The Development of an Acoustic Cone Penetrometer

by

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Summary

The cone penetrometer is a standard device for the in situ measurement of soil properties. This report describes the modification of a standard penetrometer to detect acoustic signals, generated in the soil, as the cone is pushed into the ground. Details of the signal acquisition equipment and its integration into a standard penetrometer system are given. A simple analysis of some preliminary ACPT signals is presented, comparing two methods of determining the signal’s power spectral density. The proposed experimental programme and methods for interpreting the acoustic signal are discussed. The report also serves as an account of the implementation details, recording the design of the new cone tip, data acquisition and electrical connection details.

Introduction

The cone penetrometer (CPT) is widely used for geotechnical site investigation around the world. It is an excellent soil profiling tool, and can be used for the interpretation of many soil properties and parameters (Meigh, 1987). The CPT is pushed at a constant rate (usually 2cm/s) through the soil by a hydraulic jack, which can either be mounted within a specially designed truck or on a trailer. The CPT is attached to the jack via a series of one metre long push rods, which are added after each ‘push’. A CPT field test, therefore, consists of a series of pushes of 50s duration, in which the CPT penetrates a further metre in the ground. The test’s depth is dictated by site conditions, either through the level of the base rock or on the composition and strength of the soil. Typically, tests are in the region of 10-30m in depth, but can go down to 100m in favourable ground conditions.

A standard CPT typically records two measurements; the tip resistance as the penetrometer is being pushed into the ground and the load on the friction sleeve of the cone (see Figure 1). A number of additional sensors that allow further soil characteristics to be determined can be placed within the penetrometer; including piezo elements for the measurement of pore water pressures (piezo-cones, Larsson and Mulabdić, 1991), lasers for the detection of hydrocarbon contamination (LIF cones, Lambson and Jacobs, 1995) and microphones for the detection of acoustic signals (acoustic penetrometers, Villet, 1981; Tringale, 1983; Massarch, 1986). The microphone in an acoustic cone penetrometer (ACPT) detects acoustic emissions in the soil, due to particles being crushed, sheared or deformed as the tip penetrates the soil.

The aim of this project is to infer quantitative information on the soil type and properties from the acoustic signal produced by an ACPT test. It has been shown that the ACPT is a practical tool for site investigation, capable of discrimi-
Figure 1: Schematic illustration of a CPT. The basic components are the cone tip, friction sleeve, the hollow core holding the tip and friction sleeve strain gauges, and the connector between the body of the cone and the push rods. The connector also contains the socket for the surface cable.

inating much finer layering than a standard CPT, but, to date, there has been a somewhat qualitative approach to the analysis of the acoustic signals, especially within the frequency domain. By constructing a database of ACPT signals from a wide variation of soil type and stress conditions, generated from tests within a large calibration chamber, it is hoped to characterise the soil type and properties from an analysis of the acoustic signals. The motivation behind this project is two-fold. The first is the development of improved techniques of interpretation for the ACPT signal. The second is the introduction, and hopefully successful application, of modern signal processing, classification and prediction tools into the domain of civil engineering.

Background

There are two principal strategies for the detection of acoustic information from the soil deforming around the penetrometer’s tip. In the first, the frequency range of interest is limited to the audible spectrum (30Hz to 20kHz). The pioneering work for this was conducted at Berkeley, California in the early 1980’s (Villet, 1981; Villet et al., 1981; Tringale and Mitchell, 1982; Tringale, 1983). The second strategy is to look at a much wider frequency spectrum, still containing the audible range but also covering ultrasonic frequencies. The upper limit for the highest frequency can be as high as 1MHz. This large interval frequency work, with reference to soil characterisation, is referred to by the term ‘acoustic emissions (AE)’. In general geotechnical applications, AE have been studied extensively by Koerner et al. (1976; 1977). For the particular application of interest, namely the CPT, Massarch (1986) originally described a modified CPT, referred to as the AE
CPT, using a needle tip for the detection of ultrasonic frequencies. This work has recently been taken up by Mengé and Van Impe (1995).

