Application of non-destructive techniques to assess sample quality in soft clay: a case study

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ABSTRACT: A case study about the application of non-destructive techniques to assess sample quality of soft clay samples retrieved from thin-walled samplers is presented, from a site where consolidation is still taking place due to an embankment, at the Technologic Park at University Campus, Federal University of Rio de Janeiro, Brazil. The first sample, from a lower depth, was properly retrieved, however cleaning of the borehole was not properly carried out in the second case. X-ray radiography and bender elements were used for that purpose. The radiographs allowed for visualization of shells and voids in both samples and disturbance zones and cracks in the second sample. Shear wave velocity from bender elements corroborated the results of the radiographs. For the second sample, lower velocity and smaller wave amplitude were measured, typical of disturbed samples. A description of the problems related to the sampling procedure and its relation to the sample quality is presented.

Keywords: X-ray radiography; bender elements; soft clay; sample quality; nondestructive assessment

1. Introduction

According to Ladd and Degroot [1] there is no definitive method for determining the absolute quality of a soil sample. There are different techniques that have been developed and can be applied to perform this quality assessment, among which there are those in which this is possible only after the test (destructive techniques), and others called non-destructive, like X-rays radiographs and bender elements, which allow qualifying a soil sample according to the level of disturbance.

The present paper shows a case where X-rays radiographs of soil samples were used to qualitatively evaluation of the presence of inclusions, identify layer variations and, together with the results from bender elements, identify and select undisturbed sections for test.

Samples from soft soil collected at a site in the Technological Park, located in the main university campus of the Federal University of Rio de Janeiro, Brazil, allow interesting conclusions when those two techniques were used.

2. Sample quality assessment

Verification of sample quality is a standard practice, but the criteria for assessing the quality of soil samples (or specimens) in laboratory are mostly qualitative. The most common is the simple observation of the void ratio (e) curve versus log of the effective vertical stress (σ'_v) in consolidation tests, as already shown by Hvorslev [2] see also Landon [3].

There are a few criteria for quantitatively assessing the quality of a soil sample and one of these, which has been widely used in international literature, is that proposed by Lunne et al. [4], although it has the disadvantage that it is necessary to perform the test to verify the quality of the sample, as mentioned above.

Lunne et al. [4], based on the $\Delta e/e_0$ ratio (where $\Delta e = e_0 - e\sigma'_{v0}$ being the difference between the initial void index (e_0) and the voids index associated with the effective vertical stress under which the sample was submitted in the field ($e\sigma'_{v0}$), proposed the values included in Table 1 for the classification of quality of soil samples.

Table 1. Classification of sample quality from [4].

OCR	**$\Delta e/e_0$**			
	Very good to excellent	**Good to regulate**	**Poor**	**Very poor**
1 – 2	< 0,04	0,04 – 0,07	0,07 – 0,14	> 0,14
2 – 4	< 0,03	0,03 – 0,05	0,05 – 0,10	> 0,10

Landon [5] mentions that with conventional, destructive laboratory methods for assessing sample disturbance, the geotechnical engineer will not know if the collected samples are disturbed until long after the sampling program is complete. Developing a non-destructive field method for sample quality assessment would provide engineers with a tool that could detect problems in real-time field sampling procedures so that they could be corrected as samples were collected. Such a method would also provide a means of selecting good quality samples prior to destructive laboratory testing.

Among the non-destructive methods, radiographs of samples have been employed since Hvorslev (1949), and the bender elements technique has been increasingly used due to its simplicity, accuracy and reliability [6].

The use of bender elements makes it possible to compare the shear wave velocities obtained in a soil sample in the laboratory ($v_{s\ lab.}$) with the one obtained from field test ($v_{s\ field}$), for example through the seismic dilatometer test (SDMT) or the seismic cone penetration test (SCPTU).

The criterion proposed by Landon [5] for BBC (Boston Blue Clay) is summarized in Table 2 and establishes a relationship with the criterion of Lunne et al. [4], using the ratio $v_{s\ lab}/v_{s\ field}$.

