The interpretation of advanced triaxial tests for the assessment of small strain stiffness

Apollonia Gasparre*[1], *Matthew R.* Coop[2]

[1] *Geotechnical Consulting Group, London, UK*
[2] *Department of Civil, Environmental and Geomatic Engineering, University College London, UK*
[#]*Corresponding author: a.gasparre@gcg.co.uk*

ABSTRACT

The measurement of small strain stiffness of soils is affected by the techniques and procedures used in advanced triaxial tests, including the connection between the internal load cell and the sample top platen, the resolution of the instrumentation, the ratio of shearing axial strain rate to preceding creep strain rate. The interpretation of the measured data needs to consider how these factors have affected the measured stress-strain response of a sample. This paper reviews the current practice for performing advanced triaxial tests and discusses the interpretation of data resulting from advanced triaxial tests aimed at measuring the true stiffness of soils. It is concluded that the interpretation of the small strain stiffness of stiff clays affects the shape of the stiffness curve at medium to large strain levels and it is therefore relevant for engineering problems. Suitable specifications as well as a detailed review of the results of the tests are required to ascertain the reliability of the measured stiffness.

Keywords: Stiffness, small strain, laboratory testing.

1. Introduction

The stiffness response of soils is affected by factors such as the way the stress state is approached, the creep rates prior to shearing, the strain rates during shearing and the direction towards which the stress path progresses (e.g. Jardine et al., 1984; Atkinson et al., 1990; Lings et al., 2000; Clayton & Heymann, 2001; Gasparre et al., 2007 and 2008).

These factors often affect the stiffness response at small strains more than at large strains, but they also affect the shape of the secant stiffness degradation curve with strains, which is typically used in engineering applications.

Triaxial tests aimed at measuring the true axial stiffness of soils and the interpretation of these tests need to account for the impact of the above factors on the testing procedures and also on the results of the tests.

This paper aims at providing general guidelines to the identification of the true axial stiffness of soils measured in triaxial testing by defining the factors that could adversely affect the readings.

The principles discussed in this paper apply to triaxial testing techniques and interpretation and are therefore applicable to all soils tested, although their relative magnitudes might change depending on the soil stiffness and its propensity to creep.

2. The measurement of axial stiffness

The axial stiffness of a soil from strains as low as 0.001% up to failure can be measured using a triaxial apparatus that is capable of recording the effective stress path of a sample and has an internal load cell, high resolution pressure transducers, high resolution local measurements of axial and radial strains (e.g. Jardine et al., 1984; Cuccovillo & Coop, 1997), a mid-height pore water pressure probe (Hight, 1983), stable automatic control and a high resolution data logging system.

However, to obtain measurements that are representative of the true axial stiffness of a soil, the following main requirements are to be considered in the performance of advanced triaxial tests:

- The use of high-quality samples retrieved and preserved employing techniques that minimise disturbance to the structure of the soil and the in-situ mean effective stress of the sample (Hight 2000).
- The adoption of triaxial testing procedures that avoid damage to the sample structure prior to shearing, avoid the interference of external factors during shearing, such as temperature excursions, strain localisation induced by excess of pore water pressure, creep and strain rate effects, and ensure that axial loads only are applied to the sample.
- A careful analysis of the results of the tests to verify that accidental defects of testing procedures did not occur that could have affected the readings.

2.1. Sample quality

Samples trimmed from blocks or obtained using sonic drilling or ground freezing techniques are likely to be of best quality for triaxial tests aimed at measuring the true stiffness of soils. However, these techniques could be expensive and impractical to achieve in most commercial works. Samples retrieved using rotary drilling are a suitable compromise, particularly when triple barrel rotary corer is employed.

The liner should be cut open immediately after retrieval of the core and the drilling fluid should be removed from the surface of the samples. Samples of cohesive soils also require that an outer annulus of about 5mm is trimmed off as soon as possible to avoid undue influence of the wetter layer to the mean effective stress of the core. Samples of cohesive soils and, where possible, cohesionless soils, should be preserved in a double layered sequence of cling film, aluminium foil and wax. Direct contact of aluminium foil with the sample should be avoided to prevent oxidation. Gasparre (2005) showed that with the above technique the quality of rotary core samples could be preserved for more than three years.