The ACPT described in the following sections is based on the work of the Berkeley team. The salient aspects for this decision are that the design and modification of the CPT tip are relatively straightforward, the signal acquisition hardware is relatively inexpensive and that the amount of data processing is kept to reasonable limits. The most important advantage, is that the tip resistance (which is the single most important piece of information from a CPT test) can be conventionally recorded. The acoustic signals can thus be recorded as an extra piece of data, without the loss of any of the usual CPT sensors. With the needle tip, it is not apparent how the true tip resistance can be measured, which is a disadvantage if the technology is to be adopted for mainstream use.

The needle tip of Massarch (1986) does allow for the detection of ultrasonic frequencies, as good acoustic isolation from the main penetrometer body can be obtained. The practical consequences of this are that thinner soil layers can be identified, and some extra information may be available from the higher frequencies. However, if sampling at rates in the region of 1-5MHz, the data acquisition becomes non-trivial and very much more expensive. Also, it is not obvious how much additional information would be gained from investigating the larger range of frequencies of the AE CPT. In Massarch (1986) a profile is shown where the AE CPT clearly identifies sand and clay layering, however similar discrimination has also been shown to be possible with the ACPT of the Berkeley team.

**Modification for Acoustic Signal Detection**

The major consideration when modifying the CPT, was to ensure that the basic penetrometer was unaffected after installation of the microphone. Figure 1 shows the basic components of a standard (Fugro) CPT. The 15cm² cone tip is detachable from the main body of the penetrometer via a screw thread, which allows access to the space between the tip and the strain gauges. The first strain gauge measures the tip resistance (referred to as the C measurement), while the second measures the load on the friction sleeve (K). In practice, the friction sleeve gauge also measures the load from the tip, so its actual output is C + K. Calibration of the strain gauges is carried out by Fugro, and requires a special calibration rig which allows for the independent application of loads to both gauges. A proprietary 10 core cable carries the signals from the CPT to the ground surface and the data acquisition units.
Figure 2: Details of machined cone tip. All dimensions are in millimeters.

Microphone

Two microphone cartridges were tested (the Knowles CA-2832 and the Sennheiser KE-4-211-2). Of the two, the Sennheiser microphone had the more appropriate frequency response, (i.e. an extremely flat response across the frequency range of interest), was slightly smaller, had a more robust connection system (three sturdy legs as opposed to three small solder tabs) and a strong signal output. Also, the Sennheiser cartridges are an industry standard for speech recognition work, so they are known to be of good quality. An additional bonus is that both of the cartridges are comparatively inexpensive (at around £30 per unit).

Machining of Cone Tip

The original intention was to use a standard Fugro cone tip to house the microphone. The Fugro cone tip is, however, specially hardened after manufacture and could not be easily machined. To overcome this, a number of cone tips were turned from mild steel, using the original Fugro tip as a template (see Figure 2 for dimensions). These are suitable for research purposes, but may exhibit some different acoustical properties to that of the Fugro cone tip. For our research purposes, the mild steel tip is adequate.

For ease of access and installation the microphone is positioned in a recessed machined bolt (Figure 3). The microphone is firmly held against the tip, by ensuring that it stands slightly proud of the holding bolt.

Some acoustic isolation between the cone tip and the body of the CPT is achieved by two simple measures. The first involves wrapping PTFE tape around thread of the cone tip, thus providing some damping between the cone tip and
Figure 3: Details of microphone and recessed bolt. All dimensions are in millimeters.

Figure 4: Wiring of 4-way connector between microphone and cone circuitry. Both diagrams are drawn as if looking at the pin side of each connector.

the main body of the CPT. The second step is to sandwich a thin annulus of rubber membrane between the face of the strain gauges block and the corresponding face of the cone tip. Further acoustic isolation can be obtained by insulating the metal-on-metal interface between the push rod and driving rig.

**Electrical Circuitry**

Due to the advances in CPT technology, the electrical integration of the microphone into the CPT was easier than expected. Fugro’s CPTs currently have a small printed circuit board (PCB) positioned within the hollow core holding the strain gauges. The PCB provides a stable 10V DC power supply (stepped down from an external supply of 16V) to the strain gauges, inclinometer, etc., and also provides amplification for the output signals.