Table 2. Sample quality rating for BBC based on normalized shear wave velocity adapted from [5]

Sample Quality Rating	**$\Delta e/e_0$ for OCR < 2 [4]**	**$v_{s\ lab.}/v_{s\ field}$ [5]**
Very good to excellent	< 0,04	> 0,6
Good to regulate	0,04 - 0,07	0,35 - 0,60
Very poor to poor	> 0,14 e 0,07 - 0,14	< 0,35

3. Use of radiography in geotechnics

3.1. Brief history

The first records of the use of X-ray in geotechnics to evaluate sample quality seem to have been presented by Hvorslev [2], in which the author shows several radiographs made on cylinders with varved clay soil samples greatly disturbed by sampling. Hvorslev [2] visually highlighted, for example, the effects of excessive soil spiking of the sampler, internal wall friction on the sample, and the formation of ground cones during piston sampling.

According to Ladd and DeGroot [1] X-ray radiography should be used especially in expensive projects due to the cost and equipment associated with this method or when there are a limited number of samples. Ladd and DeGroot [1] also presented radiograph results in an Orinoco clay sampling tube and compared with undrained shear strength (s_u) values. Low values of s_u in regions where the radiography identifies disturbances in the sample confirm its usefulness in identifying lower quality regions of the sample inside the tube.

On-board radiography to immediately assess the quality of offshore soil samples are sometimes used (e.g., Lacasse et al. [7]).

3.2. The technique

ASTM D4452 [8], "Standard Practice for X-ray Radiography of Soil Samples", provides recommended equipment and procedures for performing X-ray radiographs on soil samples.

X-ray recording in film (or detector) depends, above all, on some exposure parameters: density and thickness of the materials involved; distance between X-ray source and film or detector plate; voltage used; current used; and exposure time.

Also depending on the equipment used, two or three films may be required to record the X-ray of the entire sample tube, or two to three taken by the detector. Subsequently, the product obtained is then worked in an appropriate computer program and the image mosaic is assembled to present the entire tube profile in a single set.

Some features may be visible only when X-rays penetrate the correct orientation [9]. For example, a slanted air-filled slit within the sample will not be seen unless the X-ray path is parallel to the orientation of the slit.

Thus, this procedure should be repeated by rotating the sampling tube 90° to its longitudinal axis to obtain another view of the assembly and to allow identification of elements that may not have been seen in the first image.

Still in this context, a darker region recorded on a positive film (or detector) is indicative of a high density element and may result from a single denser element within the sample or several elements that are not as high but which are aligned with the X-ray path, thus overlapping the image. The rotation of the sampling tube by 90º eliminates this doubt.

Due to the diversity in sample size, shape and composition, as well as the variability of equipment, there are no fixed protocols for taking radiographs. This means that a large number of exposure parameters, such as pipe tension, current applied, total exposure time, etc., can be arbitrarily chosen, all influencing the end result [10].

The fact that X-ray radiography is a non-destructive technique for assessing the quality of a soil sample does not eliminate the need for further investigations and complementary testing on these materials. On the contrary, it is suggested a combination with other techniques that together allow a better visualization and analysis of the internal structure of the sample.

4. Bender elements

Dyvik and Madshus [11] presented a new technique that makes use of the so-called bender elements, piezoceramic elements through which it is possible to generate and record shear waves, and consequently to obtain the same velocity with better precision, considerably improving the quality of the results.

According to those authors the relationship between the sample length (known dimension) and the pulse travel time, recorded by the piezoceramic element, produces a direct measure of shear wave velocity (v_s), i.e.:

$$v_s(m/s) = \frac{L_t\,(m)}{T_t\,(s)} \tag{1}$$

where
L_t = shear wave travel length (m);
T_t = shear wave travel time (s).

In terms of the distance effectively traveled by the shear wave, it is assumed that the wave is propagated from the end of the transmitting element and is first received at the end of the receiving element, so the path length (L_t) corresponds to the end-to-end length between bender elements, i.e. equal to the height of the test piece (H), or soil sample segment, minus the length of the protrusions of the transmitter and receiver elements penetrated into it (d), according to Eq. (2).

$$L_t = \mathrm{H} - \mathrm{d} \tag{2}$$

The most important step of the whole method is the correct determination of the shear wave propagation time. However, this is the main difficulty, since interpretation processes are not yet carefully regulated.

