Interpretation of the Vane Test

L'Interpretation de l'Essai au Moulinet

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SYNOPSIS The paper describes laboratory research into the interpretation of the vane test. Basically "insitu" vane strengths are compared with "insitu" undrained compression strengths on laboratory prepared soils using methods which exclude sampling disturbance and stress relief effects. Two normally consolidated soils were examined. The work highlights a number of variables which are important in the interpretation of the vane test and although with certain provisions the vane strength is in good agreement with the undrained strength for the present homogeneous and isotropic soils, the vane test cannot generally be expected to give refined estimates of strength for all soil types.

INTRODUCTION

It is commonly assumed that the vane shear test when performed on saturated clays should yield the undrained shear strength of the soil. Unfortunately the vane test is not a fundamental test as it involves appreciable assumptions in order to interpret a result from the measured torques. It becomes difficult therefore to relate directly the vane test result with the undrained shear strength which might be measured on a more fundamentally simple test such as the triaxial compression test. Other sensitive variables such as anisotropy and influence of test rate add further complications.

Correlations bewteen field vane and laboratory measured strengths or between field vane and back analysed strengths of failed slopes or foundations are themselves not fully satisfactory. The former suffers the problem of sampling disturbance and sampling stress relief while the latter involves interpretative assumptions on failure mechanisms which make comparisons unconvincing. The importance of the effect of stress relief due to sampling on measured strength properties has become recognised in recent years, e.g. Ladd (1977).

In the research it is required to compare vane strengths with those of the triaxial compression tests by methods which exclude the effects of sampling disturbance and stress relief. Although the former effect may be reduced by using improved techniques the latter effect, by definition, cannot be avoided in natural soils tested in the laboratory. The present tests are therefore conducted on soils artificially prepared and consolidated in the laboratory. The use of laboratory consolidated soils furthermore has the advantage of reducing variables and providing "standard" homogeneous test materials to assist the quality of the comparison.

PREPARATION OF CLAYS

The clays studied were kaolin and illite and were formed by consolidation slurries of the mate~~rials~~ which were mixtures of a pure deaired water and the respective dry clay powder. The kaolin and illite powders were taken from the same original batches of these materials.

Slurry water contents of 150% of the liquid limit of the clays were found to be suitable for the mechanical mixing and the sample preparation processes and also to provide consolidated samples of suitable thickness.

Consolidation of the slurry took place in 250 mm hydraulic consolidation cells of the type described by Rowe and Barden (1966). In order to obtain a sample of suitable final thickness a double ring assembly was used. This is illustrated in the upper part of Fig. 1. Fig. 1 shows the double ring assembly with vane apparatus attached and ready for test. During the consolidation process the vane apparatus was not present and the oedometer rings sat directly on the bench top. It was of course necessary to provide accessories such as the convoluted rubber jacket, the top drainage tube and deflection dial guages with sufficient travel to accommodate the large compressions which took place during the consolidation of the slurry. Also, in view of the depth of the ring assembly care was taken to ensure a thorough lubrication of the sides with silicon grease. This process seemed to be successful in reducing side friction since it was noted during initial control tests blocks of the clay were found to be able to drop out of the rings under their own weight after consolidation and the rings themselves remained slippy to the touch. In addition no systematic differences could be detected in moisture content across diameters or down the depth of consolidated samples. A total of six of these double ring assemblies were available in the laboratory. Further adaptions to the odeometer had to be made to facilitate the vane testing. These however did not affect the consolidation process and will be described in a later section.

Fig. 1 Oedometer and Vane Assemblies

The sample preparation techniques were aimed at producing samples and consolidated blocks with high degrees of saturation and uniform distributions of water content and reproducibility of water content between different samples and consolidated blocks. The initial slurry water contents were carefully controlled and the slurry was filled into the oedometers under high vacuum. Check pressure tests performed on batches of filled slurry from the oedometers showed degrees of saturation in the region of 99%. This appeared to be confirmed by the excellent pore water pressure response measured during consolidation.

