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SHEAR WAVE VELOCITIES FOR SAMPLE QUALITY ASSESSMENT ON A RESIDUAL SOIL

CRISTIANA FERREIRA(i), ANTÔNIO VIANA DA FONSECA(ii) and DAVID F. T. NASH(iii)

ABSTRACT

For the assessment of the quality of laboratory samples, a number of methods are available, though not universally applicable to any soils. This paper examines the issue of sampling quality and its assessment using comparisons between shear wave velocity measurements in situ and in recovered samples as the base, which is very useful in naturally structured granular soils, like residual soils. For this purpose, cross-hole and down-hole tests were performed in the field and bender elements measurements were made on triaxial samples collected from two experimental sites on residual soil from Porto granite. Various sampling techniques and tools were used, including block sampling and different tube samplers. The analysis of the results has led to a new classification of sampling quality and sample condition based on the comparison of normalised shear wave velocities in the field and in the laboratory.

Key words: bender elements, residual soils, sampling quality, seismic wave velocities, soil characterisation (IGC: C6/D6)

INTRODUCTION

A laboratory-based characterisation of the behaviour of a soil is directly dependent on the samples selected for testing, and therefore dependent on their representativeness and quality in relation to the in situ conditions. Consequently, it is important to be able to assess the quality of the samples, to guarantee that only high quality samples will be used for extensive laboratory characterisation. In this context, this paper addresses the assessment of sampling quality, especially by means of the comparison of field and laboratory seismic shear wave velocities, applied to two experimental sites on residual soil from Porto granite.

BACKGROUND

Perfect sampling represents one of the greatest challenges in geotechnical engineering. Soil disturbance due to sampling operations is of major concern to the geotechnical engineer attempting to estimate in situ properties of foundation soils by means of laboratory tests (Baligh, 1985). Over the years, considerable improvements have been made towards devising good sampling practices, based on engineering judgement, experimental observations and/or analytical studies.

A sample of soil obtained by any sampling process will suffer disturbance, which can be divided into two main sources. Mechanical disturbance is induced by the penetration of the sampler into the soil. This produces shear distortions and associated volumetric strains in the soil close to the inner wall of the sampler (Bashar et al., 1997). Baligh et al. (1987) listed some of the causes for soil disturbance during tube sampling, namely: changes in soil conditions ahead of the advancing borehole during drilling operations; penetration of the sampling tube and sample retrieval to ground surface; water content redistribution in the tube; extrusion of the sample from the tube; drying and/or changes in water pressures; and, trimming and other processes required to prepare specimens for laboratory testing. While some of these disturbances can be attributed to the sampling tools and equipment, others cannot be reduced by improving sampling operations.

The second main source of disturbance is stress relief due to the removal of the sample from the ground to the zero total stress state in the laboratory. The inevitable changes of stress may modify the mechanical properties of the recovered soil sample including strength, stiffness, and pore pressure or volume change responses (Atkinson et al., 1992).

As discussed by Clayton et al. (1998), numerous researchers have investigated the extent and nature of disturbance during sampling and laboratory testing (Skempton and Sowa, 1963; Adams and Radakrishna, 1971; Lefebvre and Poulin, 1979; La Rochelle et al., 1981; Kirkpatrick and Khan, 1984; Hight et al., 1985; Graham and

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Lau, 1988; Clayton et al., 1992). However, most of this research has been focused on comparative experimental investigations.

One of the most significant advances in understanding disturbance by tube sampling was the application of the strain path method (Baligh, 1985; Baligh et al., 1987) to the deep penetration of a sampling tube into the ground, thus providing an analytical basis upon which the effects of sampling could be evaluated (e.g., Hight, 2000). This method was further extended by Clayton et al. (1998) to examine the effects of different details of sampling tube geometry, including outside cutting edge angle (OCA), inside cutting edge angle (ICA), inside clearance ratio (ICR) and area ratio (AR), as defined in Fig. 1. These authors identified the major factors controlling the magnitude of tube sampling strains as the increasing AR or increasing OCA, both of which contribute significantly to the peak axial strain in compression, and increasing ICR which has a strong influence on the peak axial strain in extension. Their results emphasise the sensitivity of imposed strain levels to details of sampling tube geometry.