Wave propagation velocity is directly influenced by many factors, including: neighborhood effects, transducer resonance, electrical noise or vibration, especially when raised and applied over short distances.

There are several existing methods of interpretation. In the present research a method based on the identification of the generated wave start point ("rising point") and the first received wave arrival moment, that is, the first response signal inflection was used. The difference between these two points is the time interval required for the wave to travel through the sample (t). In addition to the first wave inflection points, other characteristic points could be used such as the first peaks, the first valleys or the zero intersections.

In order to obtain the traveling wave time (T_t), it is first necessary to identify the delay time (t_c) for the pair of bender elements, or the difference of time between the transmitted and the received wave in a system without the soil specimen.

The delay time shall be subtracted from the time required for the wave to travel through the sample (t) to obtain the shear wave travel time for each new soil sample as indicated in Eq. (3).

$$T_t = \mathrm{t} - t_c \tag{3}$$

Another important factor is the configuration of the input wave, i.e., its frequency and shape, since aiming at clarity and ease of interpretation in the received wave signal result, an appropriate configuration of the transmitted signal is important.

5. Materials and methods

5.1. The material tested

The soil samples used in this work were retrieved from a site where consolidation is still taking place due to an embankment, at the Technologic Park at University Campus, Federal University of Rio de Janeiro, Brazil, according to Fig. 1.

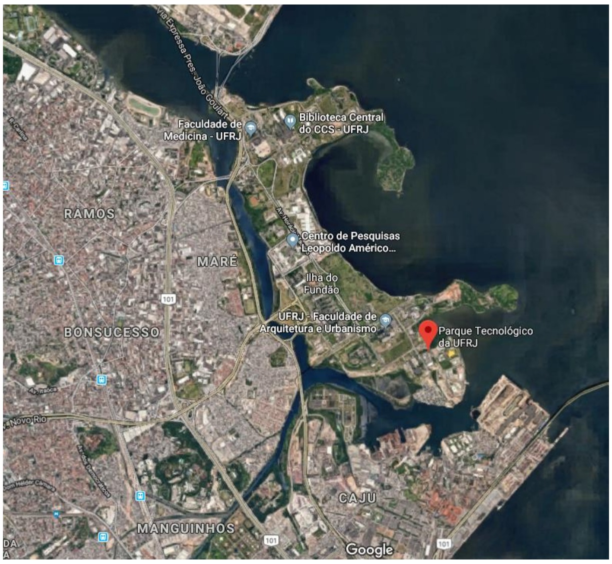


Figure 1. Sampling location of undisturbed soft soil samples [12]

Figure 2 describe the profile of the subsoil as initially presenting a embankment, a thick layer of peat-based landfill, followed by a very soft organic clay layer and finally residual soil. The geotechnical characterization of the clay showed that it is a silty clay with a water content ranging from about 75 to 110%.

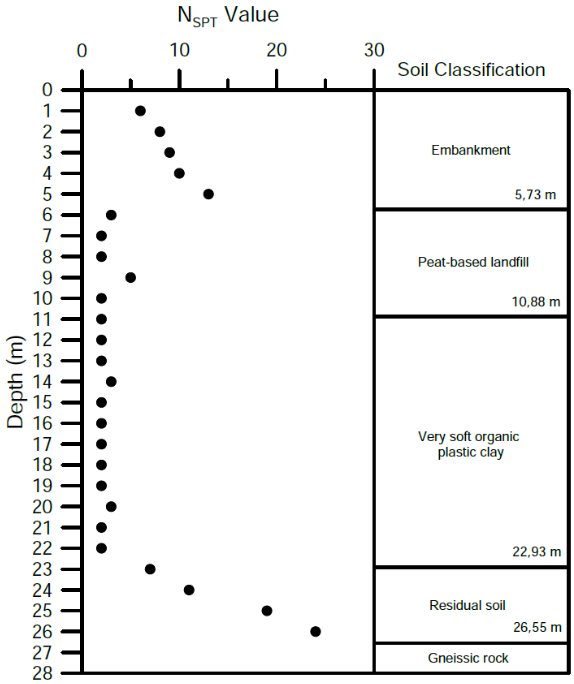


Figure 2. Typical profile of the subsoil with water level at 3m depth.

