Discussion

Separate arm analysis is unsafe

Since the publication in *Ground Engineering* August 1992 of the paper 'The assessment of in situ stress and stiffness at seven overconsolidated clay and weak rock sites' by AS O'Brien, CJ Forbes-King, PA Gildea & P Sharp, a number of questions have been asked about the assumptions and practices made by the authors.

Ground Engineering kicks off this discussion with the views of R Whittle of Cambridge Insitu on aspects of this paper, and is then answered by the paper's authors. Anne Gordon of the University of Surrey's department of civil engineering also raises a point about field values.

This paper is of some importance for users of self-boring pressuremeter (SBPM) data. The paper indicates that use of SBPM and other advanced in situ testing methods give better estimates of in situ soil properties and leads to less conservative structural designs. Because of the extensive use made of SBPM data the paper is likely to be a standard reference for persons specifying the SBPM test in heavily overconsolidated clays. Since its publication Cambridge Insitu has already been asked to use some of the interpretive techniques described in the paper.

We are, however, unhappy with some aspects of the practice employed by the authors, in particular the separate arm analysis and the derivation of in situ lateral stress from 'lift off':

The authors quote three sets of results for every test, because each strain arm is assumed to produce a valid loading curve.

This assumption is unsafe. The arms are not independent because they are coupled to the body of the instrument which is a reference for all the measure displacements. Analysing separate arm movements assumes that the instrument axis is fixed, which is safe.

See **Figure 1**. This plot shows the paths of three strain arms 1, 2 and 3, while three rebound loops, A, B and C, are taken.

The pressure decrement for loop B is greater than that for loop A. The corresponding shear modulus should be less, which is not the case for arms 2 and 3. Notice that strain arm 1 has yet to 'lift off'.

Consider that geometry at the point before loop A is started. The instrument is supported above and below the expanding membrane by the ground. The membrane is moving in the direction of arms 2 and 3, but is pressed against the instrument in the direction of arm 1 by an external force. This is balanced partly by the gas pressure inside the membrane and partly by a reaction from the instrument body.

During the unloading the external stress affecting arm 1 is unchanged, but the falling gas pressure requires an increase in the reaction from the instrument body. This reaction causes deflections of the body away from arm 1, towards a point between arms 2 and 3.

Therefore, for arms 2 and 3, the change in strain for the decrease in pressure of the reload loop is larger than it should be because of the contribution from the instrument.

It follows that the only valid loading curve is that obtained from the average displacement of all strain arms, where the movements of the instrument body cancel out.

Lift off analysis of the separate arms is a complex analytical problem. However, there is no mystery why stiff materials give a substantial range of lift off pressures.

Take as an example an SBPM perfectly drilled into an homogeneous stiff clay with isotropic properties. Imagine that this instrument is 0.2mm out of round, a

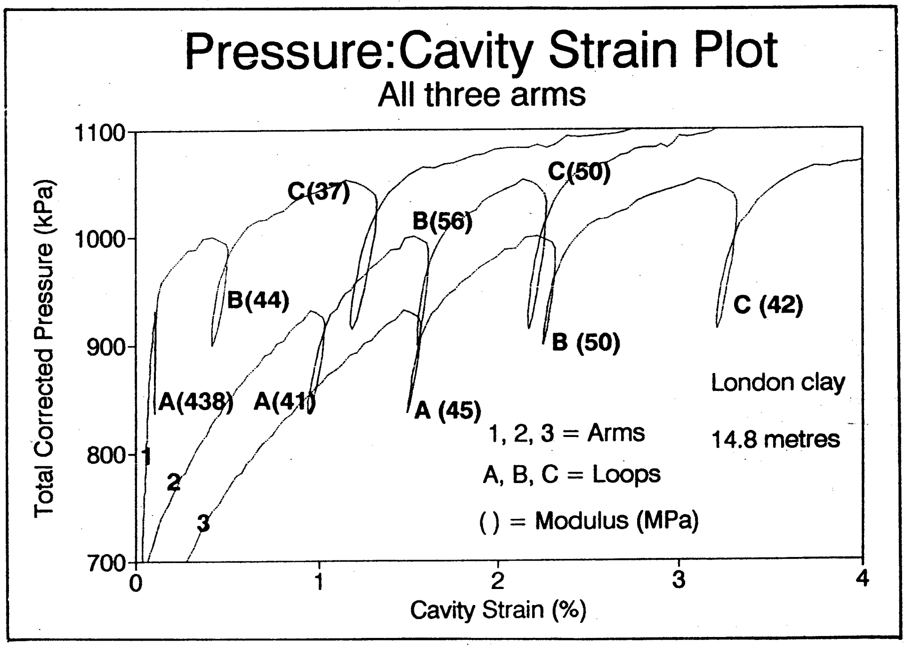

Figure 1: The effect of arm coupling on modulus.