In summary, the predicted effects of the strains induced by tube sampling include: a reduction in mean effective stress; damage to structure, manifest by the shrinking of the bounding surface of the soil; and, an increase in water content in the centre of the sample (Hight, 2000). Though mainly developed for sampling of soft clays, these studies can be generalised to any sensitive and/or structured soil.

ASSESSMENT OF SAMPLING QUALITY

As pointed out by Long (2001), the need to assess the degree of sample disturbance prior to interpretation of parameters derived from laboratory tests on soil samples is now well accepted. A number of methods for the assessment of sampling quality, that is, the level of sampling disturbance have been proposed over the years. According to Hight (2000), the most common methods are:

- Fabric inspection
- Measurement of initial mean effective stress, $p'\,$
- Measurement of strains during reconsolidation
- Comparison of in situ and laboratory measurements of seismic wave velocities

![Fig. 1. Definition of the geometric parameters of a tube sampler](image)

- Outside cutting edge angle (OCA), $\alpha$
- Inside cutting edge angle (ICA), $\beta$
- Inside clearance ratio (ICR), which controls internal friction:
  \[\text{ICR} = \frac{D_s - D_i}{D_i}\]  
- Area ratio (AR), which relates the volume of displaced soil with the volume of the sample:
  \[\text{AR} = \frac{D_s^2 - D_i^2}{D_i^2} \times 100\]

Fig. 1. Definition of the geometric parameters of a tube sampler

![Fig. 2. Fabric inspection: a) disturbance on a laminated clay sample with sand and silt layers spaced every 10 mm from Morecombe Bay (Rowe, 1972); b) clearly disturbed residual soil sample collected from CEFUEP experimental site (ES2)](image)

Fabric Inspection

The visual inspection of the fabric of a soil sample is the most immediate and simple method of identifying potential damaged samples. It is an empirical technique and, hence, involves some subjectivity; however, it is particularly important for assessing the potential for water content redistribution between adjacent sand and clay layers. Only large distortions are visible, generally in the peripheral zones of the sample; the relatively small strains, associated with yield and damage to a bonded structure, usually occurring around the centreline of the sample, are hardly detected. In Fig. 2, two examples are provided, where the disturbance caused by the penetration of the sampling tube is clearly visible. In summary, this method cannot directly indicate the effects of sampling on the behaviour of the soil, but serves as a good indicator for a preliminary selection of the samples for subsequent laboratory testing.

Measurement of Initial Mean Effective Stress

The initial mean effective stress, $p'$ corresponds to the
effective stress in the sample after its extraction from the ground. This parameter may change during sample transport, storage and even during specimen preparation. Measurements of initial effective stress, \( p' \), in samples taken from the ground and set up in the laboratory, have been advocated for many years, e.g., Ladd and Lambe (1963). The potential causes for changes in mean effective stress have been considered, showing that most processes induce a decrease in \( p' \). Comparison of \( p' \) with its value for perfect sampling, \( p_0 \), provides an indicator of level of disturbance. However, the measurement of \( p' \) alone is not sufficient, as it cannot indicate the amount of destruction that has occurred (Hight, 2000). Ladd and DeGroot (2003) proposed a hypothetical stress-path showing potential sources of sample disturbance, which cause the degradation of the initial stress in a sample from sampling to laboratory testing.

**Measurement of Strains During Reconsolidation**

In the reconsolidation to in situ stresses, the strains experienced by the sample will depend on the reduction in effective stress resulting from sampling and from destruction. Andresen and Kolstad (1979) proposed that increasing sample disturbance should result in increasing values of volumetric strains at the overburden vertical stress. This approach was also used by Terzaghi et al. (1996), who proposed the term SQD (Specimen Quality Designation), with sample quality ranging from A (best) to E (worst), corresponding to \( e_{vo} \) of 1% and 12%, respectively. More recently, Tanaka et al. (2002) concluded that this parameter cannot be universally applied for representing sample quality. As noted by Hight (2000), the absolute value of the strains will depend on the reconsolidation path followed and on the compressibility of the soil.

