Automated analysis of seismic piezocone tests

Henrique F. Bucher
Insitutek Ltd, Rio de Janeiro, Brazil

Alberto R. Ortigão
Federal University of Rio de Janeiro, Brazil

Alberto S.F.J. Sayão
Pontifical Catholic University of Rio de Janeiro, Brazil

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ABSTRACT: This paper presents a method of analysis of seismic piezocone tests. It presents a brief description of the test. Data from tests in the Rio de Janeiro soft clay are presented and analysed. The paper focuses on the automation of the analyses and a dedicated software is then employed leading to a fast analyses and error checking procedure.

KEYWORDS: Seismic piezocone, seismic modulus, field tests.

1 INTRODUCTION

In early 80's Campanella and co-workers (Campanella et al, 1986, 1987, 1989, 1994, Campanella and Stewart, 1992) introduced seismic piezocone tests (CPTUS or CPTS). The main output of this test is the shear wave velocity and the small strain shear modulus G_{max}. CPTS is relatively simple to be carried out in the field and at a marginal additional effort relatively to the piezocone test. The results lead to a direct measure of soil modulus, not a correlation as in many other tests, at a small fraction of the costs of other in situ or laboratory test that give equivalent soil parameters.

At early stages of CPTS test development, the analysis was carried out employing very simple graphical techniques. This was the case of the early stages of this research programme for the tests conducted at a research site in Rio de Janeiro soft clay. Although simple techniques lead to satisfactory results with clear and noiseless signals, the simple method is difficult to apply in a noisy environment.

Therefore, efforts were made to enhance the analysis procedure. This paper describes an automated method of analysis and the results obtained at a few sites in Brazil.

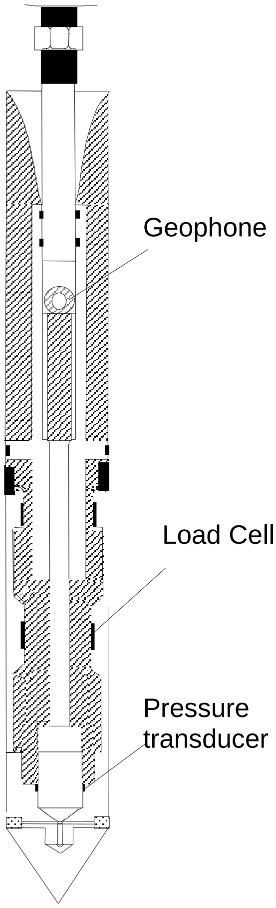

Figure 1 Seismic piezocone

2 TEST METHOD

Seismic piezocone tests are aimed at giving the shear modulus at small (micro) strains. The equipment used (Figure 1) consists of a standard piezocone, 10 cm^2 of cross-sectional area and 60^o of apex angle, in which a small device at the top is capable of detecting the arrival of shear waves. This device can consist of an accelerometer or a geophone (Campanella and Stewart 1992). This paper, however, concentrates on the use of the latter device. The cone includes an on board electronic module capable of amplifying and conditioning signals generated by the transducers. A PC notebook data acquisition system operates in penetration mode and seismic mode. In the first case it measures piezocone standard data and in the seismic mode it receives, digitises and stores the geophone signals at 12 bit resolution and at a highly conservative rate, typically 5 kSamples/s.

