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Investigation of Tube Sampling Disturbance using Transparent Soil and Particle Image Velocimetry

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ABSTRACT

This research combines a small-scale physical model of artificial transparent soil and an image recognition technique, Particle Image Velocimetry (PIV), to investigate the effects of tube sampling on soil disturbance. Using a transparent soil made of amorphous silica and an oil blend of matching refractive index has made it possible to photograph changes within the soil body during sampling to measure the strains caused. The centreline strain path (CSP) of the sample during sampling was recorded and compared to the existing analytical models' strain predictions, and some degree of correlation was observed. However, it was observed that the CSP is not constant throughout the sample, but varies with depth below the base of the borehole. It is planned that the insight gained from this research will lead to better designs of tube samplers, which will produce high quality soil samples without significantly raising the cost of site investigation.

Keywords: sample disturbance, transparent soil, PIV, non-intrusive strain measurement, Centreline Strain Path

1 INTRODUCTION

1.1 Sampling disturbance

Tube sampling disturbance is a problematic issue affecting soils being taken from the ground for laboratory testing. During sampler penetration, then during transport, storage and laboratory handling of the sample, soil within the tube experiences a range of stress states which lead to changes within its structure. Consequently the sample becomes "disturbed", and the fabric and strength properties of the soil are modified, a phenomenon which has been linked to the distortion of the in-situ soil strength. Since the implementation of the EuroCodes in 2010, there has been an urgent need for the development of a sampling tube capable of producing samples of sufficiently high quality to be considered undisturbed – or representative of the in-situ conditions – by the new standard, since the most widely used tube sampler is now classified as producing disturbed samples. Though numerous researchers have studied sampling disturbance experimentally, the real movement of soil during and immediately after tube sampling has never been measured. Investigations to date have followed one of three methods. Typically researchers have sampled a same type of soil with a range of different sampler types and compared the samples' strength characteristics. Analytical solutions for centreline strain paths have been developed. The results of these and the stress paths recorded in triaxial tests on natural soil samples have been applied to undisturbed samples in order to verify the effect of these stress paths on strains and mechanical deformation.

1.2 The Strain Path Method

The basis of the current understanding of tube sampling disturbance lies in the Strain Path Method, an analytical approach devised by Baligh (1985) to predict the strains caused by the penetration of a simple tube sampler in soil at depth. This technique assumes that in deep geotechnical problems, the behaviour of soil is strain- rather than stress-related. The analytical approach models tube sampling by treating the soil as an incompressible and homogeneous medium, subjected to a ring source flow representing a round-ended sampler. The solution firstly defines the types of strains generated at the cutting edge of the tube, and revealed that the principal component is vertical. It secondly predicts the vertical strain history of a soil element on the centreline of the sampler. This centreline strain path

(CSP) reveals an antisymmetric behaviour around the point where the element enters the tube, with an initial compression phase followed by a rapid extension and a final compression as the soil travels upwards in the tube (Figure 1). The vertical strain on the centreline (ε_{zz}) is a function of two tube geometry parameters, namely the outer diameter, B_o, and the tube thickness, t, and is expressed as a percentage (1).

$$\varepsilon_{zz} = -\ln\left(1 + \frac{2t}{B_o} \times \frac{\left(\frac{z}{B_o}\right)}{\left[1+4\times\left(\frac{z}{B_o}\right)^2\right]^{\frac{3}{2}}}\right) \times 100 \qquad (1)$$

The CSP reveals the extent of physical modifications at the centreline of the sampler, in terms of residual strain post-sampling, peak strain experienced, and hence both qualifies and quantifies the behaviour of the soil sample during driving of the tube.