A similar method was developed by Lunne et al. (1997), who proposed the use of volumetric strains in terms of \( \Delta e/e_0 \), where \( \Delta e \) is the change in void ratio and \( e_0 \) the initial void ratio. Their criteria were based on test results on marine clays covering a wide range of plasticity indices, overconsolidation ratios and water contents, from which the categories of sample quality, presented in Table 1, have been defined.

**Comparison between Laboratory and In Situ Measurements of Seismic Wave Velocities**

Many authors (e.g., Stokoe and Santamarina, 2000) have drawn attention to the potential use of shear wave velocities in the characterisation of soil properties. It is widely recognised that the most important influences on the shear wave velocity, and hence the shear modulus, are the principal effective stresses in the wave propagation and wave polarisation directions, the void ratio, the structure or packing of the soil, and also the degree of saturation (mainly for clays and silts), associated with suction levels, and the degree of cementation (natural or artificial). Therefore, by the use of the shear wave velocity measurements, different structure or fabric arrangements, as well as stress conditions and void ratio can be distinguished. Thus, the comparison between laboratory and in situ measurements of seismic wave velocities, or of maximum shear moduli, has been increasingly accepted as one of the most promising methods for the assessment of sampling quality, especially in naturally structured soils (Shibuya, 2000; Nash et al., 2006; Landon et al., 2007; Viana da Fonseca and Coutinho, 2008).

For these comparisons to be valid, the laboratory samples must be representative and should be restored to their in situ stress state because of the dependence of \( V_S \) on stress state. In order to account for the influence of void ratio, allowances must be made for changes in the void ratio during reconsolidation to in situ stresses (Hight, 2000). Measurements of \( V_S \) in the laboratory should also be made with the shear wave propagation in the same direction as in the field, with the same plane of polarisation. The different propagation and polarisation wave directions associated with the most common geophysical methods are presented in Fig. 3. For this reason, vertically propagated shear waves (\( V_{sh} \)), as typically measured in standard triaxial setups, should be preferably compared with Down-Hole results.

**APPLICATION TO CASE STUDY SITES ON RESIDUAL SOIL**

Residual soils are abundant in north-western Portugal and result from the weathering of the Porto granite, a leucocratic alkaline rock, with two micas and medium-to-coarse grains. Due to their specific genesis, these residual soils present complex characteristics, which are a consequence of the overall variability and heterogeneity of the

<table>
<thead>
<tr>
<th>Table 1. Criteria for the assessment of sampling quality from volumetric strains (from Lunne et al., 1997)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta e/e_0 )</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Very good to excellent</td>
</tr>
<tr>
<td>Good to fair</td>
</tr>
<tr>
<td>Poor</td>
</tr>
<tr>
<td>Very poor</td>
</tr>
</tbody>
</table>

[*] this description refers to the use of the soil sample for characterization of the mechanical properties
rarely as clayey sand (SC). It is usually classified as silty (SM) or well graded (SW) sand, or more rarely as clayey sand (SC).

Brief Description of the Experimental Sites

In selecting the experimental sites, it was essential to find locations where the soil characteristics were expected to be approximately constant and homogeneous within the area of study, especially for the comparison of sampling equipment and the assessment of sample quality. Two case study sites were selected for the characterisation of residual soils from Porto granite, where the natural variability of soil characteristics was considered to be acceptable for the objectives of this research.

Extensive geotechnical in situ and laboratory characterisation was carried out for each site, and many results and discussions have already been published (Viana da Fonseca et al., 2004, 2006) and more thoroughly analysed and compared with other residual soils by Viana da Fonseca and Coutinho (2008) and Ferreira (2009).

The first experimental site (ES1) is located in the region of Porto, in the grounds of the technical school CICCPON, where extensive geotechnical in situ and laboratory characterization had already been carried out (e.g., Viana da Fonseca, 2003). This site presents a typical saprolitic residual soil, resulting from the weathering of Porto granite, and it is essentially composed of alkaline granite, coarse to medium grains, two mica and albite as main feldspar.