TABLE 1

Clay Properties

Clay Type	Liquid Limit%	Plastic Limit %	Ko	Permeability Coef. (m/s)[1]
Kaolin	65.2	30.4	0.56	1.4×10^{-9}
Illite	77.8	39.5	0.68	7.2×10^{-11}

[1]at σ_{1c} = 552 kN/m^2

The consolidation processes on the oedometers were standardised for the kaolins and the illites, and ensured effective dissipation of excess pore pressure during loading. The final load increment was held for 4 days before testing. Coefficient of earth pressure at rest (Ko) data were also obtained from selected samples using an effectively rigid load cell arrangement placed in the side of the lower consolidation ring.

Vane tests were performed on clay after consolidation to a vertical pressure σ_{1c}=552 kN/m^2. At this pressure the thickness of the soil cakes in the oedometer was over 90 mm. Important engineering properties of the clays are indicated in Table 1. Other physical and chemical properties of the clay powders and the water together with more detailed descriptions and test procedures are given by Khan (1979).

INSITU TESTS

The present tests are of course not field tests on natural soils. They can be considered effectively in situ however if they can take an element of the soil from an inground condition of stress, void ratio etc., and superimpose on it the stress and strain consistent with load or deflection paths of the test itself.

The application of these conditions in practice is perhaps easier to understand in the case of the vane test than the triaxial compression test. However since the vane strengths have to be compared with the triaxial compression strengths it is sufficient for our purposes to define an insitu triaxial test as one which takes a soil element from its insitu stress state and without unloading increases the stress in the vertical direction without restraining the horizontal strains. All this in the case of the undrained test being imposed without change in void ratio.

Insitu Vane Tests

Insitu vane tests were performed in the clay in the oedometer without unloading the final consolidation stresses by inserting a laboratory vane through the base plate of the oedometer assembly. For this the oedometer base plates had three 22.5 mm dia holes bored and tapped in the base. These were placed on radii at 120° to each other and at a pitch diameter of 152 mm. The base drain in these tests was made from hard plastic drain material with holes drilled matching the base.

During consolidation sealing plugs were fitted into the base holes and the standard procedures were adopted. Once this process was completed the oedometer assembly was placed on the frame as indicated in Fig. 1 and one base plug was removed. This screwed hole was then used as the mounting position for the vane apparatus. The motorised apparatus was adapted from a commercially produced model which was based on the design of The Road Research Labatory. The original base stand of this apparatus was removed and replaced with a plate clamp and a short 22.5 mm bolt to fit the screwed plug hole. The apparatus was thus mounted for use in an upside-down position.

In Fig. 1 the mounting position is shown on the left side. The casting carrying the motor and the vane is adjustable for height and is seen in the withdrawn position. With the above......

pitch circle diameter of the three base plug holes and with the apparatus mounted in one the vane can be rotated in an arc allowing it to be centred in turn over each of the other two for testing.

The torque is transmitted from the motor or the handwheel through a torque spring to the vane end. A range of springs of different stiffnesses were available. Although it was possible to apply a constant rate of rotation to the end of the spring, the rate of rotation of the vane itself depended to an extent on the relative stiffness of the spring and the soil. These tests were not therefore properly strain controlled and the rates of rotation not constant. However by altering the relative sizes of the belt drive wheels and by conducting some tests using hand wheel loading, a range of times to failure between 2 and 25 minutes was achieved. Vane sizes of 12.7 mm d. x 12.7 mm h. and also 12.7 mm d. x 25.4 mm h. were used. The smaller vane was more popular since with this 2 tests could be performed through each hole.

In practice the remaining two plugs were removed one at a time with the consolidation pressure kept on. The vane was then passed into the clay so that the lower edge was at a distance of 2 d. inside the lower surface of the clay. The test was then performed at the selected rate of rotation. On completion and performing a dummy rod calibration the vane was removed and a small sampler inserted into the soil to take a water content sample from the sheared zone of clay. When a second test was performed in the same hole the sampler was first used to excavate into the clay well clear of the ruptured zone before the vane was re-inserted and the torque applied.

