Towards the development of a standard for the PS suspension logger

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ABSTRACT

The PS logger is a well-established seismic tool for measuring P and S wave velocities in a single borehole, using low frequency indirect excitation originating from a dipole source. Because of its low operating frequency, it is capable of generating seismic waves in slow, unconsolidated materials such as those found in offshore environments where S wave velocity is often used to estimate the small strain stiffness, G_{max} (of particular interest to offshore construction). Despite its widespread use, there is no current standard for the use of the PS logger, even though other methods operating on similar principles have well-established reference methodologies and guidelines. As such, PS logger methodology is largely dictated by user manuals written by manufacturers, which likely introduces inconsistencies in operation guidelines, and may impede consistency in data obtained by different users. In this paper, the authors conduct a literature review of existing standards for relevant methods including CPT, SPT, SCPT and downhole and crosshole seismic testing, as well as relevant ground investigation standards, identifying the need for standardisation of the PS logging method. Examination of the current state of standardisation concludes that although existing seismic testing standards could possibly be expanded to include the PS logging method, the differing constraints and operational requirements are such that the development of a specific PS logger testing standard is highly recommended. An initial framework is presented for a PS logger standard, identifying the required components, in terms of borehole requirements, testing procedure, data interpretation and best practice.

Keywords: sonic logging; suspension logging; PS logging; flexural wave; acoustic dipole; standardisation.

1. Introduction

1.1. Small strain stiffness moduli

In recent years, the expansion of onshore and offshore construction has seen an increase in demand for geotechnical investigation in order to better understand the dynamic behaviour of soil. In particular, estimation of small strain stiffness, G_{max}, has grown in importance, because of its relevance to offshore windfarm (OWF) construction.

Broadly, methods to resolve G_{max} can be categorised as either direct (physics-based) or indirect (based on empirical correlation relationships). Seismic methods can be deployed to resolve the shear wave velocity, V_s, which, combined with the formation density, ρ, directly yields the shear modulus, G, which is largest at low strains (Eq. (1)).

$$G = \rho V_s^2 \quad (1)$$

In in situ seismic tests, the shear strain amplitude is generally very low (of the order of 10^{-4} %), therefore, the equation takes the form of Eq. (2) (Campanella et al. 1986).

$$G_{max} = \rho V_s^2 \quad (2)$$

Indirect methods for obtaining shear velocity information (and hence G_{max}) are based on empirically-derived correlation relationships and include CPT and SPT, which are subject to varying degrees of international standardisation. Several different seismic test types exist for directly obtaining shear velocity data, including sonic logging methods (including PS suspension logging), Seismic Cone Penetration Test (SCPT), downhole and cross-hole seismic methods. With the exception of the PS logging, all of these methods are subject to some degree of international standardisation, however, despite widespread use, the PS suspension logger (more commonly known as the PS logger) is not standardised in any way, although it is referred to in mainstream ground investigation standards such as the UK Specification for Ground Investigation (the "Yellow Book") (AGS 2022) and the Offshore Site and Investigation and Geotechnics Committee's (OSIG) Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Offshore Renewable Energy Developments (OSIG 2022). This lack of standardisation likely introduces inconsistencies in operation guidelines and may impede consistency in data obtained by different users. Therefore, it is incumbent that a suitable standard for PS logging is developed and adhered to.

1.2. Sonic logging

The propagation velocities of body waves in a medium are a complex function of several factors, including density, porosity, and mineralogy (Rafavich et al. 1984). Sonic logs allow measurement along a borehole, activating an acoustic source operating within a frequency spectrum which then excites waves in the surrounding formation (Wang et al. 2022) of wavelength λ determined by Eq.3, where f is a given frequency within the source spectrum, and V is the velocity of the generated wave.

$$V = f\lambda \quad (3)$$

The concept of sonic logging was developed by Schlumberger in the early 20th century (Schlumberger, 1935), and described a rudimentary acoustic transmitter (above the surface) and two receivers (suspended in the borehole), used to measure the difference in travel time of a seismic signal between two receivers. At the time, however, technology was not advanced enough to perceive very small acoustic travel time differences. Subsequently, improvements have been made, particularly in terms of acoustic transmitters and receivers, and sonic/acoustic logging is now widespread as a means of developing velocity-depth profiles of the subsurface, using suspension-type loggers. The term "suspension" refers to the fact such tools, along with the source and receivers, are suspended in a borehole, in contrast, for example, to some seismic methods which use ground-based sources and/or receivers e.g. downhole seismic (detailed in section 3) or Multichannel Analysis of Surface Waves (MASW, see Park et al. 2007).