The second experimental site (ES2) is located within the campus of the Faculty of Engineering of the University of Porto (FEUP) and was initially used for an international pile prediction event, under the scope of ISC’2 (International Conference on Site Characterisation) held in Porto in 2004 (Viana da Fonseca et al., 2004). Essentially, the site is geologically formed by an upper layer of heterogeneous saprolitic residual soil from granite of variable thickness, overlying weathered granite, in contact with high-grade metamorphic rocks (gneissess and migmatites).

Sampling Methods

The sampling processes used for retrieving soil specimens from the experimental sites can be divided in three types, according to the sampling methods which are directly related with the quality of the obtained samples: a) block samples; b) “undisturbed” tube samples; and c) disturbed soil samples. A soil sample is considered intact or undisturbed when the soil structure and mechanical properties are kept as close as possible to those of the soil in the field.

There are a number of undisturbed tube sampling techniques in current use in Portugal, usually divided in driven samplers and rotary samplers. A few of these techniques were selected for borehole sampling in ES1. The experimental site ES1 served as ground for the assessment of the sampling quality of a variety of tools and techniques, with the purpose of selecting the most suited sampler for this soil to be used in ES2.

In order to obtain the highest quality samples, as undisturbed as possible, a number of block samples were collected at both experimental sites. The block sampling process can be divided essentially into the following four stages (JGS, 1995): i) rough carving of the sample, by opening of the area surrounding the intended sample; ii) trimming of the sample, performed with great care, in order to obtain the intended sample size, well-aligned for a perfect fit in the container; iii) sealing of the sample, by the insertion of the container covered with plastic film for moisture retention; iv) separation from the ground, by cutting the block on the bottom. Finally, the block is slowly and carefully tilted to reveal the bottom surface, which is immediately levelled, sealed and covered with the box cover.

This procedure is summarised in Fig. 4, using diagrams adapted from the Japanese Standard No. 1231 (JGS, 1995). Photographs of the work at ES1, where three cubic blocks of circa 400 mm were retrieved at a depth of 2 m, are presented to illustrate each corresponding sampling stage. At experimental site ES2, six block samples were collected, two at each of the depths of 1.65 m, 2.75 m and 4.25 m.

The tube sampling surveys were performed in collaboration with private engineering contractors, which were responsible for boring and extracting soil samples using the available samplers, according to their own standard procedures. The selection of the samplers used in the sites was made considering a few fundamental aspects, namely: a) the characteristics of this soil; b) some variety of geometric properties of the samplers, such as cutting edge, sampler driving method, existence or not of inside clearance, the use of liner and its type; c) availability of equipment; d) level of applicability in practice; e) expected sample quality offered by the different samplers.

At ES1, six sampling boreholes were selected to form a triangular arrangement, with an even spacing of 4 m, to facilitate seismic cross-hole testing. A different sampler was used in each borehole and soil samples were collected at the depths of 2, 4 and 6 m. A list of the samplers used, including rotary and driven samplers with standard and sharp cutting edges, and a summary of characteristics is presented in Table 2.

Preliminary results obtained by Ferreira et al. (2004) identified considerable differences between the sampling quality of the samples recovered by each of these samplers, by the comparison of in situ and laboratory shear wave velocities. The authors concluded that the least disturbed samples had been recovered by the NT81 sampler. As a result, this sampler was adopted for undisturbed tube sampling at ES2.