2.2. Testing procedures

ISO CEN 17892-9 (or BS1377-2:2022 in the UK) describes the general procedures for setting up and running a triaxial test, including the requirement for trimming the samples ensuring that its ends are flat and parallel. However, additional requirements are to be considered for tests aimed at measuring the true stiffness of soils.

Samples should be trimmed or assembled ensuring that its ends are perfectly flat. Defects in the alignment of the sample ends could induce the sample to tilt at the start of shearing, compromising the true axial load-strain response. Gasparre et al. (2014) found that the use of a suction cap minimises the risk of sample tilting at the start of shearing, particularly when combined with a half-ball connection, because it enables the adjustment of the alignment of the load cell with the sample compared to rigid connections.

High resolution local instrumentation able to measure axial and radial strains with an accuracy in the order of 0.0001% should be used and a stable temperature should be ensured to avoid interference of temperature effects on the readings of the local strain transducers. The samples should be consolidated to stresses representative of in-situ conditions without inducing large strains that could affect the natural structure of the samples and avoiding processes that could induce non-uniformities in the distribution of strains or excess pore water pressure. Any consolidation process to the estimated in-situ stresses, whether isotropic or anisotropic, should therefore be carried out by steadily increasing the confining pressures to ensure full drainage of the sample throughout the process. For practical reasons, in cohesive soils excess pore water pressure up to 5% of the mean effective stress could be allowed to develop during consolidation, which should be fully dissipated before starting shearing.

Axial and volumetric strains allowed to develop during the consolidation process should also be controlled to remain within limits that do not cause damage to the sample structure. For stiff clays such as London Clay, the limits beyond which damage to the clay structure could occur are believed to be 0.5% for axial strains (ε_a) and 1% for volumetric strains (ε_v). Lower limits might apply for softer soils. Prior to shearing, the samples should be allowed to rest to ensure dissipation of any excess pore water pressure and minimise creep strains. Detailed testing specifications are required to control the testing procedures.