A total of over 30 vane tests were performed. The torque versus angular strain curves (not shown) were of the stable type reaching a maximum with only slight drop off on further strain, the kaolins giving steeper curves and higher failure torques than the illites in equivalent tests. Generally for each clay the failure torque increased with the rate of torque appliation as did the failure angular strain. The vane shear results are compared with those of the triaxial compression tests in a later section where further data are presented and discussed.

Triaxial Compression Tests

As stated to obtain the "insitu" undrained triaxial compression strengths it is necessary to take the clay from its insitu stress condition to failure by superimposing the triaxial stress path but without unloading the sample. To do this therefore it is necessary to consolidate the clay in sample form in the triaxial apparatus prior to strength testing. It was not possible to consolidate the triaxial samples from the slurry condition due to the large volume changes which needed to be accommodated affecting the sample diameter and height. The water contents of the illites for example changed from about 120% in slurry form to below 40% in sample form. To avoid this difficulty it was decided to perform an initial consolidation in the Rowe cell by methods already described.

The early tests as expected showed that a large amount of the total volume change occurred after the early consolidation pressure increments. However the soils did not reach a stiff enough condition for handling and sample trimming until after consolidation to a vertical consolidation stress, $\sigma_{1c} = 138$ kN/m^2. Even at this pressure the soil was softish and it was preferred to allow oedometer consolidation up to $\sigma_{1c} = 276$ kN/m^2. Preliminary oedometer tests indicated that the clays which were loaded to either of these pressures and were then unloaded to either of these pressures and were then unloaded and subjected to a reloading cycle returned to the original, virgin consolidation line before a pressure $\sigma_{1c} = 552$ kN/m^2 was reached. It was for this reason that this rather high consolidation pressure was used for comparing the results of both vane and compression tests since with similar void ratios and structures (Rennie, (1972)) in the respective samples, comparisons of the results of the two tests were considered valid.

The procedure therefore in obtaining the samples for measuring "insitu" undrained triaxial strengths were as follows. After slurry consolidation in the 250 mm oedometer to pressure $\sigma_{1c} = 276$ kN/m^2 the oedometer drains were closed. The consolidated block was quickly removed from the oedometer rings and was waxed and stored. Samples 70 mm dia x 70 mm in height were later cut from the blocks. These samples were then transferred to triaxial cells, given end and side drains and lubricated platens and subjected to the relevant Ko consolidation stress path (which was measured in the Ko oedometer tests). The consolidation stresses were increased in a stage process, first by applying an increase in all-round pressure and then, after the excess pore pressure was dissipated, an increase in the axial stress. These operations were repeated until the correct final horizontal and vertical pressures had been applied. Tests were performed using 1, 4 and 8 loading stages but these variations were found to have only marginal effect on the results. The last load increment was left on for four days and after ensuring the excess pore pressure had reached low values the drains were kept closed and the undrained test was completed by increasing the axial stress to failure.

The vertical consolidation pressures were applied by a dead load hanger and weight system while the sample cell was situated on the compression load frame. The final dead load was left in place after consolidation was complete. To apply the undrained triaxial compression cycle the compression loading frame with proving ring was lowered on to the sample and the frame load superimposed on top of the existing dead load. The sample was not moved from the apparatus for this latter stage and thus had no opportunity to suffer any unloading or disturbance after reaching its insitu pressures and undrained loading.

Samples were consolidated and tested under a back pressure of 207 kN/m^2 and to ensure equalisation of pore pressure rates of strain of 0.00083 mm/sec and 0.00050 mm/sec were used respectively for the kaolins and illites.

The insitu undrained strength was established over a range of consolidation pressures between $\sigma_{1c}' = 414$ kN/m^2 and $\sigma_{1c} = 800$ kN/m^2. A total of about 15 tests were performed for each clay. The stress strain data for those tests (not shown) showed a gradual increase in deviator stress with strain to a peak at an axial strain of about 4% (for clays with $\sigma_{1c} = 552$ kN/m^2) followed by a slight drop as the strain increased. The pore pressure response was typical for clays normally consolidated under anisotropic stresses.