At ES2, from the extensive sampling collection, a number of samples from two boreholes (S2 and S5) at a range of depths from 3 to 9 m (above ground water table), were
Table 2. Tube sampler used in each borehole at ES1

<table>
<thead>
<tr>
<th>#</th>
<th>Sampler</th>
<th>Cutting edge [°]</th>
<th>Internal diameter [mm]</th>
<th>Liner</th>
<th>Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>GMPV</td>
<td>30</td>
<td>72.0</td>
<td>grey PVC</td>
<td>dynamic</td>
</tr>
<tr>
<td>S2</td>
<td>ST85</td>
<td>5–6</td>
<td>75.0</td>
<td>PVC (often transparent)</td>
<td>dynamic</td>
</tr>
<tr>
<td>S3</td>
<td>NT81</td>
<td>5–7</td>
<td>74.0</td>
<td>coated steel (not stainless)</td>
<td>dynamic</td>
</tr>
<tr>
<td>S4</td>
<td>Mazier*</td>
<td>*</td>
<td>74.0</td>
<td>blue PVC</td>
<td>rotary</td>
</tr>
<tr>
<td>S5</td>
<td>Osterberg</td>
<td>30</td>
<td>n/a</td>
<td>none</td>
<td>stationary</td>
</tr>
<tr>
<td>S6</td>
<td>Shelby</td>
<td>30</td>
<td>77.5</td>
<td>none</td>
<td>stationary</td>
</tr>
</tbody>
</table>

* sharp cutting edge ahead of the drill bit
selected for the assessment of its sampling quality.

**Laboratory Testing Procedure**

Following the sampling surveys and after careful transport, storage, handling and preparation of the samples, these were tested in triaxial chambers equipped with local instrumentation for strain monitoring and bender elements for seismic wave measurements in the geotechnical laboratory at FEUP (www.fe.up.pt/labgeo); details of the equipment are given by Ferreira (2009).

The soil samples were consolidated back to the estimated anisotropic stress conditions in situ before sampling; the value for the in situ \( K_0 \) is usually assumed equal to 0.5, based on extensive previous investigations on these soils (e.g., Viana da Fonseca and Coutinho, 2008). Hence, all laboratory samples were anisotropically consolidated to the in situ stresses using \( K_0 = 0.5 \). The reference laboratory value for comparison of field and laboratory seismic wave velocities was taken at the end of consolidation. Subsequently, samples were saturated, first by percolation and then by application of a back pressure up to 300 kPa, and then sheared in triaxial compression.

**Assessment of Sampling Quality by the Measurement of Strains during Reconsolidation**

The results obtained for the testing programme were analysed for sampling quality assessment by the measurement of strains during reconsolidation (Lunne et al., 1997). This method was applied to a number of ES1 samples, from various tube and block samples, where a greater variety of tube samplers was used. The obtained results in terms of \( \Delta e/e_0 \) are summarised in Table 3.

Despite the clear differences between the various samples collected in ES1, the values of \( \Delta e/e_0 \) obtained in this exercise were all below the minimum proposed value of 0.04 (cf. Table 1), except for one of the reconstituted samples, which were included as an indication of the poorest quality sample (in which the original soil structure has been completely lost). It can be concluded that this method alone is not appropriate for assessing the sampling quality on this soil, since it would classify all samples as very good to excellent quality samples. Clearly, the relatively low compressibility of this soil compromises the direct application of this method.

In order to establish a more suitable sample quality classification, different limits or scale ranges for each category would have to be defined for this type of soils. This method is however considered useful for a qualitative and comparative analysis of the tested samples.

**Assessment of Sampling Quality by Comparison of Seismic Wave Velocities**

For the measurement of shear wave velocities in the laboratory, bender elements (BE) were mounted in the top and bottom platens of triaxial chambers. These transducers are a powerful and increasingly common laboratory tool for determining the shear wave velocity, \( V_S \) and hence the small strain shear modulus, \( G_0 \) in geomaterials. There are several advantages of BE testing, namely its simplicity and ease of use, but there is still no standard developed for the testing procedures, nor for the interpretation of the results. This often leads to high degree of uncertainty and subjectivity in the interpretation.

In this research, the framework for BE testing and interpretation proposed by Viana da Fonseca et al. (2009) was applied. This procedure consists on the combination of time-domain and frequency-domain methods in an automated tool, which enables unbiased information to be obtained regarding variations in the results to assist in the decision of the travel time. Its application effectively reduced the subjectivity in BE testing and proved to be a systematic and objective approach to the measurement of shear wave velocities for sample quality assessment.