Traditionally, tools have been fitted with monopole sources which emit a radially symmetrical sound wave in all directions within the borehole fluid (Kurkjian and Chang 1986). These tools rely on refraction at the critical angle to generate a shear wave which propagates parallel to the borehole wall, however, this system fails in slow formations as there is no critically refracted shear wave (Kurkjian 1986). In order to mitigate this issue, dipole-type tools were developed by the oil industry which generate the flexural or bending wave mode, which, at sufficiently low frequencies, travels at the formation shear velocity. Tools for oilfield applications are rigid and very long, however, for geotechnical applications the PS logging method provides a flexible alternative (Mari and Vergniault 2018).

1.2.1. PS Logger

Terminology - There is some historical inconsistency in the industry regarding the terminology used: academics will likely be most familiar with variations on the term PS suspension logging, using the PS suspension logger, and historically, the method has also been referred to as PSL, PSSL or simply suspension logging. In recent years, industry parlance has converged, adopting the term PS logging, therefore, for the purpose of developing a standard, it is suggested that the term PS logging be used. The terms PS Logger® and PS Suspension Logger® are registered trademarks of Robertson Geo.

The PS logger (Fig. 1) is a sonic logging tool, with principal features comprising a dipole hammer source (i.e. transmitter) separated from two receivers by acoustic filter tubes, deployed within a fluid-filled borehole. The seismic source emits a dipole signal, by means of an internally mounted solenoid-operated shuttle set within a steel cylinder. Firing causes the shuttle to strike the inner surface of the cylinder (see Fig. 2), constituting a uni-axial force which indirectly excites the borehole fluid, exciting both P and S_f (flexural) waves along the borehole in both fast and slow formations. Separate measurements are made in two horizontal directions (positive and negative x-directions), producing flexural modes 180˚ out of phase (as shown in Fig. 3). The source centre frequency is at approximately 1.5kHz (Robertson Geo 2023), avoiding the need for dispersion correction (Schmitt, 1988). Acoustic filter tubes are fitted between the source and the near receiver, rendering the recorded signal more coherent and separating out the compressional (P) and flexural (S_f) wave arrivals. The standard filter tube length is 1m, however a 2m filter tube may instead be inserted if greater separation is required between the two principal arrivals. The PS logger is fitted with hydrophones and geophones, which are configured to measure P and S_f (flexural) wave velocities, respectively.

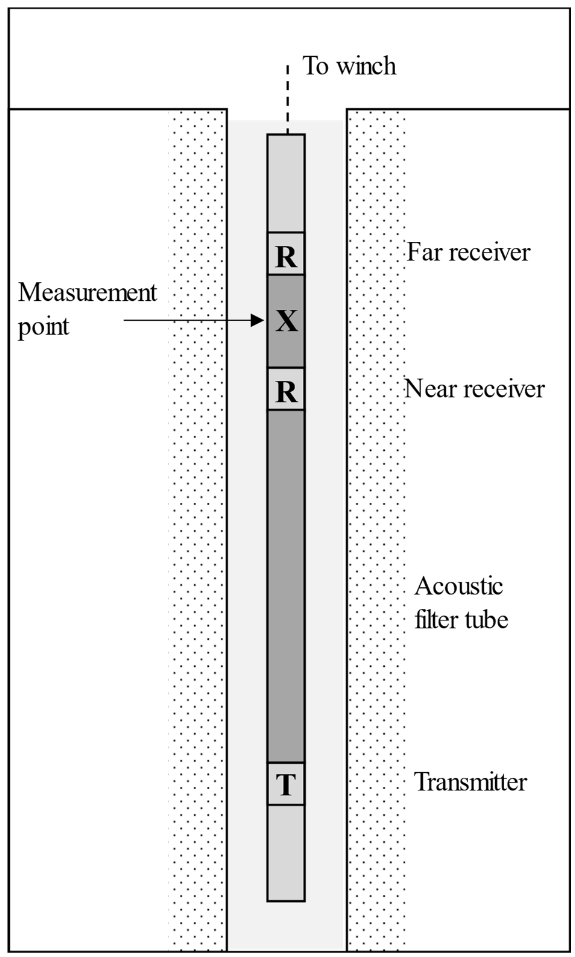

Figure 1. Basic schematic of PS logger. Note, near and far receiver stations comprise geophones and hydrophones.