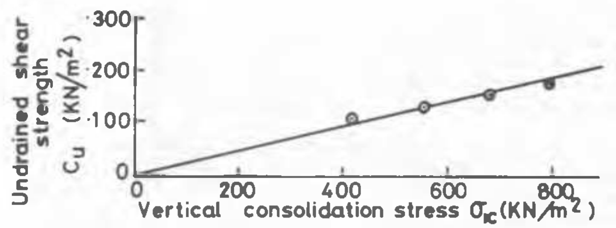

Fig. 2 Triax Shear Strength (Cui) vs Consolidation Pressure.

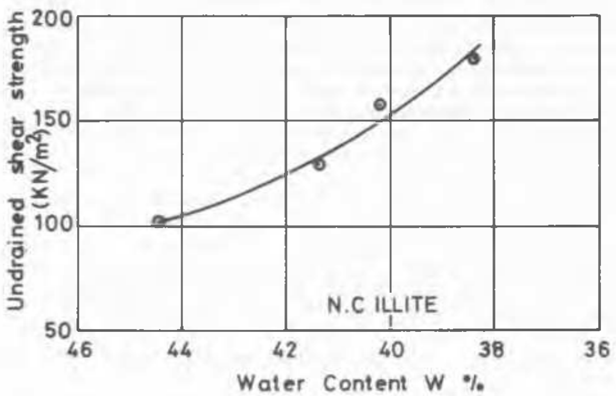

Fig. 3 Triax Shear Strength vs Water Content.

Fig. 2 shows the relationship between undrained shear strength (½ maximum deviator stress) and vertical consolidation pressure for the illite. This shows a straight line relationship with zero cohesion intercept. Fig. 3 shows the relationship between the same undrained shear strength and average water contents at the end of consolidation (and failure) also for the illite samples. This shows the expected increase in strength with reducing water contents.

The equivalent data for kaolin is not shown for the sake of space economy but the curves are similar in form to those in Figs. 2 and 3 but are of course different in detail.

COMPARISON OF VANE AND TRIAXIAL RESULTS

The comparison to be made is between the undrained triaxial shear strength, Cui, of the clay and the shear strength, Cvi, which is obtained in the vane test. The suffix 'i' is given to both symbols since the strengths are considered to be equivalent to insitu values. The value of Cvi is calculated at maximum torque conditions from the standard equation

$$T_{max} = \frac{\pi}{2} Cv\left(\frac{d^2h}{2} + \frac{d^3}{3}\right) \text{ ------(1)}$$

where the symbols have standard interpretation.

Despite the precaution in ahereing to standardised procedures, slight variations occurred between average water contents of consolidated blocks and between water contents at individual vane tests. Normal variations were about 0.5%. Also, despite the indications of the preliminary oedometer tests, small systematic differences of about 1% were found between the average water contents in the vane blocks and the insitu triaxial specimens. In later tests this was reduced to between 0.5% and 0.7% by reducing the load increment ratio in the oedometer consolidation below the value of unity initially used. This was taken as satisfactory considering the natural variation which existed between individual blocks and samples.

Obtaining undrained compression data over a range of consolidation pressures allowed the results to be compared with the vane tests on the basis of both equal consolidation pressure and equal sample water content. The trends illustrated by both comparisons were similar but the scatter of results was improved when the latter basis was used. This is shown in Fig. 4 for kaolin and illite. To obtain the data in Fig. 4 firstly the vane strength Cvi was calculated using equation 1. The adjusted insitu undrained triaxial strength Cui was interpolated from Fig. 3 (or equivalent for kaolin) for the actual water content of the vane test soil. The ratio Cvi/Cui is plotted in Fig. 4 against the times of failure.

Over the range of failure times the kaolin vane strengths are seen to drop by about 10% while the less permeable illites drop about 20%. Compared with the insitu triaxial compression shear strengths the vane values range between 102% and 92% for the kaolins and 97% and 82% for the illites.