For the comparison between laboratory and in situ measurements of seismic wave velocities, the results obtained for the tested specimens of both experimental sites were analysed at the estimated in situ stresses. For a more consistent comparison, the shear wave velocities were normalised to the respective void ratio. The need for normalisation to the void ratio derives from the observation of significant differences among the initial void ratios of the various tube samples and the block and in situ conditions (cf. Table 3). The tube sampling process tends to compress the samples, inducing some degree of disturbance. Since the shear modulus is strongly dependent on the void ratio, this normalisation enables to clearly capture sampling disturbance, since it comprises not only destructuration but also a volume change in the soil sample. For example, the sample with the lowest void ratio (more severely compressed) exhibits a higher shear modulus than the in situ data, despite its destructuration; after normalisation, this sample has the lowest normalised modulus.

It was assumed that the block sampling process did not induce any measurable changes in the compaction conditions of the soil, that is, the void ratio of the block sam-
SAMPLE QUALITY ASSESSMENT

Samples was assumed identical to that of the soil at natural in situ conditions, at the corresponding depths. Therefore, in situ CH and DH wave velocity results were normalised, considering the void ratio of the block samples. Laboratory samples were normalised to the respective void ratio, measured during testing.

For the definition of the void ratio function, various approaches have been proposed, namely those by Hardin and Richart (1963) and Iwasaki et al. (1978), by Hardin (1978) and Chung et al. (1984), and by Jamiolkowski et al. (1991) and Lo Presti (1995). These can be directly applied when no specific study is carried out to determine which is most suitable for the soil in study, or serve as a starting point for a more specific analysis. For the present soil, a specific study was carried out and the function proposed by Lo Presti (1995) provided the best match with the evolution of the shear modulus at unload-reload cycles of a reconstituted specimen, which is defined as follows:

\[ V_s = \sqrt{\frac{G}{\rho}} = C \cdot \sqrt{\frac{F(e) \cdot \sigma_{\text{inh}}}{\sigma_{\text{inh}}}} \]  

\[ F(e) = e^{-1.3} \]  

Therefore, the measured shear wave velocities were normalised as follows:

\[ V_s^* = \frac{V_s}{F(e)} \]  

A summary of the normalised results is presented in Figs. 5 and 6 for ES1 and ES2, respectively. For the ES1 samples, shown in Fig. 5, only \( V_{\text{shv}} \) were measured. The differences between \( V_{\text{shv}} \) (from cross-hole tests) and \( V_{\text{shv}} \) (from down-hole) were found to be small and, in the context of this study, these will not be distinguished.

The similarity of \( V_s \) trends in depth from both in situ and laboratory tests is evident for both experimental sites and the differences encountered can be mainly attributed to disturbances associated with the sampling processes.

In terms of the tube samples (S1 to S6) collected at ES1, the results show that the geometric characteristics of the sampler, both in terms of the cutting edge angle as well as of the area ratio were decisive. The sampler with the lowest outside cutting edge angle (S3) provided the highest stiffnesses. The good performance of the Shelby sampler (S6) is worth mentioning: it is most likely associated with the difference between the internal diameter of the sampling tube and the final diameter of the tested specimens, which required the samples to be trimmed to the appropriate size after their extrusion from the sampler. This process, despite being quite delicate, involved the removal of the peripheral areas of the sample that had experienced greater distortions during both sampling and extrusion, highlighting the relevance of careful laboratory sample preparation techniques and, whenever possible, the use of large diameter samplers.

Finally, the samples collected by the Mazier sampler were unexpectedly damaged. This disturbance was probably related with the operational requirement of applying high water injection pressures at the cutting shoe in order to reduce the friction and abrasion between the cutting tools and the coarse quartz grains of the soil. The injected water literally washed away the fragile bonds between the particles, severely damaging the natural structure of the soil.

Given the extended duration of this experimental program, different storage times (from sample collection to testing) induced distinct levels of ageing in the samples, which may also explain why the in situ shear wave velocities differ from that of same soil in the laboratory with the same state of effective stress and void ratio, as well as between laboratory samples tested on different occasions.