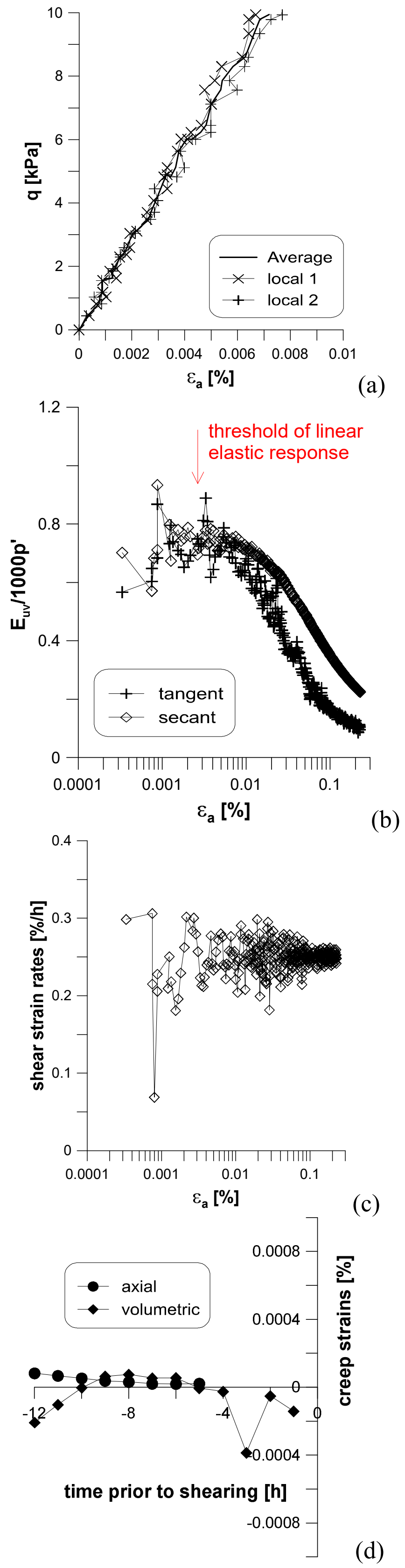

Figure 1. Response of a test with reliable stiffness measurements (a) deviatoric stress q against axial strains from local and external transducers and (b) tangent and secant stiffness curves (c) axial shear strain rate at start of shearing stage (d) axial and volumetric strain rates prior to shearing.

2.3. Analyses of test data

The results of triaxial tests should be carefully analysed to ascertain that the stress-strain response during shearing is unaffected by factors (creep, strain rate effects or non-axial loads) that mislead the measurements of the true stiffness.

Figure 1a and b show the stress strain response and the tangent and secant stiffness curves from an undrained test on a sample of London Clay that is considered unaffected by testing defects, so that the curves in Figure 1b are the true tangent and secant stiffness curves of the clay. The secant stiffness was calculated considering the origin of the stress-strain curve in Figure 1a, while the tangent stiffness was calculated considering a linear regression through a number of data points of the stress-strain curve no larger than 10% of the total number of data points in each logarithmic interval. Figure 1a shows that the local transducers move consistently and with negligible scatter. It is important to highlight that the stress strain curves in Figure 1a are the true readings obtained during the shear stage of the test without manipulation, and no linear regression was applied to these data to reduce their scatter or smoother their trend. The scatter observed in Figure 1a is consistent with the resolution of the instrumentation and legitimises the range of small strains over which the stiffness curve is defined.

As shown in Figure 1c, the sample was sheared at rates of 0.25%/h controlling the internal strains and at the start of shearing the desired strain rates were reached almost instantaneously. High resolution local axial instrumentation and fast recording system (3sec interval) enabled to capture the stress-strain response and consequently the stiffness values at very small strains. Within the linear range, whose limit is marked by an arrow in Figure 1b, the secant and the tangent stiffnesses coincide, as expected by definition. Prior to shearing, the sample was consolidated anisotropically to its estimated in-situ stress with a steady increase of confining pressures ensuring that the excess pore water pressure did not exceed 5% of the mean effective stress (p'). The sample was then allowed to rest until the pore pressure stabilised and the creep strain rates became negligible. Figure 1d shows the creep rates of axial and volumetric strains in the 12h prior to shearing, the axial strain rates being approximately 100 times lower than the shear rates.

Considering the factors that affect the stiffness response of soils and the laboratory testing techniques, the following guidelines can be followed to check the reliability of the measurements obtained in triaxial tests:

1. Verify that, prior to shearing, the sample did not undergo strains that could have damaged its intact structure. For cohesionless soils, this implies avoiding large stresses that could cause particle crushing. For cohesive soils, damaging strains could be induced by swelling or compression to stresses significantly different than the in-situ stresses of the sample. Gasparre et al. (2008) found that the stiffness of London Clay is adversely affected when the samples experience axial strains (ε_a) in excess of 0.5% and volumetric strains (ε_v) in excess of 1% prior to shearing. Lower limits might apply for softer soils.
2. Verify that the sample remained well drained during the consolidation process prior to shearing or, for cohesive soils, that low pore-water pressure gradients were generated during the process, to avoid the occurrence of strain localisation and non-uniformities in the sample. This requires that the consolidation is carried out by steadily increasing the confining pressures.
3. Verify that the local axial transducers moved freely during shearing and provide consistent responses. Disagreement in the response of the axial transducers, as shown, for example, in Figure 2a and Figure 3a, could be due to defects of the instrumentation (i.e. a non-responsive transducer at very small strains), but it could also be indicative of tilting of the sample (see Figure 2a), which implies that eccentric loads are being applied to the sample. It is often the case that the tendency of the sample to tilt causes one of the transducers to be unresponsive, as in Figure 3a, where the trend of the active transducer that moves significantly at the start of loading and kinks afterwards reveals that in fact the sample is tilting. Tests showing disagreement between the internal transducers can lead to misleading initial average stiffness measurements, which affect the identification of the elastic stiffness plateau as well as the trend of the secant stiffness curve. Figure 2b and Figure 3b show that the stiffness curves start with scattered and unrealistically low value followed by peaks when the stress-strain curves kink. Ignoring the unrealistically low values of the stiffness curves at very small strains would result in stiffness curves starting from the peak values and would mislead the location of the elastic plateau and the trend of the stiffness curves at small and medium strains. Tangent and secant data with inconsistent local transducer responses cannot be considered reliable until the local transducer trends converge and attention should be paid to the occurrence of kinks in the stress strain response.
4. Ensure that the rate of creep strains during the rest stage before shearing fall to negligible values compared to the local strain rate developed during subsequent shearing. Careful monitoring with high resolution sensors is vital. As Figure 4 shows, when the ratio between the axial shear strains and the creep strains falls below 50, the creep strains interfere significantly with the shear strains. If the shear occurs in the same direction of the shearing, the creep adds to the shear strains inducing lower stiffness response. However, when the shear is in the direction opposite to the direction of creep, the creep strains reduce the shear strains inducing higher stiffness response. A ratio between shear and creep strains not lower than 100 is recommended.
5. Check that the tangent and secant stiffness responses are consistent over the initial, linear range of stresses. By definition, tangent and secant stiffness values must agree in the initial linear

elastic range of the load-strain response, any disagreement is therefore indicative of errors in the measurements of the readings. Beyond the linear range, the curve of tangent stiffness would be expected to decay faster than the secant stiffness as this captures the progressive curvature of the load-strain response.

6. Verify that the local strain rates achieve the desired strain rates rapidly at the start of shearing, so that the sample response is not affected by strain acceleration effects. Where the strains increase slowly at the start of the tests the measured stiffness curve tends to display low initial values followed by a peak (Figure 5), which is likely to be due to accelerations of strains (Sorensen et al., 2010). The initial low values are typically discarded, and the resulting stiffness curve could be misleading showing an unrealistic high peak in the small strain range.

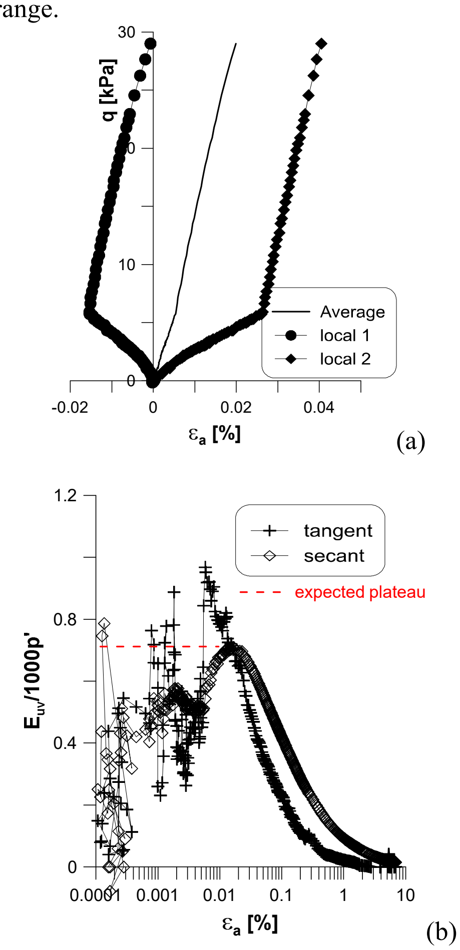

Figure 2. Unreliable stiffness measurements due to tilting of the sample (a) inconsistent response of the local strain transducers at small strains and (b) misleading stiffness response.