The PS logger cable is connected to a winch (Fig. 1), where the specific operational setup is dictated by the testing environment (onshore or offshore). A data cable connects to the operational software.

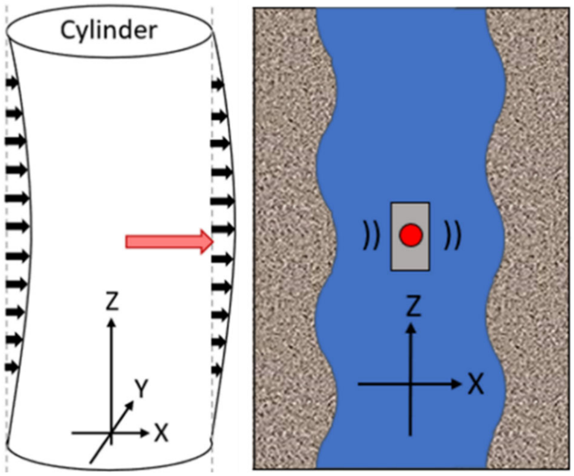

Figure 2. Illustration of flexural mode.

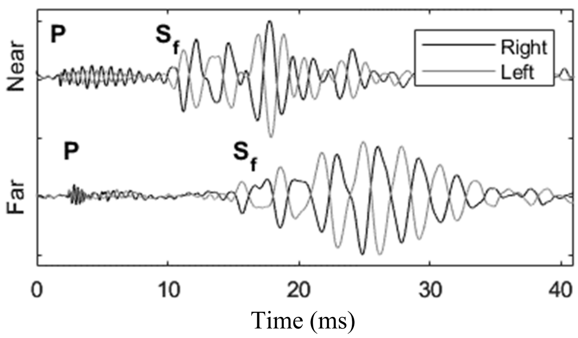

Figure 3. Example waveforms recorded at near and far receivers, on the geophone channels. Note arrival of both P and S_f waves. Time signals from both right and left hammer shorts are displayed, demonstrating out-of-phase behaviour. Data shown was captured in a slow formation ($V_s \approx$ 220m/s)

2. Scope

This paper concerns the development of a framework for the PS logger, considering all pertinent reference literature pertaining to the standardisation of relevant tools. This framework concerns the deployment of PS suspension-type loggers, both offshore and onshore for geotechnical information purposes. Oilfield applications are beyond the scope of this paper. Although general borehole practice is considered in this paper, it is not considered within the development of the PS logger standard framework.

3. Assessment/compilation of relevant standards

In the following subsections, standards pertaining to relevant in situ methods are summarised, highlighting their relevance to a PS suspension logger standard.

3.1. General borehole practice/guidelines

In general, minimal specification is given when logging engineers are contracted to undertake PS logging. Occasionally, engineers are referred to general borehole logging practice documents, including ASTM D5753-18 (Standard Guide for Planning and Conducting Geotechnical Borehole Geophysical Logging) and BS7022:1988 (Guide for geophysical logging of boreholes for hydrogeological purposes). Both standards are applicable to PS suspension logging, in so far as they are applicable to acoustic velocity logging. Both the aforementioned standards are relatively generic in nature, and state that individual procedures must be followed for specific logs, invoking the diverse nature of logging applications and methodologies. Common themes between the standards include general logging procedures, calibration and standardisation of logs, importance of accurate documentation and meticulous planning and data considerations.

3.2. CPT and SPT

The cone penetration test (CPT) involves measurement of the resistance of a cone-shaped penetrometer, advanced into the ground at a constant rate. The cone may be either electronic (friction cone or a piezocone, see ASTM D5778-20) or mechanical (see ASTM D3441-16). Due to the fact that both methods involve inserting the rod into the subsurface, the testing procedures understandably have little relevance to PS logging which involves a pre-bored hole. Both standards provide relevant but generic information such as units and significant figures, but information on terminology, apparatus, hazards, calibration is of limited transferability to PS logging due to the inherently different nature of the methods.

The Standard Penetration Test is covered in ASTM D1586/D1586M-18 describing the method for measuring the penetration resistance of soil to a 50mm diameter sampler driven over a 0.45m drive interval. Rotary drilling methods are used to drill to the test depth (usually at 1.5m intervals), and the number of blows required to advance the prescribed distance are recorded. In terms of relevance to the PS logger, there is some transferable information, but again, limited in substantiality due to the radically different nature and implementation of the method.