For experimental site ES2, as previously mentioned, only one tube sampler was used for collecting all the samples: the same tube sampler used for borehole S3 in ES1, that is, NT81. This tube sampler was selected for its good performance in terms of sampling quality of the residual soil from ES1. In this case, fewer samples was tested at the estimated in-situ stresses, as presented in Fig. 6.

The figure shows that the differences between the shear wave velocities of different samples are smaller than those observed for the samples of ES1. This was anticipated since all samples were collected by the same sampler. The evolution of the laboratory and in situ velocities with
stress, that is, with depth, is relatively similar, and it is unclear whether sample disturbance is affected (or not) by the depth of sampling.

Contrary to the results for ES1 samples, in this case, the block samples appeared to have the same loss in shear wave velocity in relation to the in situ value as the tube samples. This would mean that those blocks have the same level of disturbance, which is unlikely. A more plausible explanation for the unexpectedly lower values of the block sample results may reside in the fact that the two block samples were tested much later than the tube samples. Ageing during storage is an influential parameter in the shear stiffness of a soil, a subject which, however, was not explicitly or systematically addressed in the context of this research.

DISCUSSION

The results from both experimental sites have been combined by plotting the normalised laboratory $V_s$ values against the corresponding normalised in situ values (for the same depth, or mean effective stress), as shown in Fig. 7. Perfect agreement between laboratory and field results would fall on the 1:1 line; below this line, the points indicate that laboratory values are lower than in situ values.

As would be expected, all points appear below the 1:1 line. The slope of the line connecting each point (or the best fit line for a group of points from the same borehole) to zero provides an indication of the loss of shear wave velocity in relation to the field, which can be considered a measure of the sample disturbance.

The percentages of loss and quality indicated in the table refer to shear wave velocity, but could also be associated with stiffness or natural structure. The conclusions are similar to what was already commented in the analysis of each experimental site, but from this plot, it is possible to define different categories of sample quality (or sample disturbance). The least disturbed sample was block sample B2 from ES1, with 14% of loss, that is 86% of quality. Considering the stages of a sample from sampling to storage to preparation to laboratory testing, shear velocity losses below 15% appear to be minimal and therefore 85% of quality seems acceptable as an indicative of an excellent quality sample. A gradual scale has then been empirically and experimentally established: up to 70% for a very good quality sample; 60% for a good sample; 50% for a fair quality sample. Below 50% of quality or $V_s$ loss, the quality of the sample is poor and the sample should be considered disturbed, thus inappropriate for careful laboratory testing and characterization.

From these results, a classification of sampling quality (or sample condition) based on the comparison of normalised shear wave velocities in the field and in the laboratory is proposed, as indicated in Fig. 7 and Table 4. In this figure, the result obtained for a laboratory remoulded specimen, consolidated to the same in situ stresses as all corresponding samples from ES1, is also presented.

It is worth noting the position of the reconstituted sample, located at quality zone D, therefore not corresponding to the lowest shear wave velocity value. Two tube samples (from S2 and S4) appear below the reconstituted sample, which is indicative of their poor quality, thus enabling us to confirm the proposed limits of this classification.

There is some parallelism between this new classification and that proposed by Landon et al. (2007) based upon tests on Boston blue clay and Sukolrat et al. (2008) for Bothkennar soft clay. In their research, these authors compared laboratory and in situ shear wave velocities and used the reconsolidation strains method by Lunne et al. (1997) to define the categories of sample quality. However, their classification is less restrictive than the one proposed in Table 4: the ratio $V_{lab}/V_{in situ}$ from 0.6 to 0.8 corresponded to good to excellent quality samples; poor quality samples had a ratio of 0.35–0.6 and very poor quality samples exhibit values of $V_{lab}/V_{in situ}$ lower than 0.35.