DISCUSSION

It would have been ideal if the comparisons between the vane and the triaxial strengths could have been made when both the water contents and final consolidation pressures were simultaneously the same in both sets of

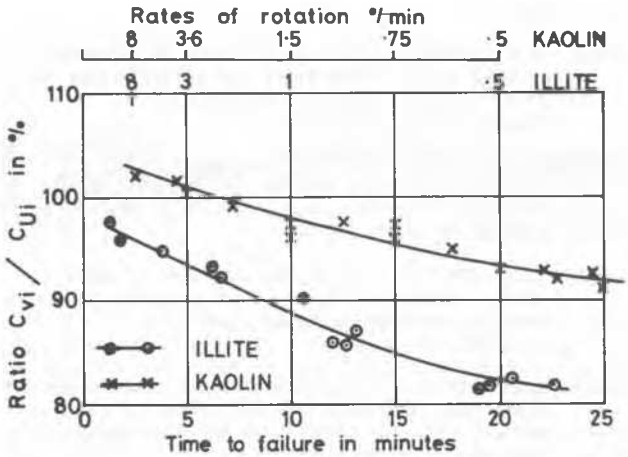

Fig. 4 Ratios of Undrained Shear Strength in Vane (Cvi) and in Triaxial (Cui) vs time of test.

samples. Although the preliminary oedometer tests indicated that this should occur evidently the slightly different procedures which were used in the consolidation had an effect.

The resultant differences in water content were not large however and the research in its wider context, which involved many additional but related tests (Khan (1979)) which are unable to be reported here, suggests that the comparisons in Fig. 4 of the vane strength with the insitu triaxial strengths at equal water contents is most justified. If, however, the strengths had been compared at equal consolidation pressures the scatter of the results would have been greater. In this case the Cvi/Cui ratios in Fig. 4 would be reduced by an average of about 7% for kaolin while those for illites would be reduced by 3%. These difference also are not large and the range of failure times between 2 and 25 minutes weighted Cvi/Cui ratios of between 100% and 90% for kaolins and 96% and 80% in the case of illites would apply and must be close to the true values.

Equation 1 was based on the assumption of strength isotropy in the test clay. The presence of anisotropy to any appreciable extent will influence the results and give different behaviours for differently proportioned vanes. This adds complications in attempting to correlate the vane test with the triaxial test. Tests by Kirkpatrick and Rennie (1972) show that normally consolidated kaolin is virtually isotropic with respect to strength, so these results can be accepted at their face value. Slight strength anisotropy may be present in illite, its effect on the results however is not expected to be marked.

The rate of test in the vane test, as with other tests in Soil Mechanics, has been considered as an important variable. Skempton (1948) suggested that at a speed of rotation of 6° per minute minimun errors occurred. Cadling and Odenstaad (1950) and others also appear to suggest the same standard rate of testing. It was found in the present tests that the faster the rate of vane rotation the greater was the angular strain at failure. Speeds of rotation of 6° per minute were towards the faster end of the test range used and resulted in times to failure in the region of 4 minutes. This time gives weighted Cvi/Cui ratios of about 1 for the kaolin and about 0.93 for the illite.

Clearly the rate of rotation is an important variable when considered over a wide range of test times. The clays in the present tests appear to be quite sensitive to test rates compared to some materials however they do not appear to be too critically influenced by small variations giving closely similar strengths over a range of rotation rates of about 3°/min to 8°/min which correspond to test times of between 2.5 and 6 minutes (see Fig. 4). These are useful practical times for performing the test. It is seen that within these rates the vane test gives shear strengths based on the direct use of equation 1 which reflect the undrained triaxial shear strengths with a high degree of accuracy in the case of the kaolin but slightly less so for the illite.

Bjerrum (1972) investigated the vane test results from a number of sites and after back analysing failures in slopes and proposed connection factors μ (as defined in equation 2) to be used in the interpretation of the test.

$$\mu \times Cv = Cu \quad \text{---------------(2)}$$

Cv and Cu are the vane and the back analysed soil shear strengths respectively. μ depended on the plasticity index, Ip, of the clay and decreased as Ip increased. This interpretation does not conform to the findings in the present test where the trend is for such a μ to increase with Ip. For failure times of 3 to 6 minutes(rotation rates 3°/min to 8°/min), μ values in the present tests were 1 and 1.1 respectively for the kaolin and illite, where Bjerrum recommended values of approxmately 0.9 and 0.8 as being appropriate to their plasticity indices.