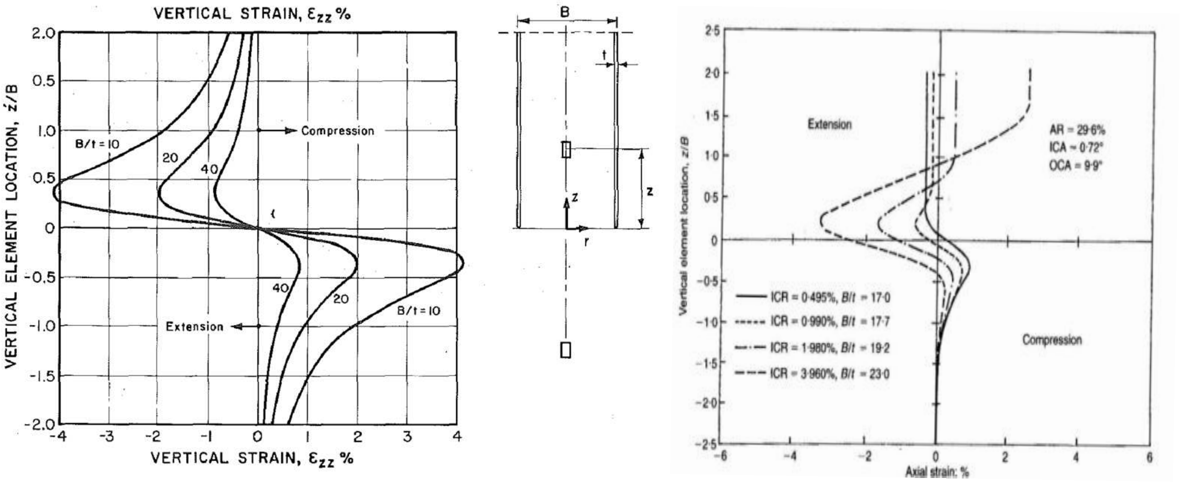

Figure 1 – Strains and Centreline Strain Path from a) the SPM (from Baligh et al, 1987) and b) Clayton et al (from Clayton et al, 1998)

1.3 Effect of tube geometry

A numerical study by Budhu and Wu (1992) yielded similar results, by comparing two tubes, frictionless and frictional, both designed with a sharp edge. The general trend followed by the strain histories was consistent with that predicted by Baligh. However the anti-symmetry of the behaviour and values of peak strain were challenged by the later study, a phenomenon explained by the addition of the sharp cutting edge to which the model flow concentrated. The frictionless sampler yielded the closest match to the SPM, while the frictional sampler introduced compressive forces much earlier during the tube's penetration and hence the curve, while similar to the SPM, was shifted right along the strain axis. A later analytical study by Clayton et al (1998) investigated the influence of cutting edge geometry on the extent of disturbance, and concluded that not only the diameter and thickness, but also the cutting edge and other geometry parameters of the tube have a significant impact on the strains and hence the mechanical deformations within the sample. This study also found that the anti-symmetry of the CSP was lost when considering the effects of sampler penetration (figure 1b). The introduction of an Inside Clearance Ratio (ICR) of almost 4%, defined by equation (2) revealed that extension strains could be significantly higher than compressive strains, while an Area Ratio (AR) of 100%, defined by equation (3), introduced higher compressive strains. The consequences of disturbance on the effective stress and hence strength parameters of a soil (c' and φ') have been quantified in a number of papers. Studies on natural clays by Santagata (2002), Tan et al (2002), Siddique et al (2009) and others concluded that soil strength decreases with increased disturbance. However, the numerical model created by Budhu and Wu predicted increased strength in disturbed normally consolidated clays, but decreased strength in overconsolidated soils.

$$ICR = \frac{internal\ dimateter - internal\ diameter\ at\ cutting\ edge}{internal\ diameter\ at\ cutting\ edge} \times 100 \tag{2}$$

$$AR = \frac{(outer\ diameter\ at\ cutting\ edge)^2 - (inside\ diameter\ at\ cutting\ edge)^2}{(inside\ diameter\ at\ cutting\ edge)^2} \times 100 \tag{3}$$

2 EXPERIMENTAL TECHNIQUE

Particle Image Velocimetry works by recognising the movement of pre-defined patches of matter over a time period, using a series of photographs. The software requires the user to define a grid of interrogation areas which will split the initial photograph into patches which will be individually tracked over the test period. The PIV software will generate displacement vectors for each frame (Figure 2), with an accuracy of a fraction of a pixel. Since transparent soil has insufficient texture to be reliably monitored with PIV, a plane of particles must be embedded at the required depth into the model, and it is the movement of these patches that will be tracked. The artificial soil material used in this study was precipitated amorphous silica (Hi-Sil T600), a fine white powder which, when mixed with pore fluid of matched refractive index, becomes near-transparent. This material has successfully been used to model a range of geotechnical problems such as penetrometer (Lehane and Gill, 2004) and pile penetration (Ni et al 2010) and continuous flight augers (Hird et al, 2011). The fluid used was a blend of N-Paraffin C10-C13 and Technical White Oil 15. The soil was initially prepared as a slurry with a solid to liquid ratio of 9% by weight to ensure successful de-airing under vacuum, and was later consolidated to the required consistency. The properties of the transparent soil have been extensively studied (Iskander 2010) and its ability to model soft clays is widely accepted. In typical studies using PIV and transparent soil to measure displacements within soil bodies, the soil is seeded with reflective particles throughout, and the single plane of interest is illuminated by means of a laser. Photography of the model during testing produces frames ready for PIV analysis.