3.3. SCPT

Electronic CPT methods may have a seismic sensor included, constituting the seismic CPT (SCPT) method, where the sensor is paused (usually at 1m intervals, Robertson et al. 1986) so that a seismic test may be carried out. SCPT are used widely onshore for geotechnical applications, but for which there is no specific standard. Brief reference within ASTM D5778-20 (electronic CPT) does not provide any further detail on the method but references the ASTM for downhole seismic methods (ASTM D7400/D7400M-19), which does provide some information on procedure, but is limited given that the SCPT involves a completely different test setup than does the downhole seismic test. The most applicable information is to do with data interpretation in terms seismic wave trains.

Some information on SCPT is available from the UK Specification for Ground Investigation (the "Yellow

Book") (AGS 2022), which states that geophones must be mounted in x, y, and z directions (i.e. triaxial geophones).

3.4. Downhole and crosshole seismic methods

Generally, neither downhole nor crosshole seismic methods are deployed offshore, whereas PS logging methods are applicable both on and offshore. Compared to the methods detailed above, the PS logging method has the most in common with the downhole seismic test, given it is a seismic test, performed in a single borehole. Key differences are that the downhole method involves a surface-mounted seismic source which generates polarised shear waves, and a non-suspended receiver system (either one or two receivers clamped to the borehole wall). Some of the more general information in ASTM D7400/7400M-19 is transferable to PS logging, including the significance and use (onshore only) of the method, and some of the data interpretation guidelines. Procedurally, there are key differences due to the inherently different natures of the tests, and information regarding energy sources has little to no applicability to PS logging on account of the fact that downhole seismic methods generate a polarised shear wave, rather than exciting the flexural borehole mode. For these reasons, and because multiple boreholes are required, the crosshole seismic test (ASTM D4428/D4428M−14) has even less applicability to PS logging.

3.5. Dipole sonic logging tools

As stated previously, oilfield tools are beyond the scope of this paper, however, it is pertinent to comment that dipole tools such as Schlumberger' Sonic Scanner tool (Schlumberger 2005) operate on the same principle of the excitement of the flexural borehole mode, but are more complex and diverse in nature than the PS logger, as such tools may have both monopole and dipole (or cross-dipole) sources, multiple receiver arrays, variable frequency spectra, and several operating modes. Like the PS logger, these tools enjoy widespread use (oilfield applications rather than geotechnical), yet are largely unstandardised, with operation guidelines dictated by manufacturers (e.g. Schlumberger).

3.6. Summary and relevance to PS logger

From the above, it is plain that more guidance exists for other geophysical and geotechnical tools than for the PS logger, despite its increasingly widespread use both onshore and offshore. In general terms, the PS logging method has most in common with the downhole seismic method (single borehole, seismic test run at incremental depths), which is not generally used for offshore applications, and which is very different procedurally (polarised shear energy source, non-suspended tool). Although other dipole tools exist, these have different applications and are far more complex than the PS logger and are similarly unstandardised. Given the diversity of oilfield dipole tools available, the PS logger is the simplest example of a dipole seismic tool, and therefore, it makes sense that a PS logger standard is developed in the first instance.

4. Initial framework for PS logger standard

The following section presents an initial framework for a PS logger standard, considering the essential components necessary for inclusion. Given the lack of relevant standards, this framework is largely based on the Robertson Geo PS logger manual (Robertson Geo 2023). For each heading, a summary of the types of information to be included is given and is loosely based on the format of the ASTM standards.

4.1. General information

Including scope, overview of method, principle of measurement, significance and use, terminology, units, significant digits, symbology, referenced documents.

4.2. Borehole specifications

4.2.1. General

Including recommended separation between boreholes, statement regarding preference for open boreholes over cased boreholes, and necessity for fluid-filled boreholes. Suggested drilling method.

4.2.2. Geometry

Typical ranges of borehole depths but no maximum depth limit. Recommended borehole diameters, with explanation that borehole diameters must be large enough to accommodate the tool and allow smooth vertical movement between measurement depths. Explanation that deepest possible measurement is dictated by probe geometry and borehole depth (measurement depth considered to be at the midpoint between the two receivers).

4.2.3. Grouting and casing requirements

Consideration of reduced borehole diameter when grouting/casing are present, casing material requirements (PVC), importance of proper installation and grouting, best practice for grouting procedure, grout density specifications. Explanation of problems caused by improper grouting/casing.

4.3. Apparatus

4.3.1. Overview

Detailed schematic of the PS logger, showing all probe sections and all of the components which are detailed further below.