Key is test quality

plausible manufacturing tolerance. It would produce a plot similar to **Figure 2**.

0.2mm represents a strain of about 0.5%. Not only is there a stress increase on one side of the instrument and a reduction on the other, but the associated strain means that the material has already failed. This is what Figure 2 shows – arm 1 is already well down the loading curve before it 'lifts off'.

However, by the same argument it follows that one direction of the instrument will not have disturbed the material at all. For an instrument with three equi-spaced arms the middle value of lift off stress always gives the better estimates of the in situ lateral stress.

These comments indicate that the major difficulty with interpreting the SBPM test curve is distinguishing between elastic deflections of the instrument and elastic deflections of the ground. To mistake one for the other is all too easily done and has occurred here. To contribute to the resolution of this we are at the moment completing the manufacture of a pair of six strain arm self boring pressuremeters; such an instrument will, we hope, establish beyond doubt what happens in the early part of a self-boring pressuremeter in stiff clay. If the authors are able to make use of this instrument we would be most happy to co-operate.

R Whittle, Cambridge Insitu.

Mr Whittle has expressed concern over two matters:

(i) The use of individual strain arm data for shear modulus derivation.

(ii) Assessment of lift off pressure.

As an example of the problems which may arise by using individual strain arm data Mr Whittle considers the derivation of shear modulus from three strain arms, during an unload/reload loop prior to lift off. Rather unsurprisingly there are discrepancies and, in particular, the shear modulus for the strain arm which has not lifted off is very high. For this situation, Whittle recommends that the shear modulus should be calculated from an average unload/reload loop. This is quite incorrect.

Prior to lift off of all the strain arms the pressuremeter cavity is, by definition, expanding in a non-symmetric manner.

The basic assumption in the derivation of shear modulus is that the pressuremeter cavity is expanding in an axially symmetric manner.

For the situation quoted by Mr Whittle the authors would recommend that the shear modulus data for all three strain arms for the first unload/reload loop is ignored, and only the data from the second and third loops (after lift off) are considered for further analysis. In general unload/reload loops should not be carried out until all the strain arms have lifted off.

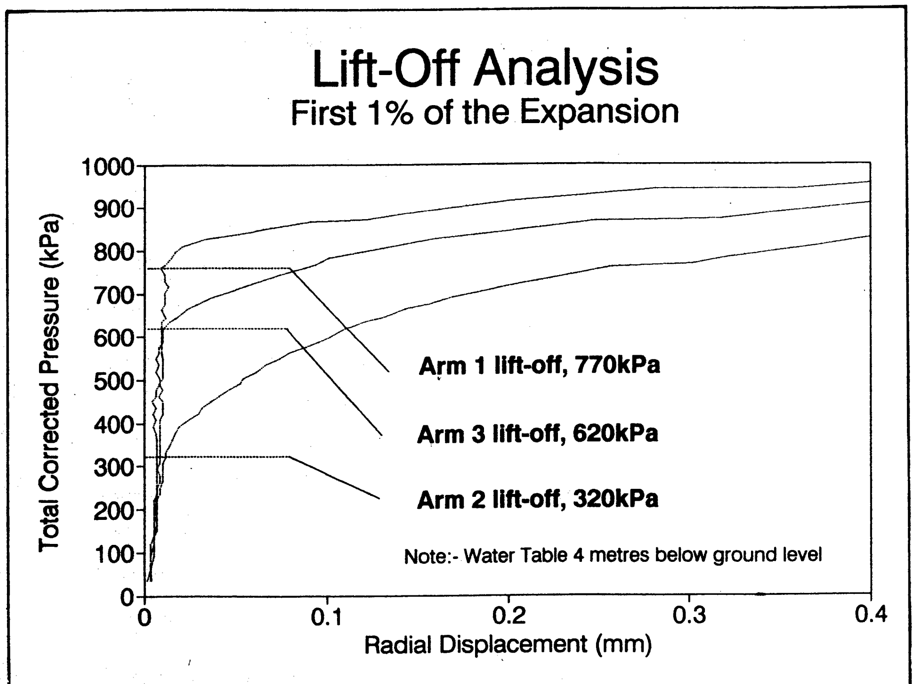

Figure 2. SBPM test in London Clay, 16m to test centre.