The lack of agreement between the direction of the trends suggested by Bjerrum and the present tests is quite important. The approach of back analysing stability cases, however, introduces many additional uncertainties and assumptions regarding homogeneity, isotropy, mechanisms of failure for foundations and slopes etc., which must make the accuracy of the derivation of a unique failure parameter uncertain. Schmertman (1975) expressed doubts about the use of the vane strength results even after application of Bjerrum's correction. Ladd (1975) also expressed concern over the large observed scatters in μ.

The vane test, although simple to perform, has a most complex failure mechanism. The failure mechanism and the stress conditions produced in the soil are probably not unique for all soils. With these consideration the use of unique correlation factors which can convert the vane strength to an acceptable soil strength for all soil types does not appear to be a possiblity. Aspects of homogeneity and isotropy of course add further complications. Variable material dependant adjustment factors of the type suggested by equation 2 would appear to be a necessity to correlate the vane strengths. Concern is expressed here that the present research suggests opposite trends of behaviour to those of other authors (Bjerrum (1972)). It is the present author's opinion that such adjustment factors would not be dependent on only one soil property such as plasticity but would be a complex parameter involving plasticity, anisotropy and aspects of structure amongst others.

The vane test remains, however, an important asset for estimating insitu undrained strength in soils and situations where smapling is difficult. In view of the above discussion the test should not be expected to give refined estimates of strength for all clays. With homogeneous and isotropic clays and rates of rotation of about 6°/min the test appears, however, to give a very good estimate of undrained strength.

CONCLUSIONS

For the normally consolidated kaolins and illites tested the following conclusions can be made.

(i) With the standard interpretation of the vane test (equation 1) the vane shear strengths were generally less than the undrained triaxial compression shear strengths.
(ii) The vane shear strengths reduced as the time of test increased or the rate of rotation of the vane reduced.
(iii) The angular strain at failure increased as the rate of rotation increased.
(iv) For rates of rotation from about 3°/min to 8°/min or times of test between 2 min and 6 min a close agreement was found between the vane shear strengths and the triaxial shear strengths.
(v) The correlations between the vane and soil shear strengths contradict findings of other workers.

These results and conclusions apply to the clays tested which can be considered to be virtually homogeneous and isotropic and while the vane test remains a valuable testing tool in Soil Mechanics the quality of the above strength correlations may not be achieved on all soils.

REFERENCES

Bjerrum, L. (1973). Problems of soil mechanics and construction in soft clays. Proc. 8th Int. Conf. Soil Mech. Found. Engg (3), 11-159.

Cadling, L. and S. Odenstad (1950). The vane borer. Proc. Roy Swedish Geotech. Inst. (2).

Khan, A.J. (1979). The influence of stress relief on the engineering properties of clay. Ph.D. thesis, University of Strathclyde, Glasgow.

Kirkpatrick, W.M. and I.A. Rennie (1972). Directional properties of consolidated kaolin. Geotechnique, Vol. 22, No. 1, 166-169.

Ladd, C.C. (1975). Discussion Proc. ASCE spec. conf. on Insitu measurement of soil properties, Vol.2, 153-160, Raleigh, N.C.

Ladd, C.C. (1977). Stress-deformation and strength characteristics. Proc. 9th Int. Conf. Soil Mech. & Found. Engg. Vol. 2, 421-482, Tokyo

Rennie, I.A. (1972). The structure and directional stress strain behaviour of consolidated kaolin. Ph.D. thesis, University of Strathclyde. Glasgow.

Rowe, P.W. and L. Barden (1966). A new consolidation cell technique, Geotechnique, Vol. 16 No. 2,162-170.

Schmertman, J.H. (1975). The measurement of insitu shear strength . Proc. ASCE spec. conf. on Insitu measurement of soil properties Vol. 2, 57-138. Raleigh, N.C.

Skempton, A.W. (1948). Vane tests in the alluvial plane of the River Forth near Grangemouth. Geotechnique Vol. 1 No. 2, 111-124.

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