4.3.2. Energy source

Specification of dipole source: uni-axial force applied indirectly via borehole fluid, exciting flexural borehole mode. Recommended operating frequency range for avoiding necessity of dispersion correction. Description of typical solenoid-operated hammer, and merit of capacity to record measurements 180˚ out of phase.

4.3.3. Receivers

Two receiver stations for measurement of difference in seismic arrival times, suggestion of both hydrophones and geophones for measurement of compressional and flexural waves, respectively.

4.3.4. Acoustic filter tubes

Explanation of role of acoustic filter tubes, material and geometry specifications.

4.3.5. Additional

Including telemetry, recording system, winch and software. Specifications and overview of requirements.

4.4. Test method

4.4.1. Free pipe test

Instructions for undertaking a probe-response test, within steel casing of known compressional wave velocity, as a means of field-calibration.

4.4.2. Planning

Guidelines for planning a borehole run, starting at the deepest measurement location. Required information including datum level, typical depth interval. Explanation of necessity for liaison with other practitioners (e.g. drilling engineers) for consideration of potentially unstable subsurface conditions, likely to result in the borehole being logged in sections. Guidelines for planning multiple runs.

4.4.3. Test instructions

Guidelines on how to select appropriate test parameters by initial borehole testing, including sample rates (dependent on formation velocity), gains, filters and shot pulse width. Detailed instructions of all aspects of the test procedure.

Offshore considerations - Specific considerations for deployment of the PS logger offshore: instability of open holes, heave compensation, mitigation of low frequency wind noise and other sources of vibration.

4.5. Data interpretation

Guidelines for data interpretation, showing schematics of typical waveforms showing compressional and flexural arrivals. Suggestions for signal processing in order to aid data interpretation.

5. Discussion

PS logging is used widely both onshore and offshore, and is an integral component of geotechnical surveys, particularly given its success in resolving G_{max}. It offers significant operational advantages when deployed offshore on heave compensated, dynamically positioned drillships as it is the only seismic method that does not involve the complications associated with an external source. Its widespread use is evidenced by its inclusion in geotechnical and offshore investigation reference texts (AGS 2022, OSIG 2022), yet there is a surprising lack of standardisation of the test method.

In general, the only specification given to industry PS logging engineers are generic in nature, and describe borehole practice, such as ASTM D5753-18 (Standard Guide for Planning and Conducting Geotechnical Borehole Geophysical Logging). Although some components of the downhole seismic method standard (ASTM 7400/7400M-19) are transferable to the PS logger, procedurally, the methods are very different, given that the former involves a ground-based source, and a fundamentally different source/receiver configuration (non-suspended, with variable source/receiver separation). Specifically, any PS logging standard must include detailed specifications for the seismic energy source, which differs significantly from sources used in other standardised methods. Given that the PS logger is frequently deployed both onshore and offshore, any such standard would necessarily address both environments.

Concerning the standardisation of the method, it is pertinent to consider whether it should be included in an existing standard or whether a specific standard is more appropriate. Within onshore geotechnical investigation practice, SCPT is also commonly used and has similar status to PS logging within geotechnical practice manuals (e.g. AGS 2022) but is subject to some degree of standardisation within the downhole seismic method test standard, ASTM D7400/7400M-19. Given the inherent difference in implementation between SCPT and downhole seismic (no borehole versus borehole), it is unsurprising that little detail on the SCPT method can be conveyed within a standard describing the downhole seismic method. Although PS logging arguably has more in common with the downhole seismic method than does SCPT (given it is deployed within a borehole), the procedural differences are significant, and as such, it would be better suited to a method-specific standard. The PS logger is functionally similar to oilfield dipole tools, but cannot be considered in any such standards, as no such standards currently exist. Given its simplicity compared to oilfield dipole tools, it makes sense to develop a standard for the PS logger in the first instance.

The previous section presents a basic framework of essential components to be included in a standard for the PS logger and is in no way exhaustive but does provide a solid basis for the development of a PS logger standard.

6. Conclusions

Given the PS logger's widespread use both onshore and offshore, the lack of standardisation of the method is notable. A review of relevant standards pertaining to other geotechnical and geophysical investigation techniques has established that there is relatively little in the way of transferability of existing standards to PS logging. Although current standards (e.g. downhole seismic method) could conceivably be expanded to include PS logging, differences in procedure, application, and implementation are such that a method-specific standard is warranted, a basic framework for which has been presented in this paper. If an eventual PS logger standard were to be developed and adopted, it would likely improve the quality of data obtained by users, and lead to greater recognition of the method within an expanding industry.

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