The sampling was conducted by the Field Testing and Instrumentation Laboratory Professor Márcio Miranda Soares, one of Prof. Jacques de Medina Geotechnique Laboratories at the Federal University of Rio de Janeiro using a Pagani rig (Fig. 3) to push the sampler at a constant rate of 10 mm/s.

Figure 3. Sampling of soft clay.

Two soft soil samples were collected using a 101.6 mm in internal diameter, 1.6 mm in thickness and 630 mm in length brass sampler, fitted with a valve. Double casing was used, the internal one with 200 mm in internal diameter, installed throughout the landfill layer, and also 300 mm into the clay layer, at 10.80 m depth. The sample was retrieved 24 hours after sampler penetration.

The retrieval of the second sample was planned to be performed near the end of the soft soil layer at a depth of 22.20 m. However, proper drilling by the drilling company was not possible, due to difficulties in extending the casing to the required depth, and also due to the presence of gas in the water, attributed to the old existing landfill layer. In fact, gas was released during the drilling operations for the second sample.

In spite of that, a second sample was retrieved following the same procedures mentioned above for the first sample.

5.2. Equipment and operating procedures

5.2.1. Radiograph

Undisturbed soil samples were radiographed at the facilities of the Nuclear Instrumentation Laboratory (LIN) of the Federal University of Rio de Janeiro (UFRJ) by a trained technician using a procedure similar to that described by the American Society for Testing and Materials [8]. The tubes were directly exposed to X-rays, limited only laterally by the lead blocks.

The X-ray emitting source used was Yxlon model Y.XPO 225 D02 and the images were recorded by a GE model DXR 250U detector. The X-ray emitting source was positioned so that it was 1 m away from the detector, and had its exposure parameters adjusted to produce a voltage of 225 kV and 2 mA current for an exposure time of 2.5 s for both samples (Fig. 4).

At the end of the X-ray emission process, with the source already turned off and the necessary safety measures taken, the tubes containing the soft soil samples were removed from the site and taken back to the cold chamber for storage. The entire apparatus was disassembled and the images captured by the detector were sent to a computer where they were worked.

An image processing program called ISee (ic-v1.10.2) was then used to work the radiographs and allow better visualization of the content, with the possibility of applying filters, contrasts, image equalization and extraction measures. Then the images were assembled together, like a mosaic, reconstituting the total length of the sampling cylinder.

Figure 4. Positioning of radiographic equipment.

5.2.2. Bender elements

For the present research an equipment produced by the University of Massachusetts (UMass) in Amherst in 2013, courtesy of Professor Don DeGroot, was used. It consists of a portable device with a height-adjustable metal pedestal with acrylic base and top bracket, where the bender elements are installed and where the specimens are positioned.

The bender elements system is composed by pizoelectric transducers, an oscilloscope and a function generator. A Fluke 271 (Wavetec) function generator, and a PicoScope 4227 (Pico Technology) oscilloscope were used in the present research.

All these devices are connected to a computer that contains a software (PicoScope 6) so that it can graphically display and control in real time the results recorded by the oscilloscope during the tests.

The function generator connects to the transmitter bender (bottom) and oscilloscope (Channel A) and the receiver bender element (top) is also connected to the oscilloscope (Channel B). Fig. 5 illustrates the equipment used in the present research.

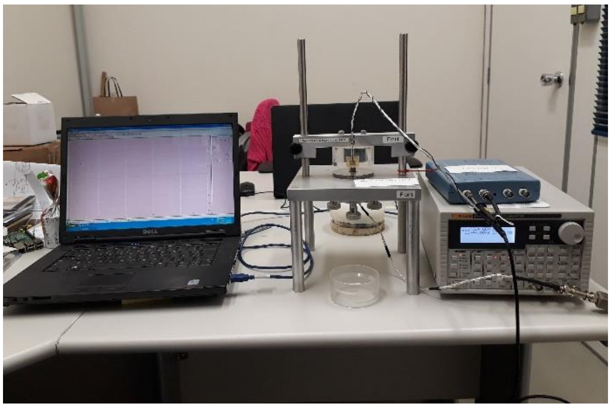


Figure 5. Bender elements test equipment, including PicoScope 4227 oscilloscope and Fluke 271 function generator.

