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An Automated System for Measurement of Shear Waves Velocity in Soil

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Abstract − An automated measurement system which aims to improving the method of "Bender Elements" for measurements of soil specimen characteristics is presented in this work. This is a well-known method for the estimation of the propagating velocity of shear waves in soil by measuring the travelling time of these waves. The system developed offers an automated acquisition and signal analysis tool which includes appropriate filtering of the incoming signal, automated identification of certain characteristics of the incoming waveform, automated measurement of the flight time of the signal, and calculation of other parameters in the soil specimen. Full range recording for all data and parameters of measurements, and measuring flexibility by using a wide set of initial parameters is also featured by this tool.

Keywords : *Bender Elements, Shear Waves, Wave Velocity V_S, Data Acquisition, Automated Measurements, LabView Programming.*

1. INTRODUCTION

The term shear waves stands for this kind of waves in which the oscillation direction of the elastic medium is vertical to the wave propagation direction (see also Fig.3). In particular the velocity of shear waves propagation, V_s, is a key parameter used for soil characterization, such as the estimation of small-strain stiffness modulus, liquefaction potential, soil seismic response, assessment of the effectiveness of soil improvement methods used in soils, identification and transportation of pollutants in soils, as well as others [1]. The measurement of shear waves velocity V_s is accomplished either by geophysical tests in the field, or laboratory tests. Among the laboratory tests, two are the most popular for the estimation of V_s: the resonant-column and the bender element tests. The bender element test method was introduced by Shirley and Hampton (1978) and it has been increasingly used recently by research teams in different countries. This paper presents the development of a computerized acquisition and analysis system, based on the bender element method for the measurement of V_s in soils.

2. THE BENDER ELEMENTS METHOD AND THE TESTING ARRANGEMENT

The bender element sensors and actuators are based on piezoelectric effect to generate and receive waves. The source (actuator) is excited by an electrical signal (input), which induces shear waves that propagate through the specimen. The receiver is then submitted to tangential displacements, which are converted to an output electric signal. The input and output electric signals are recorded and the travel time between the source and the receiver is estimated. The shear wave velocity is then determined as

$$V_S = \frac{L}{t} \tag{1}$$

Where L is the distance between the source and the receiver sensor tips and t is the travel time.

In this work the Bender Elements piezoelectritic actuator and sensor were installed at a cyclic triaxial servohydraulic apparatus manufactured by MTS. For this purpose, they were embedded in specially constructed top and bottom platens of the cylindrical specimen (height/diameter: 100mm/50mm). A function generator (Agilent 33220A) was used for the excitation of the source sensor with an electrical signal. An oscilloscope (Agilent 54642A) was used for the display and recording the input-source and output-receiver signals. The function generator and the oscilloscope are connected to a computer via a USB 2.0 and RS-232 connections respectively. Figure 1 shows the testing arrangement used for the measurements.

Fig. 1: Testing Workbench

The type of electrical signal used to drive to the actuator is a sinusoidal pulse of 10 Volts (amplitude) at a frequency of 10KHz [2]. The specific frequency value is the higher-sensitivity frequency value of the frequency response curve of the bender elements. Figure 2 shows example waveforms of the input and output signals respectively as recorded by the experimental system presented in this work. Note that the amplitude of the driving signal is 10V, while the received signal is only a few millivolts. The small level of received signal is an inherent characteristic of shear wave measurements.

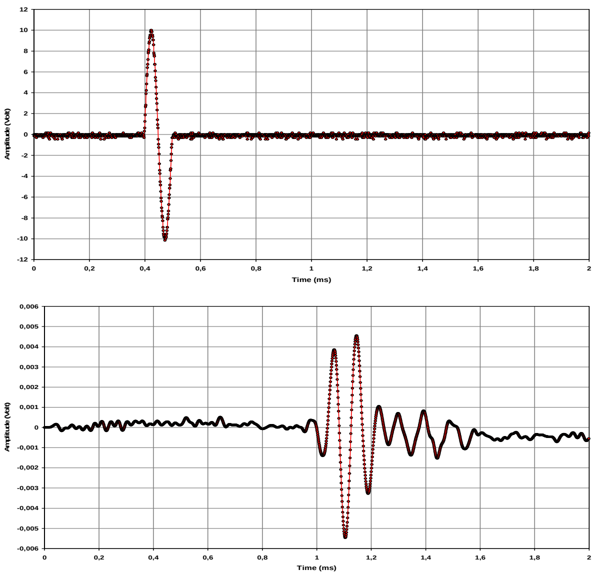

Fig. 2: Example of source and of receiver signals

3. ESTIMATION OF WAVE TRAVEL TIME

The main problem in these measurement conditions is to determine the wave travel time (time-of-flight) in specific experimental setup. Although the time lapse estimation of wave propagation seems to be a simple procedure, there is a major parameter witch affects measurements accuracy and precision. The result of stimulation of bender element source by an electrical signal is not only the expected shear wave but also a longitudinal wave (p-wave) as shown in figure 3.

