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Finite element analysis of the effect of drainage conditions on the in-situ shear vane test

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ABSTRACT: The In-Situ Shear Vane is a notionally undrained test used for estimating the shear strength of saturated fine-grained soils. The influence of drainage on the reported shear strength is not usually taken into account and previous finite element analyses of the test by the authors were performed on the basis of a rate-independent total stress analysis. Theoretical models have relied on the same assumption and in practise the test is conducted in a manner which is assumed to account for these constraints. This paper reports the results of applying a fully coupled elasto-plastic analysis to the vane geometry. The undrained solution is retrieved as a special case, however the role of drainage in the context of an effective stress analysis is given particular emphasis. The validity of the different drainage assumptions is investigated with the influence of the relative rate of rotation of the vane in the ground and compared with an alternative model of limiting drainage conditions.

1 PRACTICAL CONSIDERATIONS IN THE SHEAR VANE TEST

The In-Situ Shear Vane Test purports to measure undrained shear strength (C_u) by conversion of the torque experienced on the vane rotated in a fine-grained soil in accordance with standard procedures. These delay the start of testing after insertion of the vane to allow dissipation of excess pore pressures and limit the rate of rotation of the vane.

Previous work of the authors (Griffiths & Lane, 1990, 1991) has considered assumptions associated with the estimation of C_u from the measured torque in terms of the generation of shear stresses on the vane blades and circumscribing cylinder in an undrained, total stress condition (Figure 1).

Observations have been made that the influence of the relative rate of rotation of the vane can produce a variation in the measured response of +20 to -10% (Aas ,1965).

Whilst the standard procedures intend to minimise the influence of these considerations on the test results across different soils (Chandler (1987)) there has been no objective analysis of their potential impact.

In reality there are effective stress considerations due to the generation of excess pore pressures on insertion of the vane and during shearing. Other authors (e.g. Morris & Williams, 1994) continue to rest on the assumption of no impact.

The range of drainage conditions possible with the test are considered here in a coupled finite element analysis to assess the potential impact on the measured torque and hence the estimated (undrained) shear strength.

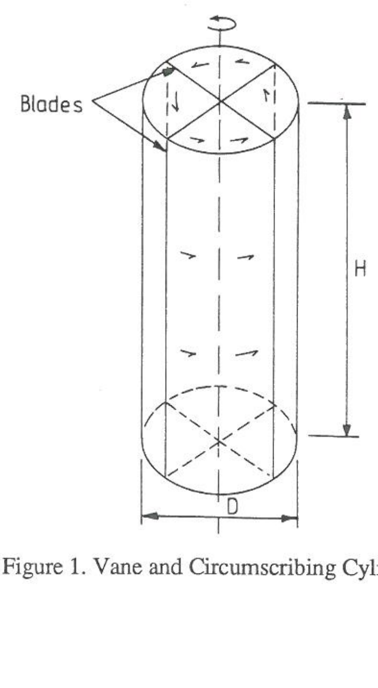

Figure 1. Vane and Circumscribing Cylinder

2 COUPLED FINITE ELEMENT ANALYSIS

The interaction between soils' applied stress, skeletal stress and its pore water pressures can be expressed explicitly by the coupled equations of Biot (1941). Their implementation in the finite element method has been demonstrated and tested in numerous examples (e.g. Smith & Griffiths, 1988).

2.1 *2-D Plane Strain Analysis*

For this analysis the coupled equations were incorporated in a 2-D plane strain model of a quadrant section through an infinitely long vane. This utilises 8-node quadrilateral elements with curved geometry (Figure 2). The mesh concentrates elements around the circumscribed arc of shear failure and the vane blades are represented by controlled tangential displacements (Δ) of two sections of the boundary (0 - R).

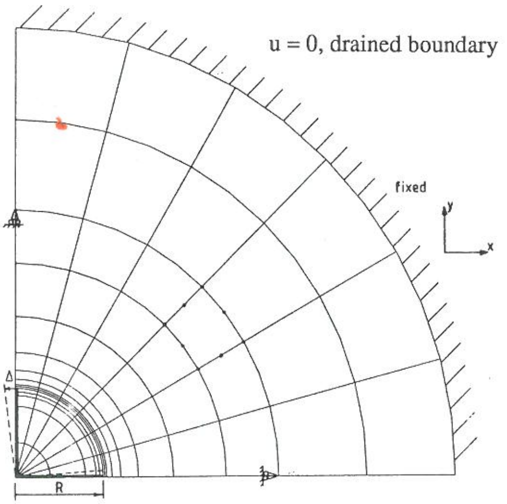

Figure 2. 2-D Mesh and Boundary Conditions

The soil is represented as a continuum with a Mohr-Coulomb strength condition and elasto-viscoplastic behaviour. The fluid behaviour is represented by 4-node curved quadrilateral elements coupled to the 8-node elements. Drainage is permitted on the external circumferential boundary but not across the radial symmetry boundaries or through the vane blades.

