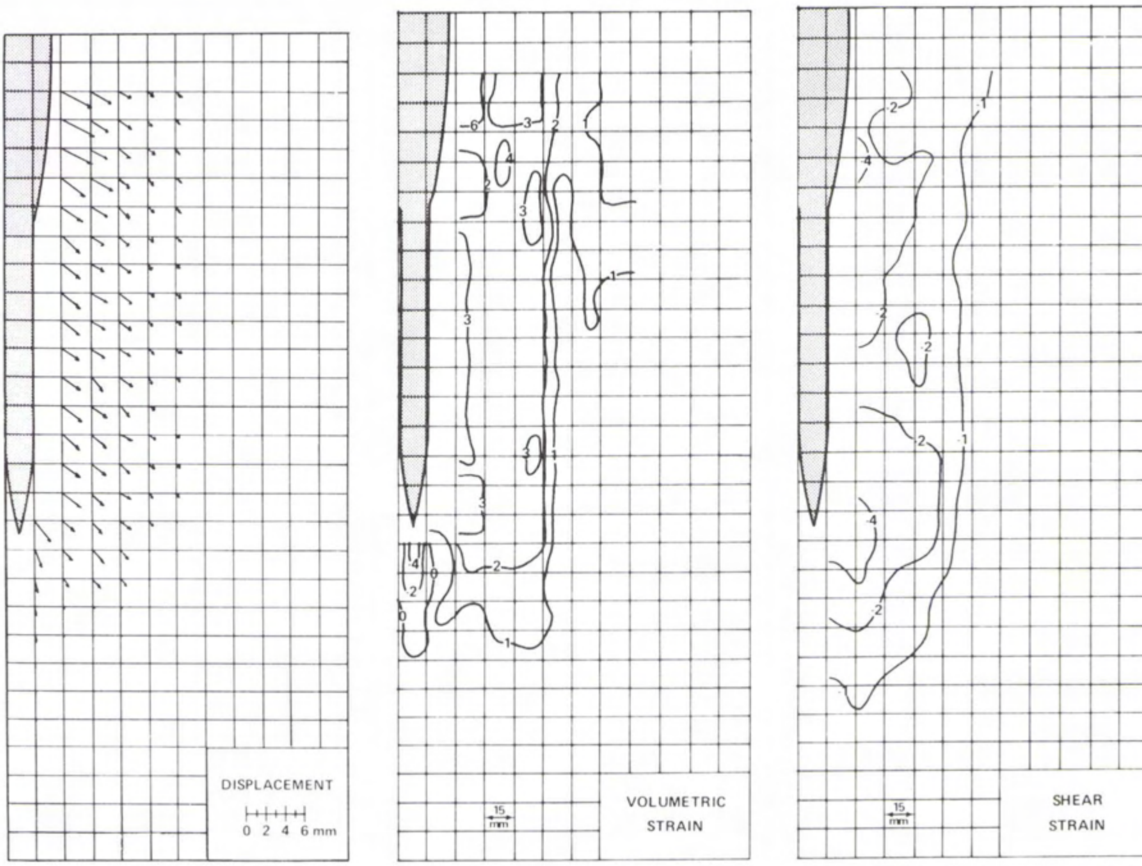

FIG. 12. (a) Blade—loose—displacements; (b) blade—loose—volumetric strain; (c) blade—loose—shear strain.

of the phenomenon dilatancy. When a very dense particulate material is sheared there is a volume increase because, in order for the particles to move or shear, they must ride up over one another.

The shear strains (Figure 11c) are primarily negative. A bulb or concentration of straining is located adjacent to the tip.

Figure 12 includes the results from a dilatometer blade test performed in a loose sand without surcharge. Displacements (Figure 12a) are all to the right and down, away from the probe. There is no surface heave, indicating that the volume of the solid probe is easily handled by sand densification.

The volumetric strains (Figure 12b) are all positive except for a few negative values directly below the tip. The contours are very uniform adjacent to the blade face, showing decreasing densification with distance from the probe.

The shear strains (Figure 12c) are all negative except for some low positive values on the symmetry line below the tip. Adjacent to the blade's flat surface the shear strains are very uniform, decreasing to zero with distance from the probe.

The geotechnical conclusion from the research was that the dilatometer, because of its smoother shape, disturbed the soil much less than did the cone, especially in the regions where measurements are made. This can be clearly seen by comparing Figures 11b and 11c, with their strain concentrations near the tip, to Figures 12b and 12c, in which the contours adjacent to the blade's flat surface are very uniform.

ACCURACY OF THE STEREO TECHNIQUE

The stereoscopic technique can be used to very accurately measure the displacements of sand grains at designated points in a viewed plane. Errors however can occur during the photographing of the model and adjusting the stereo plotter. A camera with a high quality and low distortion lens capable of providing sharp images is required. In addition, the film must be perfectly flat during exposure. Glass plate photographs are therefore preferable. Prints and enlargements on paper can result in errors due to flaws in the quality of the photographic paper and errors in the enlarger. The axis of the camera must be exactly perpendicular to the plane of the displacement field and, of course, no movement must occur between exposures. Great care must be exercised in correctly orientating the photographs in the stereo plotter.

Andrawes and Butterfield (1973) report an accuracy of measurements within ±0.03 mm for prototype displacements, and suggest ±0.005 mm accuracy could be obtained using full scale photographic plates and a 10x optical magnification plotter. Wong and Vonderohe (1981) report accuracies of ±0.08 mm and ±0.06 mm in the x and y components of particle movements.

In the current penetration study the greatest inaccuracies resulted in readings at grid points very close to the probe tips. The problem was the existence of large parallax or displacements in the direction normal to the eye line. At points where this made the stereo image very weak, the parallax normal to the the eye was eliminated by using the Y-translation movement of one projector. During the research a consistent program of rereading points near the probe tips was employed. Maximum errors of ±7 percent were found. This translates into a possible error of 0.3 mm in a typical large displacement near the probe tip of 4.5 mm. While this is large compared to the accuracies reported above, it was quite satisfactory for the purposes of the research. In this study the prototypes were full size probes. In actual modeling studies, accuracies are much more critical because measurements are multiplied by the ratio of the field structures to physical model dimensions. For example, Wong and Vonderohe (1981) used a 152-mm diameter steel pipe to model a tunnel. For a 15.2-m (50-foot) diameter tunnel, the multiplying factor would be 100.

In the current study, shear and volumetric strains were computed from the displacements. Considering the worst feasible deformation of a element, the volumetric strain error would be 7.5 percent and the shear strain error 7 percent for 7 percent errors in the displacement measurements.

The geotechnical problems of non-homogeneity and non-reproducibility of the large samples and, in the current study, the possibility of vibrations and non-vertical penetration can be much more serious.

Despite such problems, the stereoscopic testing technique described in this paper has great potential for use in geotechnical engineering and in the broad general area of particulate mechanics.

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