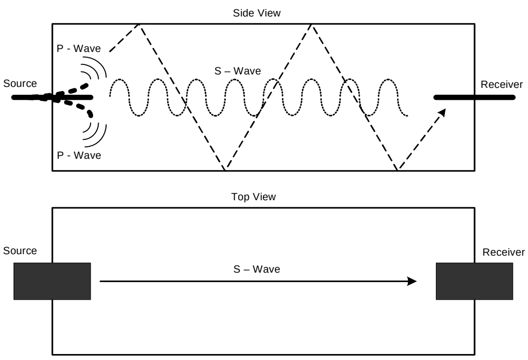

Fig. 3: Near Field Effect

Due to soil specimen geometry the longitudinal wave propagates through the sample and after a sequence of reflections finally arrives on receiver. The previous description it is well known as Near Field Effect [1]. A problem occurs when the reflected p-wave arrives to receiver almost the same time with shear wave. When this happens the receiver signal around the presumable area of wave arrival is the result of all harmonic components of s and p waves making difficult to determine if the first deflection corresponds to s or p wave as one masks the other.

Many studies about near field effect inferred that the possibility of appearance of this phenomenon is high when the sample length L is between ¼ ~ 4λ, where λ stands for wavelength of shear wave

$$\lambda = \frac{V_s}{f} \tag{3}$$

and f is the mean frequency of all harmonic components arrive to receiver. Considering that measurement parameters (as pressure applied to the soil sample) may be change during measuring procedure, the prediction of NFE area is difficult and is always determined after the time lapse estimation as a conclusion and not as a fact.

Back to estimation of wave travelling time (time-of-flight of the signal), the most common method is to identify manually the arrival point at the waveform [2],[3]. Recording the signals of the actuator and the receiver together in an oscilloscope screen is the first step for this measurement. Then the second and most important step for calculating this time interval is to identify accurately the arrival time of the signal to the receiver. This is done automatically by the tool presented here. The starting time at the actuator's side is easily defined and measured. Figure 2 shows an example of such signals during a measurement and Figure 4 represents a typical waveform of receiver signal in

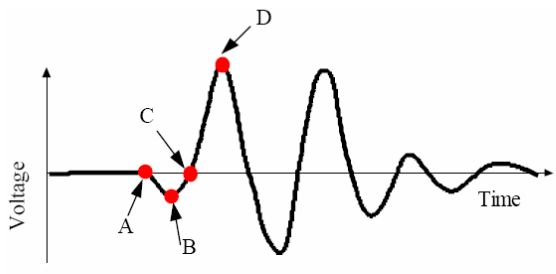

Fig. 4: General waveform of receiver signal

bender elements method. Note also that there is an additional uncertainty about the appropriate arrival point in each case. This is because the arrival point in receiver's signal should be determined as point A, B or C due to NFE presence or not, (or D if we measure time from source's maximum to receiver's maximum) [3],[4]. Experimental tests from our team has also verified the conclusion of other research teams which have showed that point B is the most correct selection for arrival point. This measuring approach is the most popular in bender elements measurements and a simple and fast way to measure wave travel time.

4. THE COMPUTERIZED TOOL

Experimental set up shown in Figure 1 is supported by the computerized tool presented here for an overall control of the measurement process, and it is developed in LabView [5],[6]. This software allows full adjustment of the function generator and oscilloscope measuring parameters, and full control of measuring process. Calculation the shear wave time of flight, using a fully computerized approach for the estimation of the appropriate arrival point at the received waveform is also part of this tool.