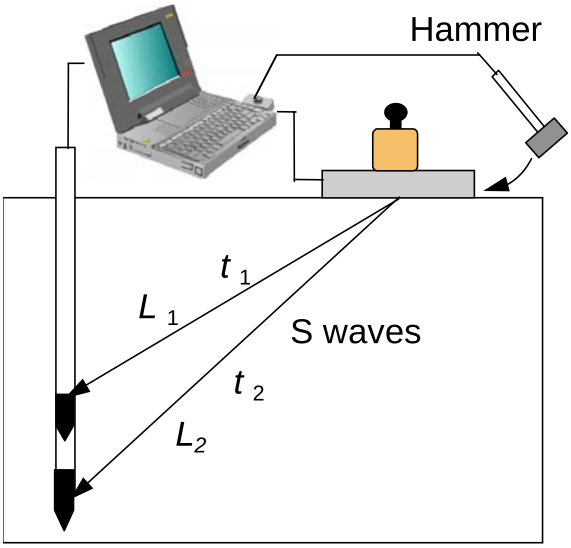

Figure 2 Seismic test

The test is carried out as shown in Figure 2. Shear or S waves are generated at the soil surface by striking a steel plate with a hammer. The steel plate is securely fixed on the soil surface by a heavy weight, which can be the wheel of a vehicle or the site investigation lorry. The hammer is electric connected through a wire to a triggering circuit in the data acquisition system.

The seismic test is normally carried out during cone penetration pauses to add new rod lengths. As the cone is at depth z_i, the strike plate is hit by the hammer and the triggering circuit starts the data acquisition. A signal versus time is obtained at each test depth z_i and corresponds to the arrival time t_i of the shear wave. The shear wave velocity V_s between depths z_i and z_{i+1} is given by

$$V_s = \frac{z_{i+1} - z_i}{t_{i+1} - t_i} = \frac{\Delta z}{\Delta t} \tag{1}$$

The shear modulus G_{max} is then computed by:

$$G_{max} = \frac{\gamma}{g} \cdot V_s^2 \tag{2}$$

where γ is the soil unit weight g is the acceleration of gravity.