7. Carefully establish the initial $q - \varepsilon_a$ origin from which secant stiffness is defined and this is best achieved by considering at least tens of measurements in arithmetic stress strain plots which can also reveal the best fitting to the initial stiffness values. Disagreement between the secant and tangent stiffness curves is indicative of errors, which typically affect the assessment of the secant stiffness.

8. Verify that the scatter of the readings is at least 10 times smaller than the range of strains over which the stiffness is intended to be measured. A stable control of stresses and adequate resolution of the instrumentation should enable the achievement of this condition without the requirement for averaging of the readings and further manipulation of the results, which could be misleading and would not justify the resolution of the stiffness calculations at strains as small as the resolution of the instrumentation.

9. Care when normalising laboratory data. Linear p'_0 normalisation could be reasonable at small strains under in-situ K_0 stresses for some soils, but lower effective stress level power-law exponents may hold for other soils, or when samples are swelled or compressed to stress conditions different from the in situ. When the change of p' imposed in a probing test is significant, such as when shearing is continued to larger strains, normalisation should be with respect to the current value of p' rather than the initial value.

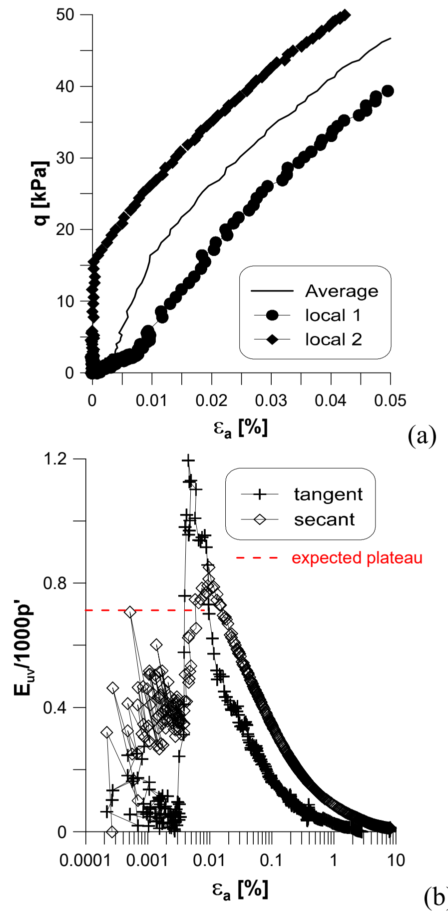

Figure 3. Unreliable stiffness measurements due to response of local axial transducers: (a) inconsistent strain response at low stresses due to an apparently unresponsive transducer and (b) associated stiffness, higher than expected for the material.

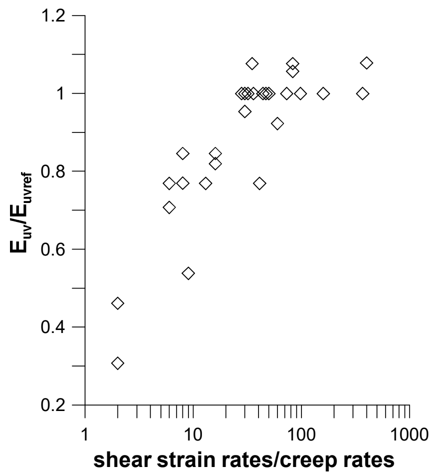

Figure 4. Dependence of normalised undrained vertical stiffness E_{uv}/p'_o of London Clay normalised by a reference value $(E_{uv}/p'_o)_{ref}$=650MPa against the ratio of axial strain rate to creep strain rate when shearing is in same direction of creep (modified after Gasparre et al. 2014).