For our ACPT the inclinometer was removed (this freed up a considerable amount of space behind the tip, also the inclinometer is not so vital in the laboratory as in the field), but it could be reinstalled if needed for field testing. A mini
Data Acquisition

A key consideration in the design of the data acquisition system was the requirement for a practical implementation that was extendible, relatively cheap in cost and used standard components. A schematic diagram of the signal acquisition system is shown in Figure 6. Two data acquisition boards are used to capture the data signals. The first is an GPIB/IEEE interface board, which records the two standard signals from the CPT (tip and sleeve) and the output from the linear potentiometer. The potentiometer measures the displacement of the cone during the test. The second board, a CIO-DAS16/330, records all the acoustic data. Synchronization between the signals is straightforward, as the instant that the penetrometer starts to move can clearly be identified in both the acoustic and the displacement signals.

Both sets of data (i.e. cone and acoustic signals) could be recorded by a single, fast A/D if desired, but as there are essentially two different sampling rates (100kHz for the acoustic signal and 1-5Hz for the others) it seemed sensible to keep the signal paths separate. By using the GPIB/IEEE board it was possible to make use of existing software for data acquisition, and also to avoid duplicating or switching over of cables by allowing the same cables to be used for a variety of test devices (e.g. ACPT and pressuremeters).

Signal Conditioning

For Villet’s and Tringale’s work the acquisition system was based on tape drive with a manually switchable, three-way gain (unity, x10 and x50). With advances in technology, it is now feasible to collect and process all the data on a personal computer, which is the approach taken in this work.

Within the laboratory environment the variation of voltage output from the microphone signal for the duration of a chamber test is minimal, especially when compared to field conditions. Considering this, a fixed-gain preamplifier is suitable for use within the laboratory. Any variation of signal output between different tests can be accommodated by adjusting the capture range on the fast sampling A/D card (from ±0.625V to ±10V). Currently, a gain of 100 for the preamplifier is being used, which gives an output voltage of typically ±5V.

For practical implementation of the ACPT on site, an important consideration is to capture signals from a range of soils. It is expected that the signal would be orders of magnitude different for clay and coarse sands (e.g. Massarch 1986 cites differences of order 100). The first line of investigation focussed on logarithmic preamplifiers, as the logarithmic response between soils does seem to have an intuitive representation. It became clear, however, that the logarithmic amplifiers are designed for unipolar signals rather than the bipolar acoustic signal.
Figure 6: Schematic representation of the data acquisition system
An alternative method is to use a preamplifier with a variable gain. Suitable amplifiers are the VOGAD (Voice Operated Gain Adjusting Device) chips which commonly used for speech compression to provide a constant output amplitude for different operational conditions. Using the VOGAD chip enables the full range of the A/D card to be used with confidence, whilst also capturing relative gain information. The gain information can be measured from monitoring an internal gain voltage from the VOGAD circuitry (a higher voltage corresponds to a low gain, and vice versa). The disadvantage is that an additional channel has to be used to capture gain information, with some additional post-processing being required to incorporate the gain information into the acoustic signal output from the VOGAD chip. The VOGAD chips were tested in the laboratory and worked reasonably well, but the fixed gain amplifier was preferred for the laboratory work, as this avoided having the extra channel for gain information, thus making any data analysis more straightforward.

Some simple analogue filtering is built into the signal conditioning circuitry to remove low frequency (less than 200Hz) and high frequency (greater than 40kHz) noise. This is, in effect, a band pass filter, which also acts as an anti-aliasing filter for the A/D card. In addition to this, it is possible, after A/D conversion, to filter digitally the acoustic signal to remove any spurious electrical or mechanical noise.

Calibration Chamber Testing

To investigate the interpretation of the ACPT signals, it is first necessary to have a reliable database of acoustic signals. As no database of this sort exists, it is necessary for us to construct our own database. The easiest method of completing this task is to use a large calibration chamber, such as the University of Oxford sand calibration chamber. The calibration chamber is a large triaxial cell, which can be used to control accurately the horizontal and vertical stresses placed on the soil sample. By carefully controlling the placement of the soil sample, repeatable experiments can be conducted. Large calibration chamber experiments have been shown to be especially useful for the evaluation of in situ testing devices, and have been used before in ACPT experimental work (Villet, 1981; Tringale, 1983).