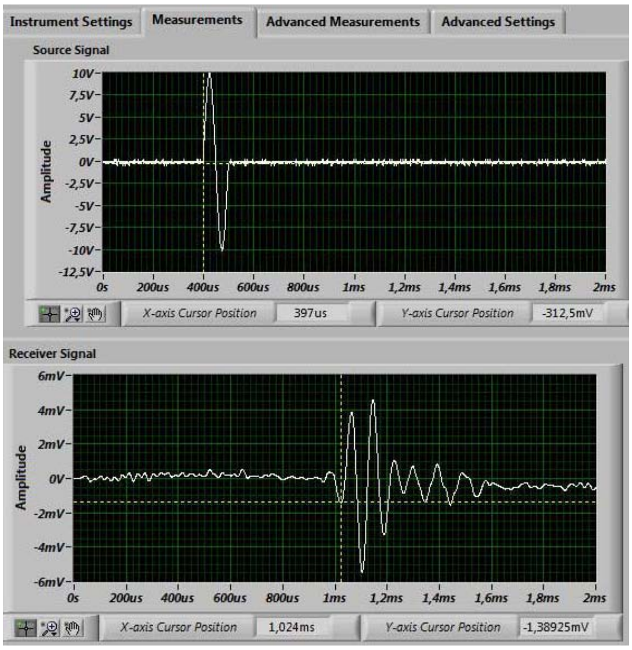

Fig. 5: Virtual Instrumentation Panel: "Measurements" Tab

The user interface of the whole measurements procedure is arranged in different tabs. The user may select the parameters of source signal and define all other measuring settings. The measurement procedure is started by the user once all other conditions of the soil specimen at the servohydraulic apparatus are properly arranged. Then a driving signal of only one period is send to the actuator (as shown in Fig.2) and a shear wave is generated by the actuator in the soil specimen. The oscilloscope records both the actuator and receiver signals and sends data to the interface. The system records both the actuator and receiver signals (Fig.5) and computes the traveling time for point to point technique either automatically by the software or by the user in case certain hand-on experiments are performed. In this later case the user may define starting and arrival points by the cursors provided in source and receiver graph respectively.

The cursor allocation may be done automatically by selecting the "Auto Cursor" option interface provides. Figure 6 shows the auto-cursor procedure in block diagram. For the starting signal, the first maximum point of the waveform is estimated and then the signal is scanned to the left until the starting point of the sinusoidal pulse is allocated.

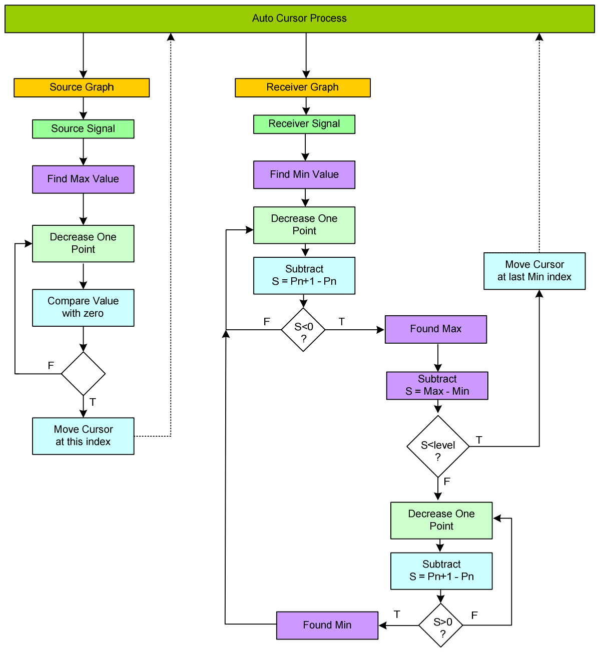

Fig.6: Auto Cursor procedure

For receiver signal, process finds the minimum value and scans the signal to the left until it finds a max, then subtracts min from max, and if the result is less from a defined amplitude level, this point is considered as "point B". If the above level criterion is not met, the routine is repeated for as times as required to allocate the right arrival point. If for signal complexity reasons, "auto cursor" process fails to allocate successfully the right arrival point in receiver signal, automatically a message appears which prompts user to allocate the arrival point manually and measuring process continues. When send and arrival points are defined (automatically or manually) interface calculates the wave travel time in "Time Estimation" indicator field and user may continue to the next measurement.

The precision of wave travel time estimation depends by the horizontal scale selection (Time/Div) in digital oscilloscope. For every measurement 2000 points for each signal of source and receiver are sampled and recorded. Using 10kHz sinusoidal pulse signal we selected 0.2msec/div horizontal resolution. That means 1μs time lapse between two sequential points in source (or receiver) graph. So, for the measurements performed by the automated system the resolution in traveling time estimation is 1μs, which is rather good and certainly enough considering that typical travel time for various soil samples measured between 400 ~ 700μs.