![Fig. 7. Proposed classification of sampling quality based on the comparison of normalised shear wave velocities in the field and in the laboratory](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>ES1</th>
<th>ES2</th>
</tr>
</thead>
<tbody>
<tr>
<td>% loss</td>
<td>32%</td>
<td>42%</td>
</tr>
<tr>
<td>% quality</td>
<td>68%</td>
<td>58%</td>
</tr>
</tbody>
</table>

Table 4. Proposed classification of sampling quality and sample condition based on the comparison of normalised shear wave velocities in the field and in the laboratory

<table>
<thead>
<tr>
<th>Quality zone</th>
<th>$V_{lab}/V_{in situ}$</th>
<th>Sample quality</th>
<th>Sample condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$\leq 0.85$</td>
<td>$\leq 0.006$</td>
<td>Excellent</td>
</tr>
<tr>
<td>B</td>
<td>$0.85-0.70$</td>
<td>$0.006-0.01$</td>
<td>Very good</td>
</tr>
<tr>
<td>C</td>
<td>0.70-0.60</td>
<td>0.01-0.02</td>
<td>Good</td>
</tr>
<tr>
<td>D</td>
<td>0.60-0.50</td>
<td>0.01-0.02</td>
<td>Fair</td>
</tr>
<tr>
<td>E</td>
<td>$&gt;0.50$</td>
<td>$&gt;0.02$</td>
<td>Poor</td>
</tr>
</tbody>
</table>

(1) These ranges correspond to about a 1/7 of those defined by Lunne et al. (1997) for NC clays.
For the purpose of comparison, it is interesting to analyse the relationship between $V_{s \text{lab}}/V_{s \text{in situ}}$ ratio and the reconsolidation strain ratio $\Delta e/e_0$ used in Lunne et al. (1997) method, as illustrated in Fig. 8. In order to do so, some degree of scaling is required for their application to these soils. Given the much lower reconsolidation strains observed in these samples, the ranges proposed by Lunne et al. (1997) have been scaled down by a factor of 7 to better fit to the data. This factor results from a comparison between the maximum measured reconsolidation strain ratio (around 0.02, cf. Table 4) and the highest value proposed by the method for very poor samples (0.14, cf. Table 1). The resulting classification ranges are as follows: below 0.006 for excellent samples; 0.006 to 0.01 for very good samples; 0.01–0.02 to good to fair samples and above 0.02 for very poor samples. A good correspondence between the velocities and the reconsolidation strains ratios can be observed in the figure, which demonstrates the potential of this new approach. Even though the classification ranges differ slightly, both methods converge to the same sample quality classification. Therefore, it can be concluded that the proposed sample quality scale is well distributed and in agreement with the behaviour of the soil sample during reconsolidation.

As discussed above, the effects of sampling disturbance on the stiffness of the soil, especially at small strains, are clear; however, with regard to soil strength, these effects are less evident. From the results obtained in this experimental program, we were not able to detect a direct relationship between the strength parameters and the sampling method due to the minimal variations of these parameters. Hight (2000) presented significant differences in measured strengths as a consequence of sampling disturbance on clays, which were not observed in this research. Nevertheless, the observation of the configuration of the stress-strain curves of the tested samples can be indicative of sample disturbance. Higher quality samples exhibited steeper (that is, stiffer) stress-strain curves, and lower yields and failure strains.

CONCLUSIONS

The use of seismic wave velocities is undoubtedly an optimal method for the derivation of a number of relevant soil properties and parameters. In this paper, these velocities were applied to the assessment of sampling quality in two experimental sites in residual soil from Porto granite.

For this purpose, the comparison between in situ and laboratory shear wave velocities was made, where the differences encountered in terms of normalised velocities (to the respective void ratio function) were directly related with sample quality. Based on the database of results from the two experimental sites studied in this research, a new classification of sampling quality, or sample condition, was subsequently proposed.

It is worth highlighting that, among the commonly used methods for assessing sample quality, this method is the only one capable of effectively considering the effects of destructuration in soils with low reconsolidation strains, as in the present case.

Taking into consideration the growing need for geotechnical design of a reliable soil characterisation at small to medium strains, the selection of the best quality samples for such characterisation is fundamental, for it is at those strain levels that the disturbance induced by sampling is most influential.

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