2.2 *Drainage Parameters and Vane Rotation Rate*

The drainage condition of a soil in a failure situation varies according to the relative permeability of the material with respect to the rate of failure. In the In-Situ Shear Vane Test this is the permeability of the soil with respect to the rate of rotation of the vane.

For a unitary homogeneous permeability (k_x=k_y=1) the rate of rotation of the vane blade is represented by the size of the time interval (dt) in the incremental form of implementation of the coupled analysis (Griffiths, 1994) relative to the displacement increment ($d\Delta$) applied to the node at the tip of the notional blades and proportionally along the line of intermediate nodes.

The quantity $d\Delta/dt$ varies in the order of 10^9 between 'fast' loading, representing the undrained condition, and 'slow' loading representing drained conditions. Intermediate conditions can also be represented.

2.3 *Calculation of Measured Torque.*

The torque that would be measured by the vane in the test is estimated from the summation of the moments of the bodyloads back-calculated at the displaced nodes representing the vane blades.

It is possible to evaluate the bodyloads due to the total or effective stresses. Distinguishing between the effective and total stress contributions illustrates the influence of the generated pore pressures on the estimated torque.

In the in-situ test the undrained shear strength (C_u) would then be evaluated in accordance with the calibration for a particular size and ratio (D/H) of vane based on the assumption of full mobilisation of shear strength over the circumscribing cylinder and vane ends (Griffiths & Lane, 1990).

Allowing for the potential difficulties associated with this evaluation procedure (see Griffiths & Lane, 1990) the variation in the measured torque will represent the variation in the estimated C_u and hence it is the variation in the torque which will be considered here.

To aid qualitative consideration of the results the calculated torque is compared with that obtained from a comparable 2-D plane strain analysis utilising the 'equivalent bulk modulus' approach for modelling the drainage condition of the soil (Naylor 1974). The equivalent bulk modulus is varied to produce drained and undrained conditions (Lane 1993) as the upper and lower limits expected with the coupled analysis varied between fast and slow. The mesh and other model conditions are identical for the two approaches.

3 RESULTS OF 2-D ANALYSIS

The results are presented on the basis of the rate of rotation (fast, slow or intermediate cases 1 and 2) or drainage condition (drained, undrained). The torque is also designated as being derived from total (T) or effective (F) stresses and the method being either coupled (UPV) or equivalent bulk modulus (BSV).

3.1 *Elastic Results*

For the elastic analysis the total torques developed under different drainage conditions are comparable, with the undrained equivalent bulk modulus model giving the highest values and those of the fast, intermediate and slow results converging with that of the equivalent bulk modulus drained value (Figure 3).

The 'effective' torque results show a greater variation in that the values vary from slow/drained which is coincident with the 'total' value (by definition) down to a ratio of about 20% of the total result for the equivalent bulk modulus undrained model.

As predicted the equivalent bulk modulus model represents the upper and lower boundaries of the results with the coupled analysis producing comparable and intermediate values. The 'Int(1)' result is based on a time step 10^3 times that of the 'fast'.

The total torque calculated for the first increment of the fast and intermediate rotations is equal to that of the first increment of the effective results before rising to that of the slow/drained total values. For this first increment insignificant excess pore pressures are generated. The displacement increment size was chosen to produce an elastic result for the first step and this seems to be the case.

3.2 *Elasto-plastic Results*

Again the equivalent bulk modulus approach represents the limits for the total undrained and effective undrained calculated torques (Figure 4). The coupled model with the fast rotation produces a total torque equal to that from the undrained bulk modulus approach while the effective torque for the fast case is comparable to that of the undrained bulk modulus approach, at some 10% of the total result. All these results appear to be producing a defined failure with the calculated torque reaching an upper plateau.

Both approaches produce identical results for slow/drained conditions which are some 90% of the fast/undrained total result and produce an abrupt iterations limit failure with zero excess pore pressures.

The intermediate (1) and (2) rates show results as expected. Intermediate (2) has a time interval some 106 times that of the 'fast' value (and hence some 10^3 less that of the slow rate). Int(1,2) produce total torque results comparable to that of the fast case and effective results which are corresponding close to either the slow (Int(2)) or fast (Int(1)) torque results.