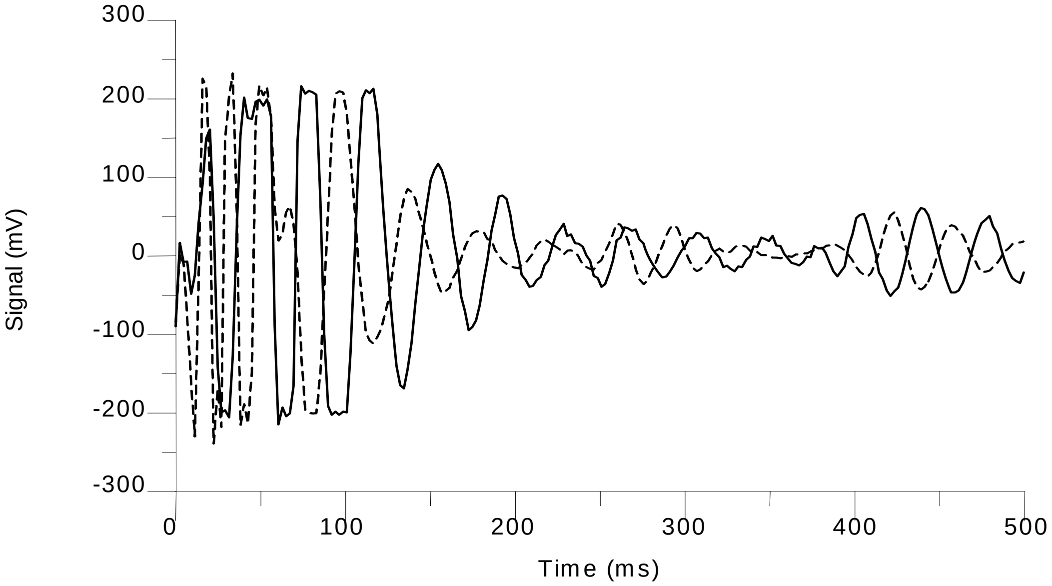

Figure 3 First data series of CPTS tests

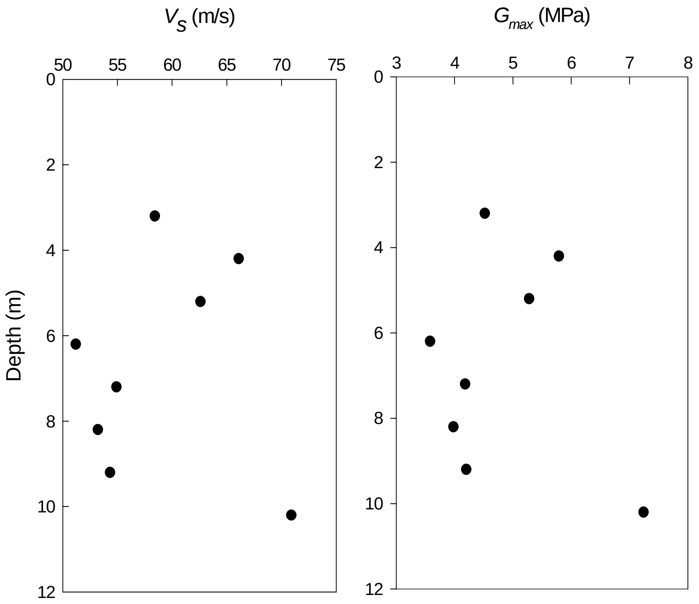

Figure 4 Results of CPTUS tests in Rio de Janeiro soft clay (Sarapui test site)

Small strain G_{max} values can be corrected to the macro-strain domain, which corresponds to most geotechnical engineering applications (*e.g.*, Ortigão et al, 1997), by the use of a single laboratory test or theoretical degradation curves.

2.1 Tests in Rio de Janeiro soft clay test site

The initial stage of testing was aimed at to set up the equipment and to obtain the first results in a soft Rio de Janeiro clay, close to Sarapui River, which properties have been studied since the late seventies (Sayão, 1980, Ortigão et al, 1983, Ortigão, 1995). The details of the equipment and how it was set up were described in detail by Francisco (1996).

Typical signals acquired by striking the plate with a hammer are shown in Figure 3. The time gap between these signals was manually obtained by plotting the signals and graphically determining the time gap between them. This process, however, is very tedious and sometimes can be in error due to noise.

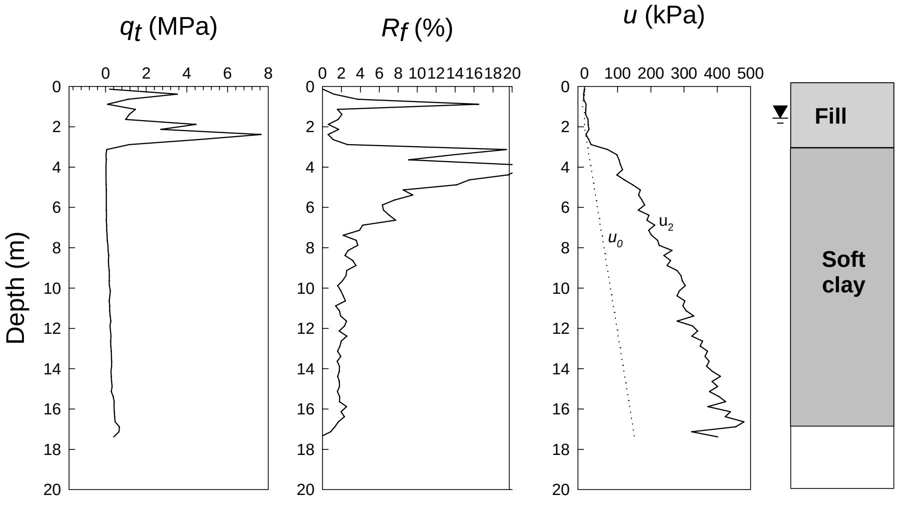

Figure 5 CPTU interpreted profile, São Luiz, Maranhão

The final results of this test series are presented in Figure 4, showing considerable scatter and no information for error checking.

2.2 Second phase of the research programme

The second phase of the research programme was carried out to:

- Improve the quality of the data acquisition system
- Checking the repeatability of signals
- Automate the analysis.