The Oxford University sand calibration chamber (Figure 7) can hold a sample approximately 1m in diameter and 1.5m in height. The ACPT is pushed into the centre of the cylindrical sample at a constant speed of 20mm/s, which is the usual speed used on site for CPT tests. The maximum thrust provided by the driving rig is 100kN. When using the calibration chamber, a single test lasts for 70 seconds, but the turn-around time between tests is approximately one day.

The independent control of horizontal and vertical stresses allows for a wide range of stress states to be investigated. Typically, the maximum working pres-
Figure 7: Illustration of the Oxford University sand calibration chamber.

Pressures are in the region of 150kPa, but pressures up to 250kPa have been studied in the Oxford chamber. Another parameter that can be controlled is the relative density of the sand sample. Three relative densities of sand can be placed in the chamber, referred to as loose, medium and dense. Loose corresponds to a relative density ($R_d$) of 20-35%, medium in the range of 50-60% and dense from 80-95%.

**Preliminary Tests**

Prior to this report being written, and before an extensive re-design of the chamber’s lifting tackle, five trial tests were conducted. For these tests, the chamber was only half filled with sand, and no pressure was applied to the sample from the vertical or horizontal membranes. The objective of the tests was to estimate the mechanical and electrical noise within the system, and therefore obtain an estimate to get some feeling for the signal-to-noise ratio for the equipment. The signal conditioning box had not been manufactured, so the microphone signal was AC coupled to remove the DC component, and recorded using a 8-bit sound card, sampling at 44.1kHz (CD rate). For tests to be conducted in the future, a 12-bit A/D board will be used (see Figure 6), sampling at 100kHz.
Figure 8: A preliminary test for a half full chamber. The full test lasted 70s (the x-axis).

The signal from a full preliminary test is shown in Figure 8. The instant when the driving rig is switched on is clearly noticeable, and this point can be used to synchronise the two computers being used for data acquisition. There is a clear difference between when the ACPT is penetrating air and sand. It should be noted, that when the penetrometer is at rest there is very little noise (either electrical or mechanical in the system), but while the device is being pushed by the driving rig there is a small amount of mechanical noise, which is responsible for the signal in air. Once, the tip enters the sand, the amplitude clearly increases with depth, thus an obvious first conclusion is that the magnitude of the signal is clearly influenced by mean stress level.

Five preliminary tests were conducted to assess consistency and repeatability of the generated acoustic signal (Figure 9). The five tests appear similar from visual inspection, and the frequency content of the signals are also similar when transformed using a fast Fourier Transform (FFT) into the frequency domain.

In Figure 10, two full tests are shown, with Figure 11 showing the corresponding plots of cone tip resistance against depth. After the tip has penetrated through the top 300mm of the sample, the magnitude of acoustic signal, as well as its power spectral density, was very stable for the remainder of the test. Both tip resistance profiles show that a good soil sample, with a consistent density throughout, had been prepared. The values of tip resistance ($q_c$) given the stress state and density of the sample, are consistent with other published results and proposed empirical formula (Houlsby and Hitchman, 1988; Schnaid and Houlsby, 1991).
Figure 9: Raw acoustic signals from five preliminary tests. Note some clipping of the signal, which will be avoided in the acquisition of the signals for the ACPT database. The duration of each signal is approximately 30s.

Figure 10: Two signals from full tests using Leighton Buzzard sand placed to a loose relative density. The duration of both signals is approximately 70s. Note that these tests are not directly comparable to those of Figure 9, as different signal acquisition equipment has been used for the different tests.
Figure 11: Plots of cone tip resistance profiles for two tests in loose Leighton Buzzard sand. The respective acoustic signals are shown in Figure 10.

