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Phase velocity approach for Suspension P–S Logging data analysis

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ABSTRACT

Due to the short receiver interval, results of Suspension P–S Logging are sensitive to the picking of first arrivals, which is currently carried out by manual picking in the time domain. However, manual picking can be ambiguous and depends heavily on the data quality and analysts' experiences. Furthermore, no information regarding the effective frequency is obtained from first arrival times. A data reduction method based on phase velocity analysis of borehole acoustic waves is proposed herein. The aim is to provide an automatic procedure for more objective velocity analysis. The procedure utilizes the two-channel dispersion curve analysis, but becomes semi-empirical because an additional assumption is made to simplify the calculation and avoid the phase un-wrapping problem associated with the lack of low-frequency information. Some field data were used to evaluate the empirical parameter for calculating the shear wave velocity. Results show that the velocity difference between the proposed method and the conventional method based on manually-picked first arrivals is mostly within 15%. The proposed method can be automated and provide the effective frequency of the obtained shear wave velocity.

1. Introduction

Evaluation of shear (S) wave velocity in actual field condition has important meaning in many fields of applied and pure geophysics. S-wave velocity (V_s) within several hundred meters of the Earth's surface is essential in specifying earthquake ground motions for earthquake engineering. In smaller scale, it is also important and useful for geotechnical problems, such as site characterization, liquefaction analysis, settlement analysis, and quality control of ground improvement (Stokoe et al., 2004). Methods for measuring subsurface V_s can be divided into two major groups: non-invasive surface methods (e.g., surface wave method and seismic refraction method) and invasive borehole methods (e.g., down-hole method, cross-hole method, and Suspension P–S Logging) (Stokoe et al., 2004; Boore and Asten, 2008). While non-invasive surface methods are advancing and gaining popularity, direct measurements of waves in boreholes by logging remain to be the most effective means. Among the borehole methods, the Suspension P–S Logging is efficient and advantageous in that it only requires one borehole (uncased or PVC cased) and its measurement depth can be up to more than 200 m without losing its spatial resolution and signal strength. The Suspension P–S Logging system is a velocity logging system based on the principles of unlocking type receivers and indirect excitation type sources (Kitsunezaki, 1978; Kitsunezaki, 1980; Ogura et al., 1980). Since its invention, it has been increasingly used in geotechnical engineering for shallow depth investigation (Diehl et al., 2006; Boore and Asten, 2008; Biringen and Davie, 2010). More recently, other more advanced sonic well logging methods have been developed for deeper applications in oilfield (Arroyo Franco et al., 2006). However, these advanced tools have not been adapted for shallow and smaller diameter boreholes and made readily available for engineering applications. The Suspension P–S Logger has accumulated tremendous amount of experiences in the past 20 years and continues to be a popular tool for seismic microzonation and other geotechnical engineering studies.

In a Suspension P–S Logger, a non-symmetric seismic source and two receivers spaced 1 m apart are built into a single probe suspended by a cable. The source exerts pressure on the borehole wall via borehole water and the pressure wave is converted to seismic waves (P and S) at the borehole wall. The propagation of P wave and S wave along the wall is measured by detecting the behavior of the borehole water through receivers (a combination of hydrophone and geophone) of floating type. In this study, we focus on S wave since it is most relevant in earthquake and geotechnical engineering. The elapsed time between arrivals of the waves at the receivers is used to determine the average velocity of a 1-m-high column of geomaterials around the borehole (Ohya, 1986; Nigbor and Imai, 1994). Currently, the data reduction of Suspension P–S Logging is based on the travel-time analysis by manually picking the first-arrival times of the seismograms (i.e. by visual inspection of the amplitudes and waveform changes). The estimated shear wave velocity is subjective, particularly in noisy data, and very sensitive to the picked arrival times because the two receivers are only 1 m apart. When large amount of seismograms is involved, picking of first arrivals is time-consuming and the uncertainty of V_s estimation can be very large.

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Several automatic first break picking methods were proposed to increase the efficiency of data processing, such as STA/LTA method (Anderson, 1978; Earle and Shearer, 1994), Akaike Information Criterion (AIC) method (Maeda, 1985; Zhang et al., 2003), Artificial Neural Network method (Zhao and Takano, 1999), and Modified Energy Ratio method (Wong et al., 2009). However, in the context of Suspension P–S Logging, none of them is practically robust and large bias from the desired picks is often encountered. Most techniques work in the time domain to determine the transition between noise and noise plus signal by detecting rapid changes in a certain attribute (e.g. energy ratio, entropy, and fractal dimension). The spectral characteristic of the signal is not considered and the effective frequency of the measurement is unknown.

In the Suspension P–S Logging, the ultimate goal is to obtain the S wave velocity from each paired measurement. In this study, we proposed a new approach based on phase velocity analysis of borehole acoustic waves. The aim was to provide a somewhat automatic procedure that avoids determining the onset of the first break and achieves more objective velocity estimation. First the fundamental of Suspension P–S Logging and characteristics of borehole acoustic waves are examined. Then the procedure based on the two-channel dispersion curve analysis is introduced. The validity of the proposed approach is investigated using some field data.