A series of CPTUS boreholes were carried out at a soft clay site near the northern City of São Luiz, Maranhão. Typical interpreted piezocone profile is presented in Figure 5. The plots present the tip resistance q_t, the friction ratio R_f and the porepressure u and the interpreted stratigraphy. It consists of a 3 m thick layer of sand fill followed by soft clay.

Seismic tests were carried out at regular intervals in the soft clay. At regular depth intervals of one meter the plate was hit five times by the hammer and the signals were recorded. The analyses consisted in the application of signal analysis techniques and the results are discussed in the following text.

3 VISUAL INSPECTION

The first stage in signal processing is a check on signal repeatability. This is carried out by visual analysis of all signals at a time in the time and frequency domain. The frequency domain is obtained through Fast Fourier Transform (FFT) analysis. The computer program used by the authors displays both graphs on the PC screen (Figure 6). The user can decide to keep all signals at a certain depth, or to delete an undesired signal.

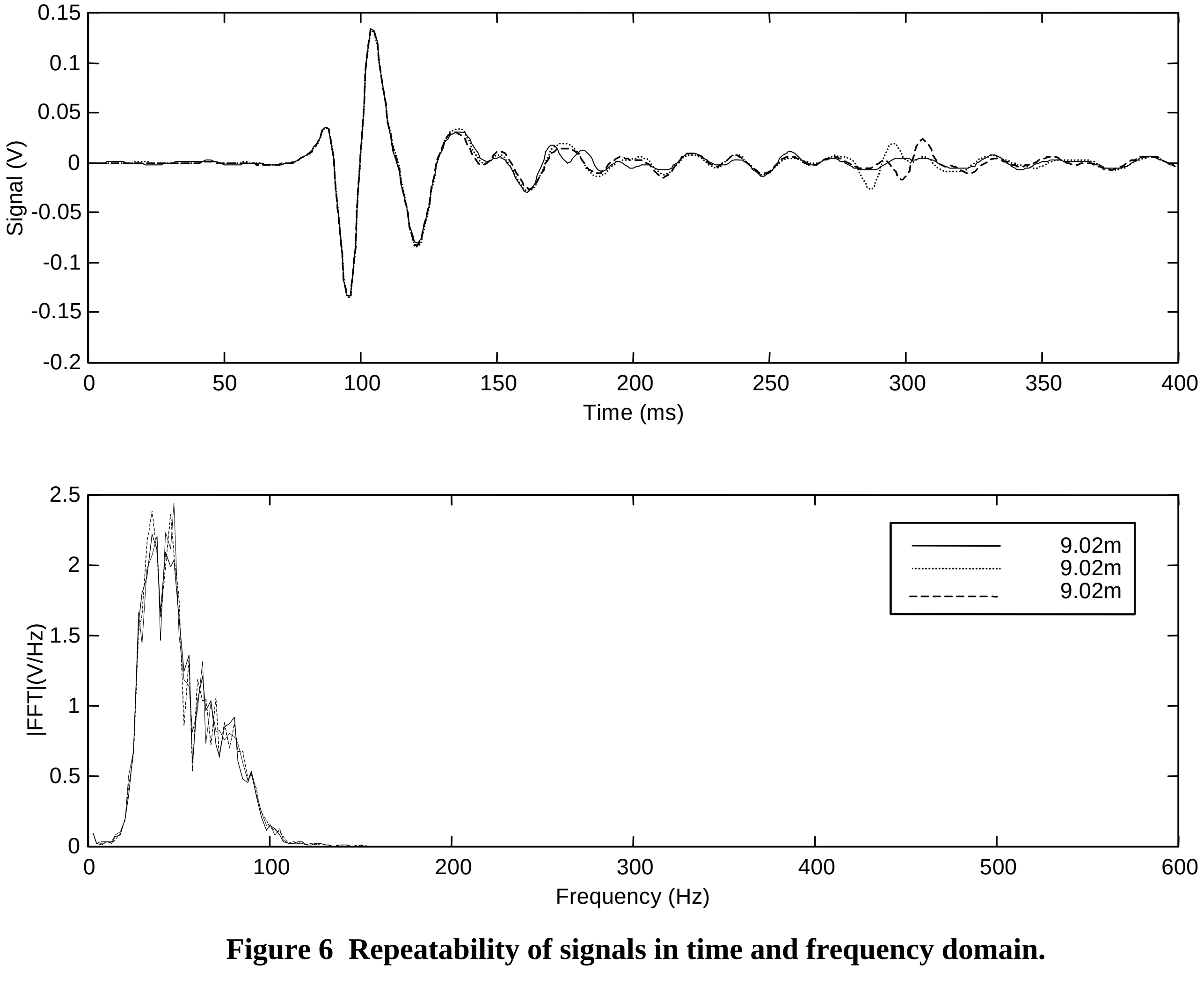

Figure 6 Repeatability of signals in time and frequency domain.

4 ANALYSIS PHASE

Velocity calculations requires the determination of the time gap Δt between two signals at different depths

If the signals are well behaved, graphical analysis and determination Δt is easy. However this is seldom the case. All sorts of unavoidable ambient noise interfere and even the most sophisticated filter technique is not able to make this process easy.

Therefore, a considerable effort was made to automate the process of signal comparison by using a mathematical procedure called *cross-correlation*. It has been used by (Campanella and Stewart, 1994). The cross-correlation ($R_{jk}(\tau)$) of two signals is given by:

$$R_{jk}(\tau) = \int f_j(t) f_k(t+\tau) dt \qquad (3)$$

where $f_j(t)$ is the signal corresponding to the first signal (j^{th} signal) and $f_k(t+\tau)$ is the second (k^{th} signal) which has been shifted in time by an amount of τ milliseconds.

Signal noise presents an important property: its mean tends to present a nil value, implying that the integration of a signal over the range of time will tend to give a nil result. Cross-correlation functions get their robustness from this property. Equation (3) can be optimised by using its analogue form in the frequency domain. This is accomplished by applying the FFT to the signals before obtaining the cross-correlation:

$$R_{jk} = IFFT\left\{FFT\{f_j\} \cdot FFT^*\{f_k\}\right\} \qquad (4)$$

IFFT refers to the inverse transformation, *i.e.*, from frequency to time domain and the asterisk refers to the complex conjugate needed in this equation.

Given two signals $f_j(t)$ and $f_k(t)$, the cross-correlation function $R_{jk}(\tau)$ will show a maximum exactly at the true time gap $\tau = \Delta t$ between these signals (Figure 7).

The analysis of a borehole with N signals $f_j(t)$, $j = 1 \ldots N$, including several signals at the same depth, will result in N^2 cross-correlation functions $R_{jk}(\tau)$, where $j = 1 \ldots N$, $k = 1 \ldots N$. The resulting N^2 time gaps are, then, arranged in a time gap matrix $\mathbf{[T]}_{NxN}$.

5 STATISTICS PHASE

At this phase statistics are performed over the time gaps matrix, what yields a mean time gap vector $\mathbf{\{\Delta T\}}_{N-1}$ and its respective standard deviation vector $\mathbf{\{\sigma T\}}_{N-1.}$ Then, velocities and shear moduli are obtained through equations (1) and (2).