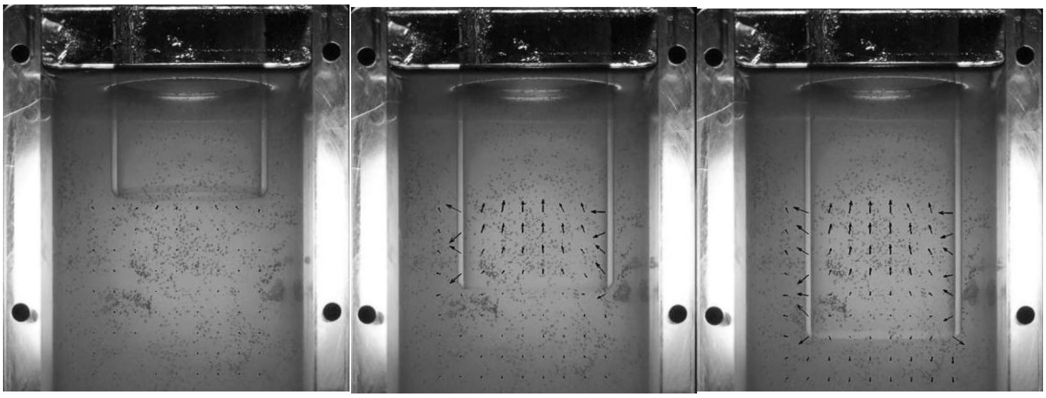

Figure 2 – Vector fields generated by PIV analysis of tube sampling in transparent soil

The reliability of the analysis is dependent on the size (in pixels) and texture within the patches, as well as the rate at which the accepted appearance of the patch is updated (as the elements within the soil change appearance it becomes more difficult for the software to recognise them. To account for this, the appearance of the patch can be updated at a set rate).

In previous studies the dimensions of the physical model have been limited by the tendency of the soil to decrease in transparency with depth. This has a double effect on visibility: the intensity of the laser illuminating the plane of interest is lessened in the direction in which it acts, and the material between the plane of interest and the front of the model blocks a clear view to the plane. By using a white light source and a seeded plane in the area of interest, the depth to the plane of interest can be greatly increased, and in this study has been increased from the previously achieved 50mm to 100mm. This is beneficial since the boundary effects of the box base are expected to have an influence on the peak strain values. White light reflecting off the front of the Perspex box will significantly decrease the contrast between the soil and the particles, thus decreasing the effectiveness of the PIV analysis. The soil must therefore be backlit (Figure 3), and by placing a black curtain between the light source and the camera while eliminating all sources of ambient light, a good texture and contrast can be obtained.

The plane of particles can be seeded at the required location within the soil model by a painstaking and controlled process of horizontal, and later vertical, consolidation. The custom made Perspex box is initially placed horizontally and filled with enough slurry to produce a 100mm layer once consolidated, during which time the volume of the soil decreases by approximately 50%. Typical pressures used do not exceed 9kPa, which ensures that the majority of the consolidation is vertical, as would occur in natural soils. The seeding is done by sprinkling the consolidated surface with 500-600µm coloured spherical glass particles. Spherical particles reduce the risk of particles becoming unrecognisable during testing as they undergo non-perfect translation. The model is then filled and consolidated. The pressures are chosen so as to ensure minimum consolidation of the lowest layer under the weight of the highest. This process creates a perfectly plane seeded surface the width of one particle. The box is then placed vertically and subjected to pressures up to 100kPa to finish the consolidation phase. Tube sampling is modelled by continuously driving a rounded glass tube (B=51mm, t=2.9mm, B/t= 17.6, AR= 36.8%, ICR= 6.3%) into the transparent soil and recording the resulting displacements by still photography at a rate of 2.4fps.