**Experimental Programme**

The control parameters that can be investigated in the testing programme are the effects of relative density $R_d$, $K$ (the ratio of horizontal to vertical effective stresses, $\sigma_h' / \sigma_v'$), specific lateral and horizontal stresses and sand type. Other known soil parameters (such as friction angle, stiffness) could be correlated in further analyses.

Currently, three different sands are available for testing:

**Leighton Buzzard** (14/25) This sand has been used extensively by Schmaid (1990) for a series of cone pressuremeter tests. It is a quartz sand which is frequently used in calibration chamber testing around the world, and has been the principal sand used for tests in the Oxford calibration chamber.

**Dogs’ Bay** A carbonate sand from the West Coast of Ireland (Connemara). The sand is composed of skeletal material from invertebrate fauna, and as a result it has very different mechanical properties from the more commonly tested quartz sands. This sand has been used previously for pressuremeter testing by Nutt (1993).

**Hokksund** This sand is an angular fluvial glacial deposit from the Drammen river valley near Oslo. It is a feldspatic sand with a significant silicate component
Table 2: Nominal stress states for proposed experimental programme for ACPT database. Each of the above stress states will be tested for loose, medium and dense samples of Leighton Buzzard sand. For the Dogs’ Bay and Hokksund sands a more flexible experimental regime will be adopted.

(45% feldspar, 35% quartz, 10% mica, 5% amphibole and 5% unidentified). This sand has also been studied by Nutt (1993) and also by Last et al. (1987).

Table 2 shows the nominal stress states (i.e. the combination of horizontal and vertical stresses applied by the calibration chamber) that will be used in the experimental programme. These follow previous studies and published work (Houlsby and Hitchman, 1988; Schnaid and Houlsby, 1991; Nutt, 1993), and cover a reasonable range of conditions, thus providing a degree of variation among the individual tests for the database.

It is proposed to test exhaustively the Leighton Buzzard sand first, and then conduct preliminary signal analyses on these tests. These analyses would concentrate on showing whether the acoustic signal provides enough power to discriminate between the different tests in the database. If the acoustic signals are capable of providing discrimination between the tests, then the Dogs’ Bay and Hokksund sand can be tested. If the acoustic signals do not provide adequate discrimination then a re-evaluation of the ACPT design and acoustic isolation procedures will be undertaken. Once the tests on all three sands have been completed and the signal analysis has been completed, a more varied regime of testing could be followed. Such tests could involve trying to identify layers composed of different sand types or using cemented layers.

**Signal Interpretation**

The key area in which the project is seeking to make a contribution is in the interpretation of the acoustic signal. Previous work (Villet, 1981; Tringale and
Mitchell, 1982; Tringale, 1983) has shown that the amplitude of the signal (root-mean-square voltage of the amplitude) provides a good method of discriminating between soil types (Villet, 1981), and can predict the average grain-size of Monterey-type sands. Tringale (1983) looked at both the amplitude and frequency content of the signals, and studied the effect of amplitude against cone resistance, grain size, rate of penetration, moisture content (dry or saturated), re-penetration and the effects of damping on the acoustic cone. The work based on the frequency analysis was more qualitative in nature with the main findings being that the predominant frequency associated with the maximum spectral amplitude increases with increasing cone resistance. A predominant frequency at 4.5kHz at lower penetration resistances was believed to be associated with particle rolling and/or sliding. At higher resistances, the predominant frequency shifted to 6.0 to 6.5kHz, and was thought to be associated with particle crushing.

A schematic diagram of the proposed signal analysis is shown in Figure 12. Most of the analysis will be in the frequency domain of the signal, for which the power spectral density is the most common method of comparing signals. There is a large body of literature comparing the numerous methods of spectral estimation methods (Kay and Marple, 1981). The Berkeley team’s interpretation of the ACPT signal was based on the fast Fourier transform (FFT). Our analysis could utilise the FFT, and use these coefficients as input features to a classification or prediction model. Alternatively, an autoregressive (AR) model (Figure 13) can be generated to characterise the time series (Chatfield, 1996) and the AR coefficients used for inference. Typically a FFT is used because of its relative speed, however the spectral resolution and problems with sidelobe leakage can lead to poor results. Where there is a high signal to noise ratio AR models have been shown to produce better estimates of the spectral density, but there can be problems with spurious peaks in the spectrogram. Also the problem of model order selection (i.e. the number of coefficients) must be fully considered to produce a reliable AR model.