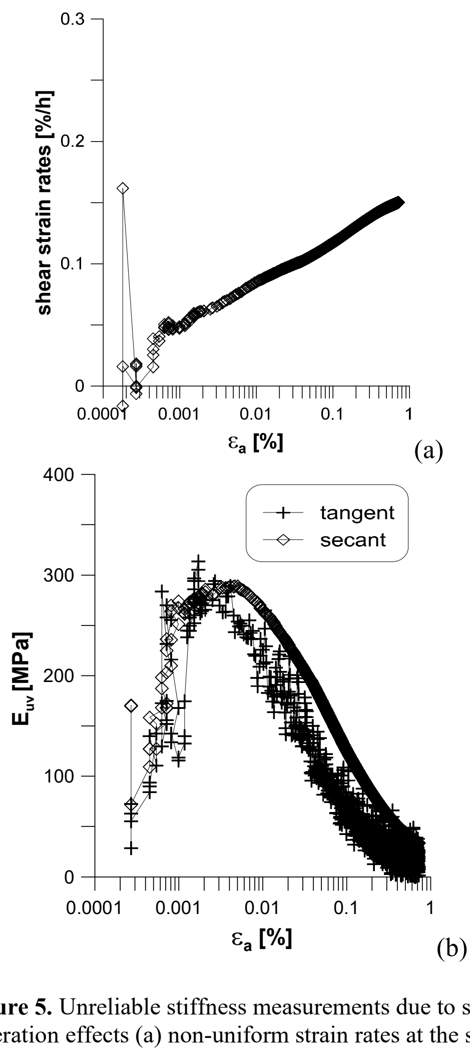

Figure 5. Unreliable stiffness measurements due to strain acceleration effects (a) non-uniform strain rates at the start of test (b) misleading profile of stiffness curves, with no linear elastic plateau and unrealistic peak.

3. Measurements in commercial laboratories

A review of advanced triaxial tests performed by commercial laboratories in the UK between 2005 and 2010 revealed that the measured stiffness curves were affected, to various extents, by defects in testing procedures, as discussed above, which compromised the reliability of the measured stiffness, particularly over the range of small to medium strains.

The tests were performed by commercial laboratories across the UK on high quality samples of stiff clays and sands retrieved using rotary coring techniques. The samples were tested following similar specifications, which included consolidation to stresses representative of the sample in-situ stresses and undrained shearing in compression or extension. All tests employed a rigid connection between the load cell and the sample top cap.

More than 100 tests on samples of London Clay and Lambeth Group were analysed. Approximately 40% of the tests were affected by defective readings of the local transducers, with one or both local transducers not moving freely at the start of the shearing stage; 14% of the tests showed clear tilt of the samples; 28% of the tests also combined defective readings of the transducers with significant acceleration of strains at the start of shearing and 22% of the tests showed a significant scatter at the start of shearing that, in combination with the relatively large scatter due to the resolution of the readings, gave a misleading origin of the stress-strain curve for the calculation of secant stiffness, although visual inspection of the tests provided a clearer trend of the stress-strain response.

Similar trends were observed from the review of tests on Thanet Sand, although a more limited number of tests was considered.

It is important to notice that for most of the tests the resolution of the local transducers was approximately ±0.001%, hence the stiffness measured in these tests could not be resolved at strains lower than 0.01%. The low resolution also did not enable to verify with accuracy the creep strain rates and therefore the impact of the ratio of shear to creep rates. Any potential impact of these factors was masked by the issues related to the resolution of the instrumentation.

The impact of defective readings or tilting of the samples resulted in a misleading trend of the stiffness curves in the medium to high strain range, as well as a misleading location of the linear elastic stiffness plateau, as discussed in point 3 of Section 2.3.

It is interesting to notice that the defects of the tests affected the secant stiffness responses in a more marked and extensive manner than the tangent stiffness response. Figure 6 shows defective tests on high quality samples of London Clay retrieved at various depths from boreholes drilled at the same site. The secant stiffness curves define a very large range of values, particularly in the small to medium strain range, which results from defects that occurred at the very early stage of shearing. However, the tangent stiffness curves for the same tests plot within a narrower range, because they vary with the curvature of the stress-strain curve and do not retain the defects affecting the small strain range in the medium to large strain range. The family of tangent stiffness curves therefore defined the indicative location of the linear elastic stiffness plateau in a more reliable manner than by the secant stiffness curves.