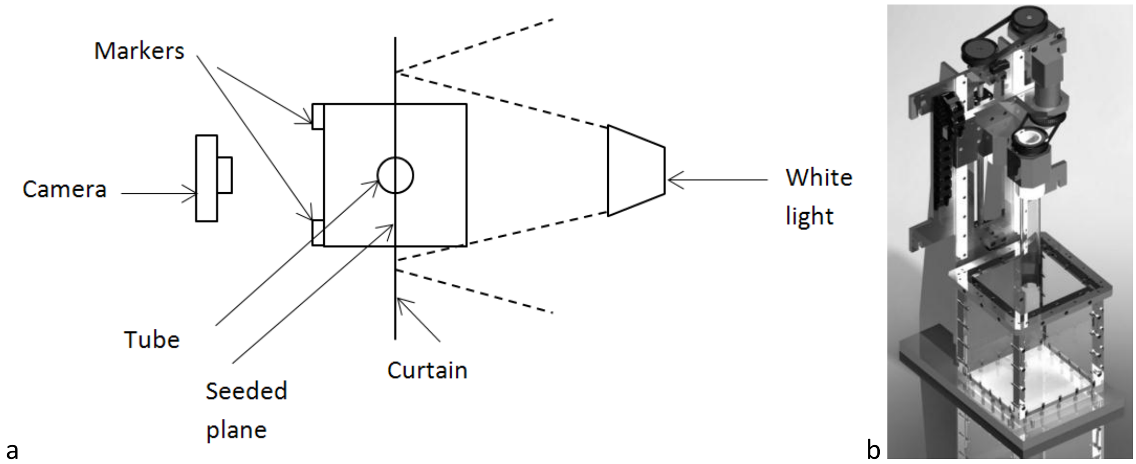

Figure 3 – experimental setup, a) viewed from above and b) viewed from the side

Once acquired, the photographs must be corrected for camera shake and lens distortion, unavoidable problems caused by the very nature of photography. Even when mounted on a stable tripod it is impossible to avoid small movements of the camera between shots. Fixed reference points must be mounted on the box, the tracking of which over the test period will allow for camera shake correction. Lens correction is done by measuring the total optical distortion caused to a plate precision-drilled with holes at known positions, photographed through 100mm of consolidated slurry, a half glass tube and a wall-thickness of Perspex.

3 RESULTS

Two tests were conducted on the scale model (100mm to the plane of interest, 80mm wide and 160mm high), and the photographs of the test were analysed using GeoPIV, a PIV tool run in Matlab developed by White and Take (2002) for use in geotechnical models. The centreline strain path was plotted for elements at varying depths in the model (Figure 4). In previous analytical models, the centreline strain path was assumed to be constant throughout the sample, however in this study it was revealed to be – and is therefore studied as – a function of depth below the base of the borehole. The depths analysed were 51 mm (1B), 70mm (1.37B) and 87mm (1.7B). It is of note that 87mm depth lies within the lowest 80mm of the soil model and therefore its peak compressive strain may be exaggerated. Furthermore, a small percentage of values (around 3 %) were removed from the results due to the appearance of isolated wild vectors.

While the PIV process measures displacements, these are easily converted to strains by calculating the difference in displacement between two close patches. For strains to be accurate, the chosen patch size must be small, thereby reducing the space averaging which can happen in larger patches. Where patches cannot be easily recognised, such as when the contents change drastically between two images, wild vectors can appear. These are characterised by isolated non-characteristic displacement vectors, which can only be removed from the vector plots in cases where the user is certain that it is an error, and not a phenomenon being observed. The soil is seen to undergo the three phases of compression-extension-compression predicted by Baligh and others. However, the behaviour is not anti-symmetric and peak compressive and extensive strains are not equal. The values are also significantly higher than those predicted in Baligh's Strain Path Method. This is due to the lack of restraint of soil elements at the base of the borehole, which are free to expand upwards during sampling while the tube travels vertically downwards, creating large extensive strains.