2. Suspension P–S Logging

The principle of suspension S-wave logging was first introduced in Kitsunezaki (1978, 1980). It dwells upon the working of an indirect-type source effective in radiating shear wave and suspension type receivers of neutral buoyancy. A common available system is shown in Fig. 1. The system consists of a source, a pair of receivers, and a winch unit. The source is connected to the two receivers with a rubber tube in between and suspended by a cable lowered by the winch. It can operate either in un-cased or in PVC-cased borehole but must be in fluid-filled condition. In its early developments, the source was designed to effectively radiate only shear waves while minimizing radiation of P waves. The force is applied to a borehole wall indirectly by producing pressure changes of plus and minus in front and rear sides of the impact body in motion, resulting in indirect excitation on the borehole wall through consequent water motion (Kitsunezaki, 1978, 1980). To increase the radiation power and allow generation of P wave as well, current Suspension P–S Logging system uses fixed solenoid coils to drive a metal hammer to strike the inner surface of a thin walled cylindrical sleeve surrounding the sonde body, sending a pressure pulse out into the borehole fluid (Tanaka et al., 1985). After the probe is lowered to the specific depth for testing, the solenoid source generates a pulse (typically several hundred Hz to a few kHz) and the propagating waves are received by the lower and upper receivers spaced 1 m apart. Each suspension type receiver is composed of a two-directional horizontal geophone and a hydrophone. It detects horizontal motion of the borehole wall (ground motion of shear wave) through corresponding water motion. The seismograms from the horizontal geophones are used for S-wave velocity analysis. To facilitate shear wave identification, a reversed pulse is generated to produce another set of seismograms with a 180 degree phase difference. The S-wave velocity is determined by the time difference between the arrivals of shear waves at the upper and lower geophones.

3. Waves in a fluid-filled borehole

The wave field generated in a Suspension P–S Logger was treated approximately as that of a point single force in an infinite homogeneous medium, if the wavelength is much longer than the borehole diameter (Kitsunezaki, 1980). However, the acoustic waves in a borehole are actually quite complex, depending on the energy source and the properties of the formation and the borehole (Haldorsen et al., 2006). When a monopole source is used, the transducer produces spherically symmetrical outgoing compressional waves in the borehole fluid, which in turn excite P and S head waves in the formation. According to the Snell's law of refraction, the shear head waves generated as shear waves traveling up the borehole are only measurable in fast formations, in which S-wave velocity of the formation is higher than the fluid velocity. In addition to body waves, the interface (or surface) wave, known as Stoneley wave appears in nearly every monopole sonic log. Its speed is slower than the S wave and fluid velocity, and it is dispersive, which means different frequencies of Stoneley wave propagate at different speeds. In order to measure S-wave velocity in slow formations (with S wave velocity lower than the fluid velocity), a dipolar source is used to displace the borehole wall horizontally to generate shear waves. Arriving with shear waves, and spreading out behind it, is the dipole-

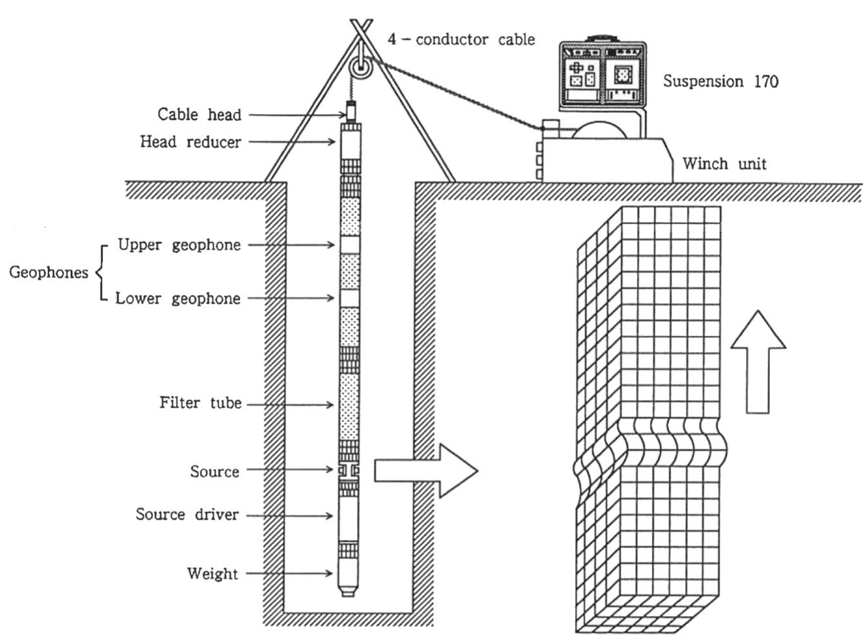

Fig. 1. Schematic of the Suspension P–S Logging system (O.Y.O. (1998)).