In the last few years, the quality of advanced triaxial tests performed in commercial laboratories has significantly improved, mainly due to improvements in the resolution of the instrumentation, which enabled to resolve strains lower than 0.001%.

A review of more than 50 tests carried out in commercial laboratories in the UK between 2018 and 2022 reveals that the percentage of unreliable tests affected by the factors discussed above has reduced by approximately 30-50%, depending on the material tested, with clays being generally more greatly affected than sands by potential testing defects.

The tests reviewed were performed on stiff clays and sands following specifications similar to those adopted for the older tests. Most tests employed a rigid connection between the samples and the load cell, although about 20% of the tests adopted a suction cap connection.

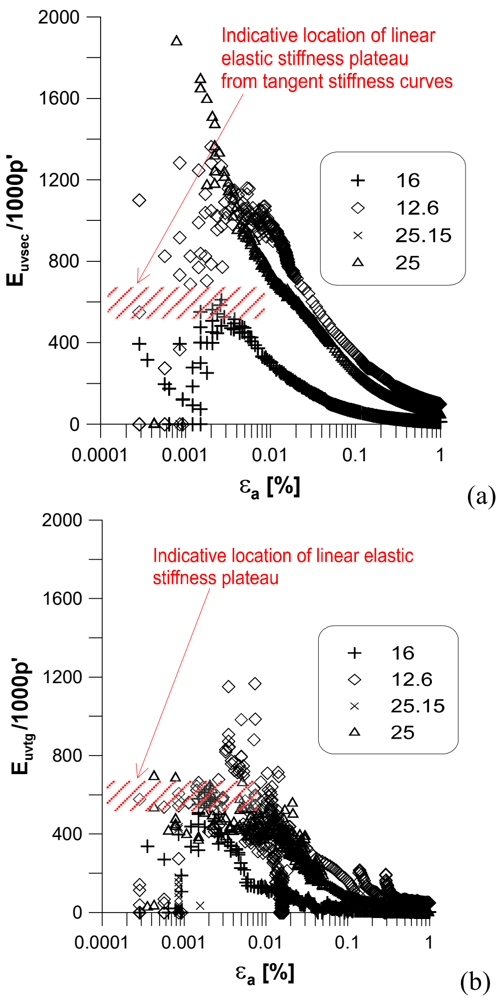

Figure 6. Stiffness curves normalised by the initial effective stress (p') from tests on London Clay affected by testing defects (a) secant stiffness curves showing a large range of stiffness values (b) tangent curves showing a narrower range of stiffness for the same tests.

In most tests, the stiffness measurements continued to be affected by defective readings of the local instrumentation due to the transducers not moving freely or the samples tilting at the start of the shearing stages. Approximately 20% of the tests showed non-constant strain rates and acceleration effects in the small strain range.

The factors adversely affecting the measured stiffness could not be controlled with testing specifications nor during the performance of the tests and required a detailed review of test results.

4. Conclusions

The stress-strain response of soils depends on factors such as the way the stress state is approached, the creep rates prior to shearing, the strain rates during shearing and the direction towards which the stress path progresses. The procedures to be adopted in triaxial testing aimed at measuring the true stiffness of soil need to account for these factors.

However, the correct specifications of advanced triaxial tests might not be sufficient to avoid the interference of adverse factors on the measurements of true stiffness.

In order to ascertain the reliability of the measured stiffness, a detailed review of the results of advanced tests is required that considers the behaviour of the individual local transducers and the strain rates prior and during the shearing stage, as well as full adherence of the test procedures to specifications aimed at avoiding the interference of adverse factors on the stress-strain response of soils.

Nomenclature

E_{uvsec}	vertical undrained secant stiffness
E_{uvtg}	vertical undrained tangent stiffness
p'	mean effective stress
p'_o	mean effective stress prior to shearing
q	deviatoric stress
ε_a	axial strains
ε_v	volumetric strains

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