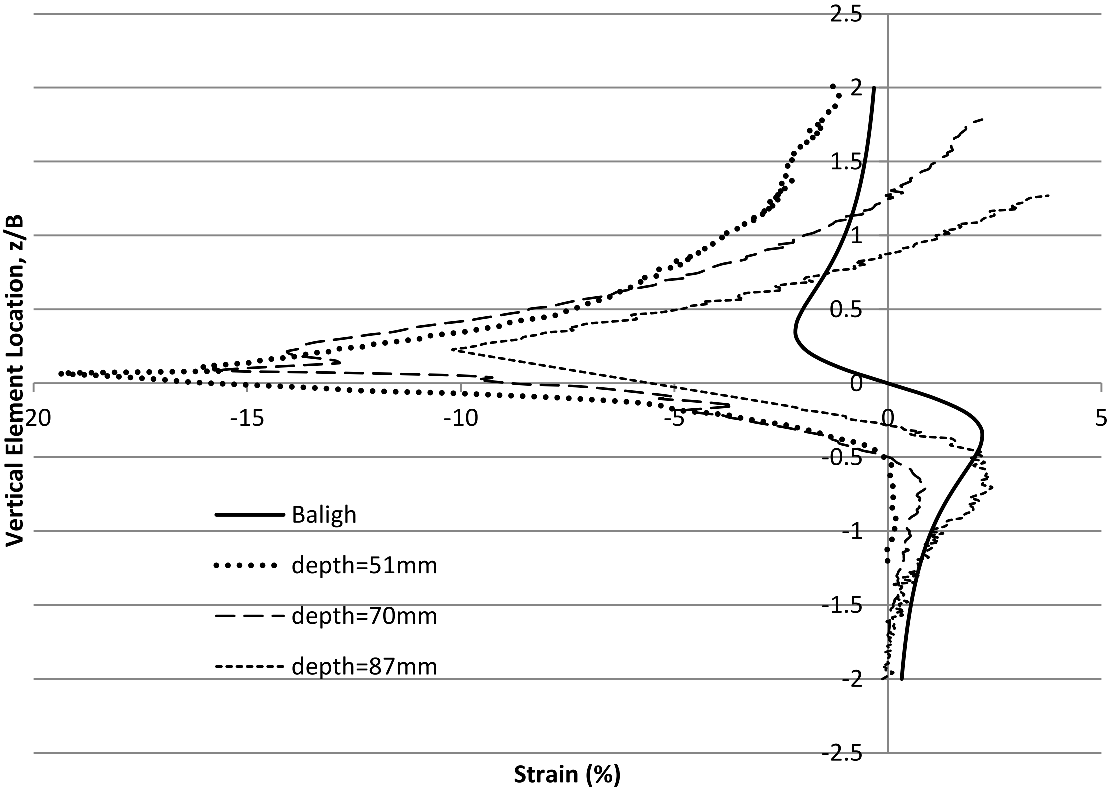

Figure 4: Centreline strain path at varying depths

It must be noted that this extension phase is rapid and occurs over a depth of 1 tube diameter. As elements lower in the sample are considered, the peak extensive strains reduce considerably. This is consistent with research by Hvorslev (1949) on natural clays who concluded that soil within 2 to 3 tube diameters below the base of the borehole was to be considered severely disturbed and was therefore unsuitable for laboratory testing. It is also consistent with the results of Clayton (1998) for the addition of the ICR parameter. The centreline strain path cannot therefore be taken as a constant over the sample's length. It must also be noted that the peak strain is achieved at a lower depth than that predicted by Baligh's Strain Path Method.

4 DISCUSSION OF TEST LIMITATIONS

The research presented in this paper is on-going and aims to improve the experimental technique in future tests. The strain paths are dependent on boundary effects. It has been estimated from the results of initial tests that the peak strain is highly influenced by the distance from the patch of soil to the base of the box, with significant effects within 80mm of the base. The model can be improved by deepening the depth of soil so that three distinct situations can be modelled: the soil immediately below the base of the borehole, the soil at depth which is assumed to behave independently from the surface, and soft clay deposits lying over a harder deposit. The test results presented in this paper were corrected for camera shake but not for optical distortions so while the behaviour patterns have been presented with confidence, the exact values of strain are expected to be documented more accurately at a later stage.

5 CONCLUSIONS

This research has provided an insight into the physical changes within a soft clay sample during sampler penetration by tracking the movement of patches of soil on the tube's centreline via photography and analysis with Particle Image Velocimetry. It has in particular concluded that:

- the strain history at the tube sampler's centreline comprises three stages of compression, extension and compression
- the CSP is not anti-symmetrical and peak compressive and extensive strains are unequal
- the final stage of compression is greater than the initial compression stage, which would result in a denser sample within the sample tube
- the CSP is depth-dependent and elements close to the surface will be very heavily disturbed and are therefore unsuitable for laboratory testing of engineering properties, including strength.

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