The device was firstly settled to obtain the so-called tip-to-tip time lag (wait or delay time) of the element, i.e., the time it takes the wave to be emitted by one element and captured by the other without any soil sample (Fig. 6).

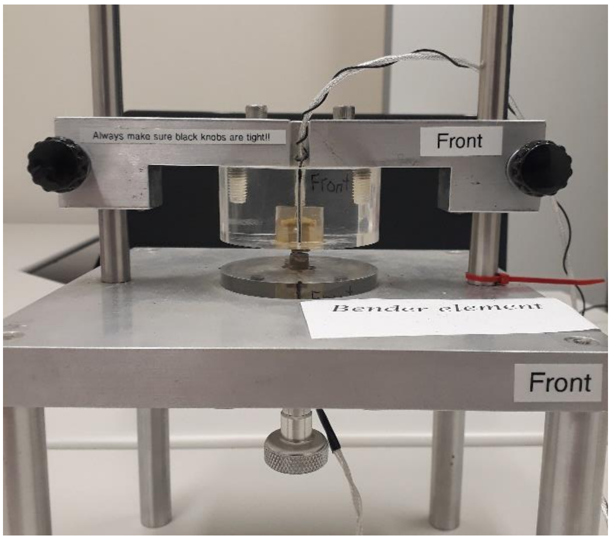


Figure 6. Tip-to-tip bender element calibration.

In the present case, the wave generator was configured to transmit, through the lower element, a 20 V sine wave and 4 kHz frequency. The time difference corresponding to transmitted (blue) and received (red) waves is the delay time (Δ = t_c), which is 6 µs in the present case (Fig. 7).

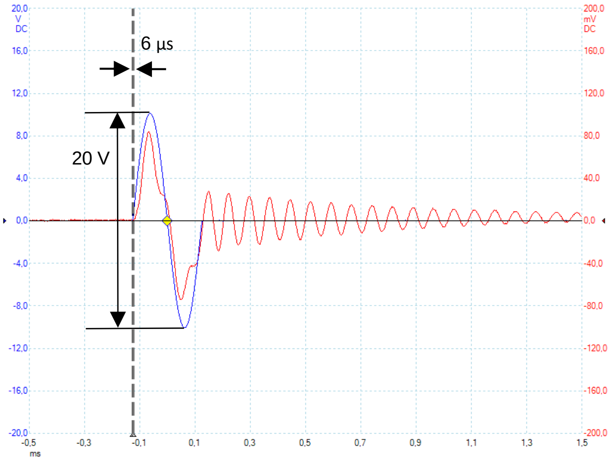


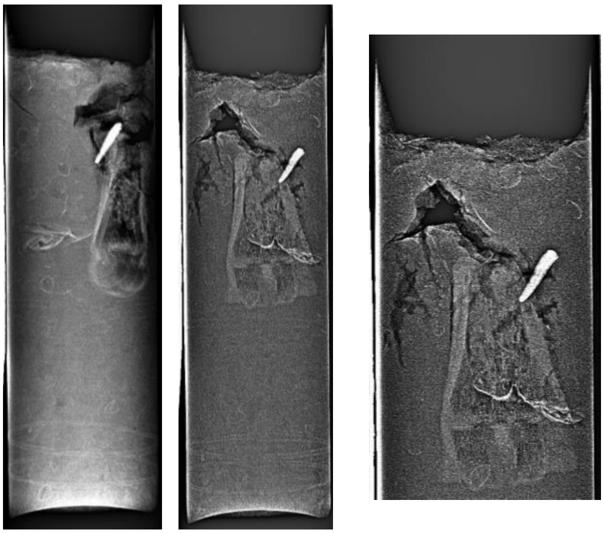
Figure 7. Bender elements calibration.

6. Presentation and analysis of results

6.1. Radiograph

Radiographs taken on the first sample are shown in Fig. 8 obtained with negative film detector. In these images, the contrast between the densest and least dense elements can be clearly seen according to the color pattern for negative films presented above.