The tool developed includes also the option of filtering the received signal. This signal is usually a low level signal (a few mV only) with high noise level. A low-pass Butterworth filter 10^{th} order with cut off frequency at 40kHz was including in the virtual instrumentation system. With filtering process there is an important improvement on signal distinctness that offers significantly improved accuracy to the identification of the arrival time point in the received waveform, without significant influence from the filter-induced phase delay. Figure 7 shows the same receiver signal before and after filtering.

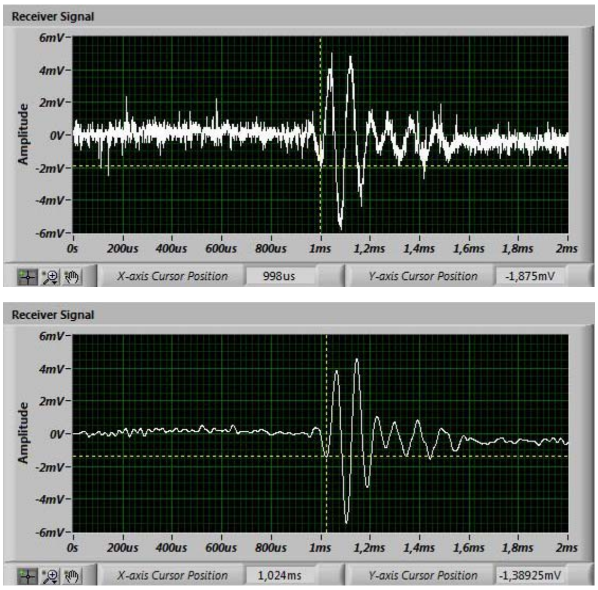

Fig.7: Example of receiver signal before and after filtering

This filtering procedure has been developed using Butterworth coefficients in LabView, and phase-delay is calculated and translated to time-delay. This time-delay is automatically removed from wave traveling time calculations when filtering is active. In addition, time delays for other frequency values around 10 kHz have been calculated. In "advanced settings" tab there is a table for setting time delays for several frequencies. Also the user may set are other major parameters, such as filter's cutoff frequency, filter type, filter order and Auto-Cursor parameters.

All data for each measurement are stored appropriately. Storage options include all the values of the parameters and all measured waveforms and related calculated results for every measurement such travel time and other measuring parameters (Pressure, Velocity, Sample Length, etc).

5. EXPERIMENTAL RESULTS

The whole system has been tested and all above-mentioned procedures are working properly. The above described signal analysis system was used for the measurement of V_S of three different sandy soils, named as A, B and C at Table I where a set of typical experimental results are presented. Measurements of shear waves velocity are performed at three different levels of effective isotropic confining stress (shown as σ_o in the first column of table I). In the second volume is shown the length of each specimen, while in the third is the time interval of the time-of-flight of shear waves. This is actually the measurement result obtained by the system. The wave velocity and other parameters are calculated as shown in Table I. Note that e is void ratio, ρ=soil density, and G is the small-strain stiffness modulus.

Table I. Experimental results for three different types of sandy soil

Type of Sandy Soil	σ'_o (kPa)	L (mm)	**t (μs)**	V_s (m/s)	e	ρ (Kgr/m^3)	G (MPa)
A	53	105,784	**491**	215,45	0,764	1942,3	90,16
	97	105,764	**431**	245,39	0,762	1945,0	117,12
	205	105,730	**371**	284,99	0,759	1948,7	158,27
B	50	106,340	**558**	190,57	0,684	2018,6	73,31
	95	106,326	**474**	224,32	0,679	2024,5	101,87
	190	106,300	**411**	258,64	0,674	2030,8	135,85
Γ	55	107,255	**629**	170,52	0,577	2063,5	60,00
	118	107,238	**507**	211,52	0,575	2065,5	92,41
	208	107,212	**434**	247,03	0,574	2067,1	126,14

6. CONCLUSIONS

An automated system for measurements of soil characteristics and more specifically for the measurement of shear waves velocity Vs was tested for different types soil specimens with reliable results. The automated instrumentation system has improved a well known method for soil characteristics measurements by providing a flexible and automated measuring interface to be used in future research in the field. Research in different time estimation techniques [7],[8] and further experimental verification of the accuracy and precision of the measurement setup developed is ongoing.

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