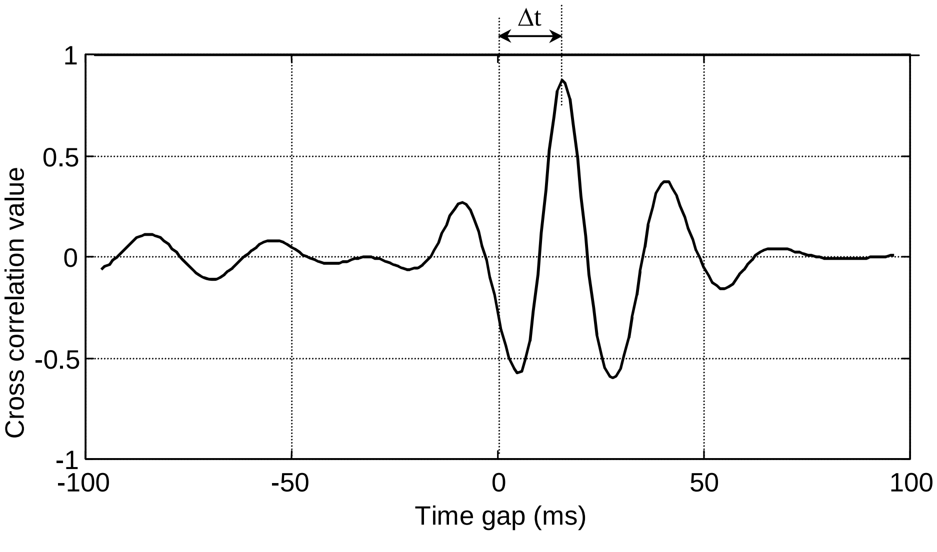

Figure 7 Typical cross correlation function of two seismic signals

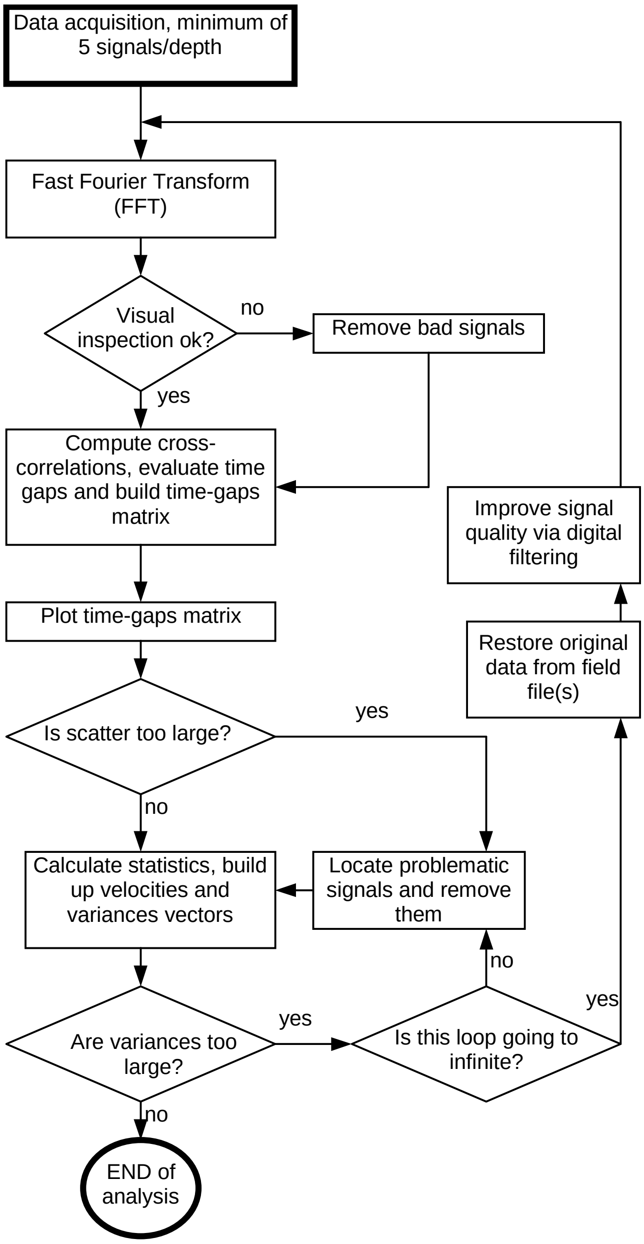

Figure 8 Flow chart of analysis operations

This is not the only form of reducing data. An alternative way is to calculate a "mean signal" by summing point-to-point multiple signals obtained at the same depth (repetitions) and, then, process the calculus of time gaps. This appears to take advantage of the nil mean value property of noise, but this kind of summation makes sense only if a number of blows above 10 is available. For 10 blows the residual error to be added to intrinsic signal variance is 25%, as the Student's distribution prevents. For the minimum value adopted in this research, 5 blows, this error is 70%, what suggests avoiding the use of this approach.

However, statistics can reveal signal problems. If a large set of signals were removed and the results still present high variance, a digital band pass filter designed with a short frequency band (~40Hz) centred at the highest energy peak of the spectra almost often correct the signals. The flow chart presented at Figure 8 summarizes author's experience.