Once lift off has occurred then the measurement errors caused by instrument body movements are likely to become far less significant. The authors have compared 'averaged' shear modulus data with individual strain arm data (following correction for strain level effects), and there is little significant difference between the two sets of data. The key factor is the quality of the test data, tests which show signs of disturbance should not be used for further analysis. This is the main advantage of inspecting the loading curves for individual strain arms. Features which may indicate disturbance can usually be more readily identified from individual strain arm data than from the 'average' loading curve obtained from the three main arms.

Considering the assessment of lift off pressure Mr Whittle describes the effects of manufacturing tolerances ('out of roundness') on the magnitude of lift off pressures. This is a valid point. However, the authors do not agree with his 'solution'. Where is the evidence that using 'the middle value of lift off stress always gives the better estimates of the in situ lateral stress'? There is no logical reason why the 'middle' strain arm should be related to the 'out of roundness' of the pressuremeter, and therefore is unlikely to be related to the location of 'undisturbed material'.

Figure 3 summarises some in situ stress measurements from a series of SBPM tests carried out at London Clay site one. These measurements can also be compared with the passive limit for horizontal stress (based on effective stress strength parameters) and on the 'stress history' profile for the location under consideration. The stress history profile was derived using the approach described by Burland, Simpson & St John (1979), but modified by assuming that the horizontal stress prior to reloading by superficial deposits had reached its passive limit (based on effective stress strength data for the site) throughout the depths of London Clay.

Compared with the passive limit and stress history profiles it can be seen that both the arithmetic mean and the middle value of the lift off pressures (as recommended by Mr Whittle) are unreasonably high. Whereas the lift off pressures for strain arm which showed small cavity strains prior to lift off are much lower and more reasonable. It should also be noted that these lower bound lift off pressures are similar to those derived from the averaged loading curve for the three strain arms. Prior to lift off the use of an averaged loading curve can be particularly useful for derivations of lift off pressure, due to the instrument body movements described by Mr Whittle.

Although the absolute magnitude of the SBPM in situ stress measurements at the London Clay site one were considered to be rather high, the SBPM provided valuable data on variations of in situ stress across the site particularly adjacent to man-made features, such as tunnels, (O'Brien & Newman, 1988).

'Out of roundness' can affect the magnitude of lift off pressures, but other factors may also have an affect. Jamiolkowski et al (1885) have summarised reports by various authors which indicate that the phenomenon of different lift off pressures may be attributed to one or more of the following:

- Mechanical compliance of the instrument;
- Deviation of the probe from vertical;
- Disturbance during self-boring, which may create several different effects including a non-circular hole around the pressuremeter;
- Non-uniform shear stress at the probe soil interface;
- Anisotropy of the horizontal in situ stress.

The mechanism described by Mr Whittle only addresses a single possible cause of the discrepancy in lift off pressures between strain arms. Therefore, it is important to understand the behaviour of the pressuremeter being used at a particular site, rather than oversimplifying the interpretative process. Clarke (1992) has recommended that it is important to understand the 'signature' of each strain arm. This is in essence the same as the procedures which have been used by the authors in the past. It is always important to review all the relevant data from a series of tests, rather than studying individual test data in isolation. It is only by doing this that the various factors listed above may be eliminated, or a least their significance assessed.

A point which Mr Whittle has not mentioned, but which will have a particularly important influence on in situ stress measurements is the quality of self-boring, which is a combination of drilling and pushing in. In order to measure the 'true' in situ stress it is necessary for the drilling and pushing in of the instrument to be balanced precisely. If the instrument is over pushed or the shoe of the pressuremeter becomes temporarily blocked then the 'lift off' pressures will exceed the in situ horizontal stress. Perhaps this is one of the main reasons for the view, held by some experienced users of the SBPM, that there is a tendency for the lift off pressure to be rather too high compared with accepted ideas of in situ stress conditions.