In Fig. 8, two radiographs are shown, the first with the sample positioned at 0º and the second with 90º rotation, respectively.



(a) (b) (c)

Figure 8. Radiographic images of the first sample, obtained with negative film detector. a) sample positioned at 0º; b) sample rotated at 90º; c) enlargement in the disturbed part of the sample rotated at 90°.

This first radiographic sample was taken when approximately the lower part of the sampler (roughly 50%) had already been cut to be used in laboratory testing. It must be noted that the regular practice used in the laboratory is the one recommended by Ladd and DeGroot [1], where the sample is not extruded.

In the upper part of the sample, it is possible to observe whitish elements, identified as shells. Still in the upper part of the sample there are clearly a number of large and small voids, identified by very clear dark stains on the negative film radiography, a sign of very low density.

In addition to what is described above, an element of greater volume and density, initially unidentified, is clearly visible within the sample.

In order to inspect the soil sample and identify what this unknown element was about, an extruder was used. The element was then carefully removed from the soil sample and cleaned, and identified as a bone (see Fig. 9).

Figure 9. Bone image of an animal belonging to the order Artiodactyla found inside the soil sample.

After cleaning, the bone was taken to the UFRJ palaeontology department, which preliminary identified it to be from an animal belonging to the order Artiodactyla. The origin of this element is still unknown and under study.

Despite the presence of the shells and the unexpected presence of the bone, the lower part of the sample appears to be of good quality.

The second radiograph sample was taken in the whole sampler, with a useful length of 630 mm, and is shown in Fig. 10.

The presence of a large number of cracks scattered along the entire length of the sample and in different orientations cab be clearly observed. These cracks clearly show the degree of disturbance that the second sampling was subjected. The cracks appear as darker in the radiographs because X-ray photons traverse low density elements and are captured by a negative film detector.

It is hypothesised that the appearance of such cracks is due not only to the inadequate process of cleaning the hole, which did not properly remove the soil inside the casing, but also to the release of gas bubbles from the landfill, when the casing was to be installed for the second sampler by the drilling team, as described above.

Also along the entire length of the sampling cylinder, the presence of closed and open shells (valves) can be observed, the color of which appears whitish in Fig. 10.

Figure 10. Radiographic images of the second sample, obtained with negative film detector. a) sample positioned at 0º; b) sample rotated at 90º; c) magnification in the upper part of the sample rotated at 90º; d) magnification at the bottom of the sample rotated at 90°.

Another remark, also of relevance, that can be observed in Fig. 10, is the presence of a large amount of curvilinear distortions at the bottom of the sample, near the walls of the sampling cylinder. It is believed that such distortions were caused by excessive penetration, again maybe related to improper cleaning of the borehole.

6.2. Bender Elements

The first sample positioned in the bender elements apparatus is shown in Fig. 11, and the waves generated and received in Fig. 12.

The same procedure was done for the second sample, and the corresponding results are shown in Fig. 13.

A proper comparison cannot be undertaken by the simple observation of Figs. 12 and 13. In fact, the maximum value of the amplitude in Fig. 12 is 200 mV, whereas is 50 mV in case of Fig. 13. The magnification in Fig. 13 was necessary in order to allow the received wave to be observed.

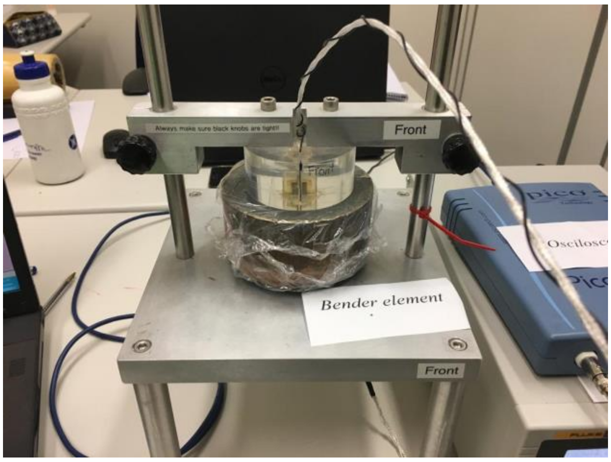


Figure 11. Sample positioned in the apparatus.