6 RESULTS

The final result of the cross-correlation analysis is shown in Figure 9. Shear wave velocities and shear modulus are presented. The shaded area corresponds to +/- the standard deviation around the mean value, and since it is a quite narrow area, it is an indication of the quality of the results. As part of the output of this research a dedicated PC program called SPAS (Seismic Processing and

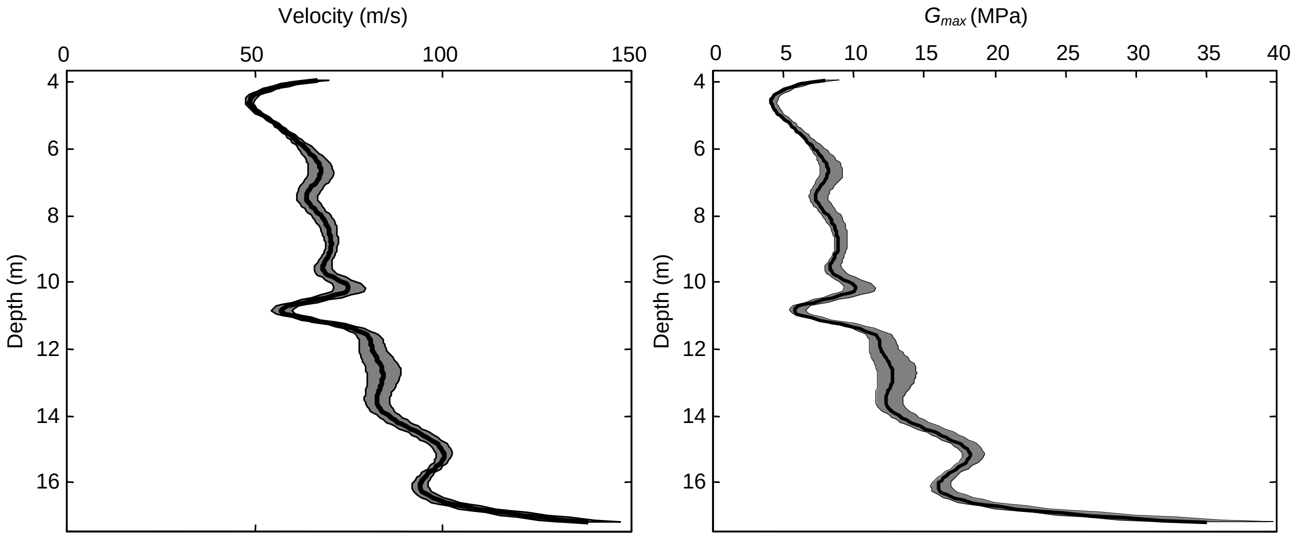

Figure 9 Results from the cross-correlation analysis

Analysis Software) was developed.

7 CONCLUSIONS

Graphical analysis of seismic cone data can be difficult if signals are affected by ambient noise. Automatic analysis employing digital analysis techniques can provide a robust and fast way of obtaining shear wave velocities and shear modulus, which also give indication of data quality.

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