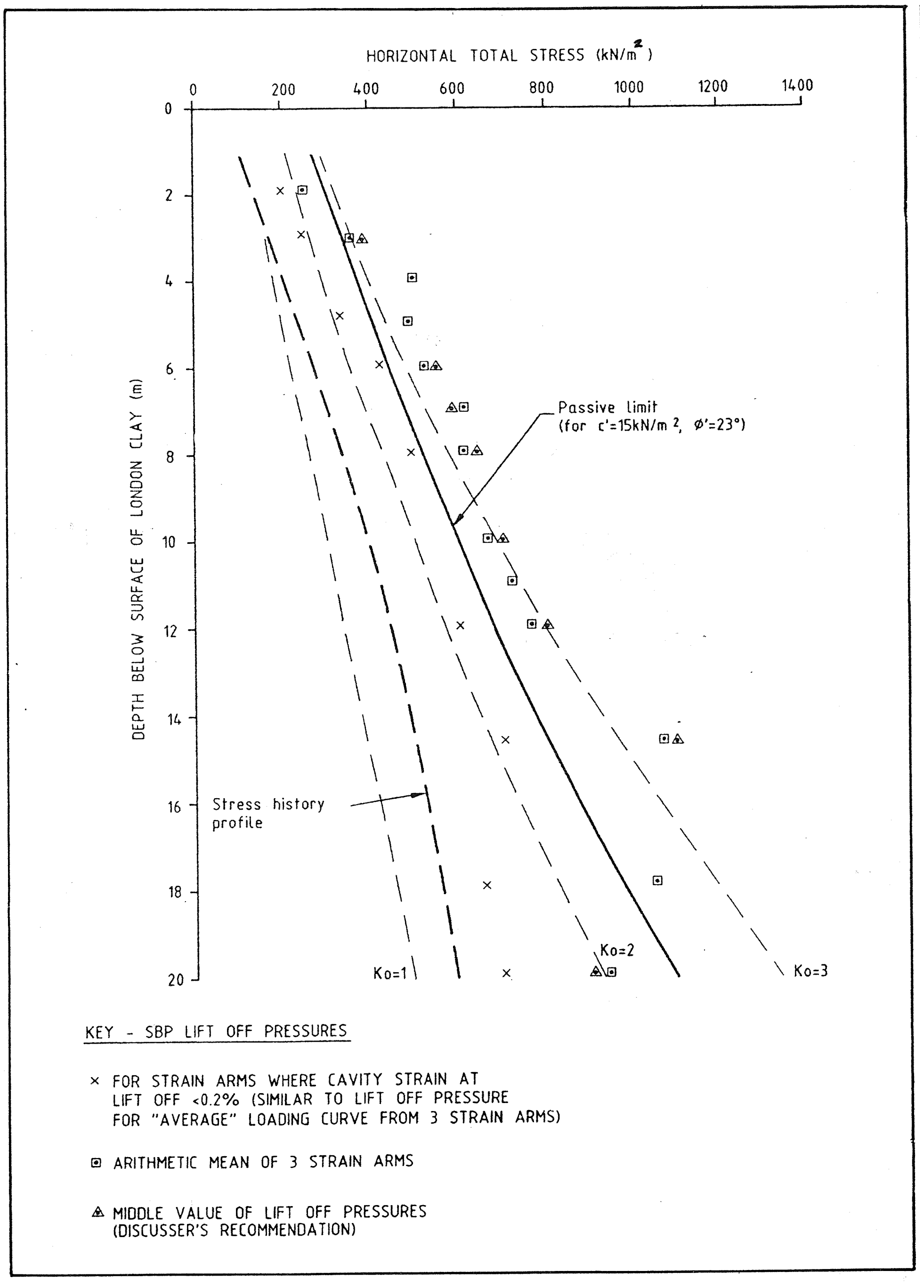

Figure 3. Horizontal stresses for London Clay – site one.

As discussed by Clarke (1992), recent improvements in SBPM strain arm design have reduced the errors caused by instrument compliance behaviour. However, installation problems can still be problematical. The development of a 'six strain arm' SBPM is an interesting and worthwhile development. However further knowledge of how different self-boring procedures may affect in situ stress measurements may be of more practical value.

To conclude the authors would wish to emphasise that there are no panaceas for determination of in situ stress and stiffness, which remain complex and demanding tasks.

It is only by using a range of investigative techniques (including high quality sampling and laboratory testing) and analysis procedures, and evaluating all the available data within a framework of a relevant established empirical correlations and soil mechanics theories that appropriate parameters for design can be identified.

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Authors of '*The assessment of in situ stress and stiffness at seven overconsolidated clay and weak sites.*

Anne Gordon of Surrey University asks: 'When driving a design profile by normalising Eu with respect to vp'k, i.e. Eu/(vp'k)lab and subsequently multiplying this ratio by (vp'o) field, how are field values for the specific volume obtained?'

The matter raised by Anne Gordon requires further clarification and refers to **Figure 16** of the paper (p31, *Ground Engineering*, September 1992). From small strain triaxial tests, both specific volume and mean effective stress can be measured. However, the values measured in the laboratory on a particular test specimen may not be representative of those in situ (i.e. 'field' values). The 'field' values of specific volume are based on laboratory measurement of moisture content obtained from a representative number of samples which have been taken throughout the depth profile under consideration. From this data a design profile for the variation of moisture content with depth can be determined, and therefore field values of specific volume derived. This can then be combined with the 'field' values of mean effective stress, in order to correct the laboratory measurement of undrained secant Young's modulus.

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