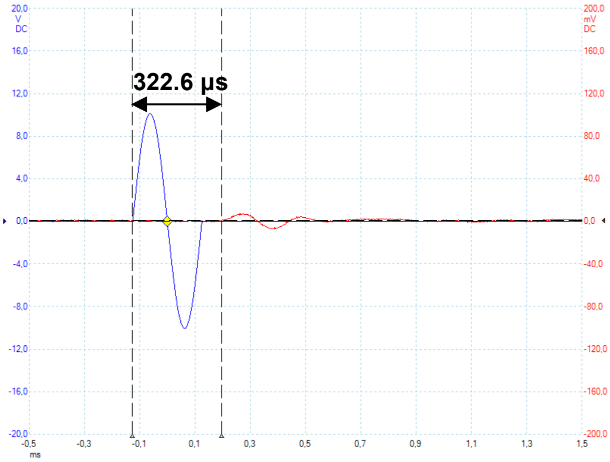


Figure 12. Bender element test in the first sample.

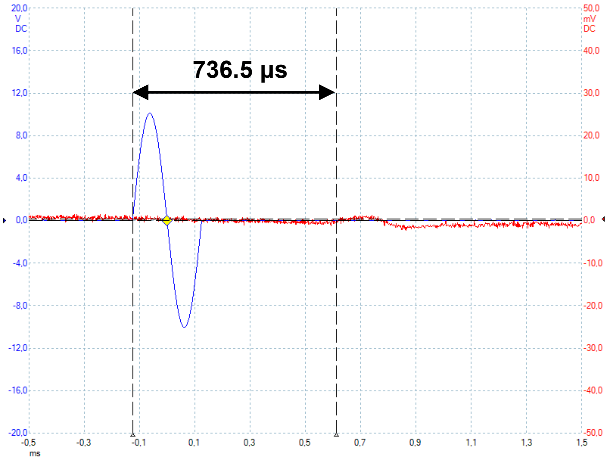


Figure 13. Bender element test in the second sample.

The shear wave velocity of both samples are calculeted by equation (1). The result is shown in Table 3.

Table 3. Test results.

S	tc (µs)	H (mm)	d (mm)	Lt (mm)	Δt (µs)	Tt (µs)	Vs lab. (m/s)
01	6,00	40,0	12,9	27,1	328,6	322,6	84,0
02	6,00	40,0	12,9	27,1	742,5	736,5	36,8

Where:
S = sample: 01 - undisturbed; 02 - remoded;
tc = system calibration time obtained when Lt is zero µs;
H = length of sample section or specimen in mm;
d = length of transmitter and receiver bender elements penetrated inside the sample in mm;
L_t = shear wave path length in mm;
Δt = time difference between the initiation of the source wave and the arrival of the shear wave µs;
T_t = shear wave travel time in µs, $T_t = \Delta t - tc$;
v_s = shear wave velocity in m/s.

To evaluate the sample quality, the regular procedure is to compare the results of laboratory and field shear wave velocity, as mentioned before.

However, as the field shear wave velocity was not available, a comparison between samples 1 and 2 was undertaken.

As can be seen, the difference between shear wave velocities of samples 1 and 2 is quite significant (47.2 m/s difference). As disturbance affects significantly the vs values, the obtained results are consistent with a much better quality of sample 1 with respect to sample 2.

7. Additional comments and conclusions

Although the application of X-ray radiography technique is becoming more widespread and used in geotechnical research and engineering projects, with much to offer, challenges still need to be overcome, regarding more standard specifications of the equipment and the procedures to be used.

The radiographs of the samples performed in the present paper illustrate their usefulness to select the parts of the sample to be used for different types of soil tests. The qualitative observation of the radiographs was consistent with the results obtained from bender element tests, where it was shown that the sample 1, below the bone found in the sample (v_s = 84,0 m/s), was of a much better quality than sample 2 (v_s = 36,8 m/s).

The results in the present research suggest that radiographs should be incorporated into routine soil investigation, in combination with bender element tests.

Acknowledgments

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