The main advantage of the AR model over the FFT is that the AR model requires a much smaller number of coefficients for the adequate description of the time series than the FFT. This has the major benefit of reducing the dimensionality of the features extracted, which aids and removes many possible problems with the pattern recognition/interpretation task. This technique has been used to good effect in the classification of complex medical signals (Roberts and Tarassenko, 1992; Pardey et al., 1996). Figure 14 shows example spectra for Tests B and D in loose Leighton Buzzard sand. The spectra have been averaged over a 5 second period using a 10ms frame size. The most noticeable aspect is the difference between the FFT and AR model’s spectra. The FFT’s derived spectra (512 coefficients) is less smooth than that of the AR spectrum (15 coefficients), however the underlying form of the spectra are similar. The AR spectra do slightly differ between the two tests, which is encouraging.
Figure 12: Overview of proposed signal analysis.

Figure 13: Forward and backward linear prediction (after Pardey et al. 1996).
Figure 14: Example power spectra (derived from both FFT and AR models) for two different stress states in Leighton Buzzard sand, placed at a loose relative density.
The key to successful interpretation is to identify good features which characterise the ACPT signal. The features need to provide enough discriminatory information to classify the various signals. The coefficients from the AR model can be thought of as one set of features, which could then be used in conjunction with additional features derived from the time series and the other CPT sensors.

Alternative features could be extracted from the time series, including the signal’s entropy, along with two common measurements which have been used previously for geotechnical problems. These are the Root Mean Square (RMS) voltage, which was the principal measurement investigated by the Berkeley team, and the AE-counts, which records the total counts (of a specified duration) for which the signal exceeded a series of thresholds. As the name suggests, the AE-counts are frequently reported in work on acoustic emissions.

As all the tests for one sand (Leighton Buzzard) will be completed before tests on the others are started, it will quickly become apparent whether there is any noticeable difference between the signals in the database. If the signals sound different to the ear then there is a good chance of being able to discriminate between them. Within the laboratory environment it is quite probable that the different sand types will be easily discriminated, especially as the three sands are very different in composition. If discrimination is possible between all of the controls, then it may be possible to suggest some empirical relationships between the acoustic signal and soil type and parameters. These empirical relationships may then be correlated with field tests, to test their validity.

There is, however, a wide gulf between calibration chamber testing and field testing, the most notable difference being that of soil moisture content (zero in the laboratory, saturated in the field). At present, it is not known to what extent the acoustic signal is affected by moisture, but it is highly probable that it is, as a result of moisture acting as a damper between both tip/sand contacts, and sand/sand contacts. The effect of water damping on signal intensity and frequency content is presently unknown, but it can be expected that some difference in acoustic signal could be expected for a variety of soil types. In fact, it is well known that in the field, personnel conducting a CPT field test can perform some qualitative inference of the acoustic signal by listening to the push rods. The effect of soil saturation on any interpretation of field data, based on the laboratory tests, will cause the model to extrapolate. If a model is extrapolating, then any confidence intervals around a prediction become very large, so as to make the prediction virtually useless (Press et al., 1992).
Present Status

The ACPT has previously been demonstrated to be an excellent profiling tool. However, the interpretation has been mainly qualitative in nature, and it is hoped that this work will put a more quantitative basis to the interpretation, and demonstrate that there is additional information in the acoustic signal that has not previously been used.

To date, a new, prototype ACPT has been designed and built, allowing for the acoustic signal to be captured in addition to the standard CPT signals. The software for data acquisition and analysis has been written. Currently the laboratory testing programme for the creation of a good quality database of acoustic signals has been started, with the ACPT producing excellent acoustic signals.

Once all the laboratory tests on the Leighton Buzzard sand have been completed, it should soon become apparent just how much information can be extracted from the acoustic signal, and how much discrimination is possible between the database tests. Until that point it will not be known whether either the design of the ACPT or experimental programme are adequate or will need to be re-evaluated.

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