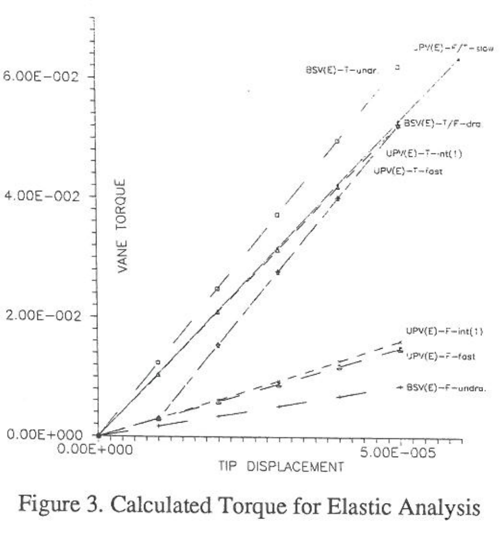

Figure 3. Calculated Torque for Elastic Analysis

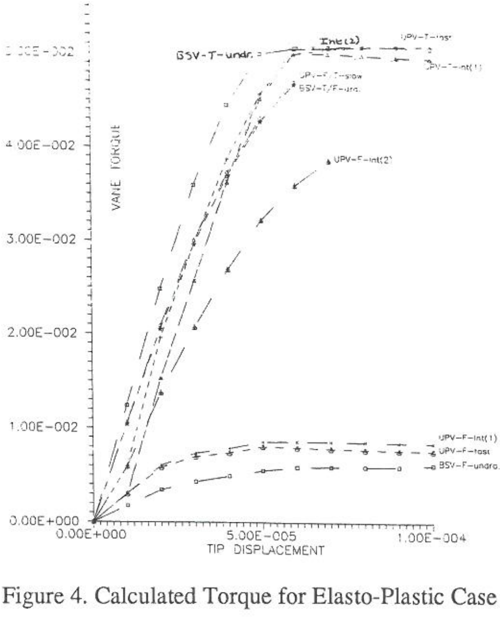

Figure 4. Calculated Torque for Elasto-Plastic Case

The total torque results for both Int(1) and fast loading conditions both demonstrate the reduced value on the first increment observed in the elastic analysis before returning to the higher values seen in the Int(2) and slow conditions.

3.3 *Variation of Pore Pressures*

If the coupled model is realistic and, based on previous work by the authors, then it may be expected that the excess pore pressures generated in the fast/undrained (and intermediate) conditions will develop at the vane blade tips as the shearing resistance increases.

Figure 5 illustrates this development with increasing displacement in the undrained case. As there is no drainage within the vane blades the pore pressures in front of and behind the blades are also increasing adding to the total torque experienced by the vane.

This variation in the pressures between the vane blades is comparable to that noted by Morris & Williams (1993).

The variation in pore pressures is based on the assumption that the soil is able to accommodate suctions which may be possible to some extent in a fine-grained material. No limit is placed on these suctions.

Figure 5. Generation of Excess Pore Pressures Around Circumscribing Cylinder

4 INTERPRETATION OF RESULTS AND CONCLUSIONS

It is assumed that the In-Situ Shear Vane Test measures a torque generated from the total of effective stresses and pore pressures resisting the motion of the vane blades through the soil and limited by the shearing resistance of the soil on the circumscribing cylinder and ends of the vane. In this analysis only the cylindrical contribution to the measured torque is considered together with the effect of the drainage condition of the soil in relation to the rate of rotation of the vane.

4.1 *Evaluation of Results*

All the conditions considered produce calculated values of torques which appear to represent a shearing failure condition as expected in the shear vane test. If the measured torque in the in-situ shear vane test is assumed to be that from the total stresses including generated pore pressures then the limits of the drainage conditions produce a variation in the calculated torque (and hence estimated C_u) of the order of 10%. This is comparable to that observed in the field.

The expression of the torque in terms of the effective stress contribution and the explicit evaluation of the pore pressures illustrate how the measured torque varies in its contributory factors by an order of 10. This is in contrast to the low variation in the total results noted above.

4.2 *Limitations of Results*

The results presented are within the limits of the assumptions of the models utilised. For example:

(1) the vane blades are perfectly rough;
(2) there is no separation from the soil at the the back of the vane blades;
(3) the soil is able to bear pore pressures and suctions equally;
(4) the area of influence is not greater than three times the vane radius;
(5) the soil is adequately modelled as an elasto-viscoplastic Mohr-Coulomb material

The soil has also been assumed to behave in an non-dilatant manner. Preliminary consideration of this assumption illustrates that, as expected for a confined problem, there is an impact on the calculated results and the possibility of a defined failure condition of the inclusion of dilation. This might be experienced in an over-consolidated material and the observation of an increased measured response of up to 20% may be associated with this potential effect.

4.3 *Conclusions and Further Work*

One of the many factors influencing the estimation of undrained shear strength from the In-Situ Shear Vane Test is the rate of the test relative to the drainage characteristics of the soil. Guidance is given on the method of conducting the test to minimise the potential influence of the generation of excess pore pressures but without an explicit evaluation of them.

Observation had suggested an influence in the order of +20 to -10% on the measured torque. The results presented showed an influence of the order of 10% of the rate of rotation and hence the drainage condition on the calculated response. This is comparable to the observed response.

The test is defined as producing an estimate of undrained shear strength but is conducted under conditions that are intended to allow for drainage. The appropriateness of the estimate of C_u must be considered in terms of the nature of the failure that is being considered. For the particular conditions of a field in-situ shear vane test, where some drainage is assumed, conducting the test at too fast a rate could lead to an over estimation of C_u.

The problem was considered with two different models of pore pressure response and the results were comparable and robust. Further development will therefore be pursued to consider other potential influences and for possible calibration with reported results and analytical approaches.

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