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A confidence classification scheme for P and S suspension logging data

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ABSTRACT: P- and S-wave velocities are used as input for key parameters for offshore foundation design, such as small strain shear modulus, and as input for enhancement of ultra-high resolution seismic (UHRS) reflection data, such as UHRS-derived cone resistance. P and S suspension logging (PSSL) is a common borehole geophysical logging technique performed for offshore geotechnical site investigations to derive these velocities. Recorded data acquired by PSSL require processing to derive interval velocities within a formation by determining arrival times of acoustic waves of interest at both receivers on the logging tool, i.e. arrival time picking of a trace pair. Recorded traces may be influenced by ground, borehole, and metocean conditions, as well as other factors which can affect interpretability. This paper presents a confidence classification scheme for PSSL data, whereby traces are manually assessed on the confidence of their interpretation. The classification scheme consists of four confidence levels: high, medium, low, and insufficient. A class is assigned at each test depth for each acquired wave type: P-, S1-, and S2-wave. Four criteria are used for class determination: (1) first arrival visibility, (2) noise impact, (3) polarized behaviour (S-waves only), and (4) velocity repeatability. Trace data assessed as insufficient confidence are not considered for velocity processing. This classification approach has provided a practical framework for over 3000 test depths.

Keywords: P and S Suspension Logging, Classification, Confidence, Signal Quality, Borehole Geophysical Logging

1 INTRODUCTION

Compression (P) wave velocity (v_p) and shear (S) wave velocity (v_s) are physical quantities of particular interest in the context of offshore foundation design as they serve as inputs for key parameters, such as the small strain shear modulus (Masters et al., 2019). Moreover, these acoustic velocities can be used for other applications, for example as input for the enhancement of ultra-high resolution seismic (UHRS) reflection data, such as UHRS-derived cone resistance.

One method for acquiring these acoustic data is P and S suspension logging (PSSL), a borehole geophysical logging method standardized by ISO (2023). PSSL is commonly employed in offshore site investigations, especially for offshore wind farms.

Several interchangeable terms and abbreviations are used in the industry for this method, such as: P and S suspension logging (ISO, 2023), PS suspension logging, PS logging, suspension PS logging, P and S logging, PSL, and PSSL (Ohya et al., 1984; Diehl et al., 2006). For this paper, the term "P and S suspension logging" and the abbreviation "PSSL" are adopted to help distinguish this specific stationary borehole geophysical logging method from other acquisition methods for determining v_p and v_s, where data processing may differ. The borehole geophysical logging tool used to perform the measurements is referred to generically as the P and S suspension logging tool. While tool specifications may vary between the different available models, the basic measurement principle is the same.

The PSSL method provides derived values of v_p and v_s in diverse ground conditions, including soil and rock. Recorded data must be processed for velocity derivation and may vary in suitability to this end. Thus, for further application, it is prudent to classify the level of suitability of recorded data for velocity derivation. This paper presents a novel confidence classification scheme for PSSL data, whereby traces are manually assessed on the confidence of their interpretation. This scheme is detailed in Section 3. Section 2 provides a concise overview of PSSL hardware, acquisition, and processing, as necessary for understanding of the classification scheme.

2 P AND S SUSPENSION LOGGING

2.1 Hardware Configuration

The PSSL tool is equipped with one dipole type transmitter source in the bottom section of the tool and two receivers in the top section. The two receivers are placed at different distances from the transmitter along the tool long axis, where the nearer and farther receiver are referred to as the near receiver and the far receiver, respectively. Each receiver contains two collocated sensors: (1) one piezoelectric type sensor for P-wave measurements, and (2) one geophone type sensor for S-wave measurements.

Between the transmitter, near receiver, and far receiver, there are flexible isolator joints (sometimes referred to as acoustic filter tubes) used to prevent source acoustic energy from travelling directly along the tool housing to the receiver stations, i.e. direct tool arrivals. The distance from the source to the near receiver is variable; it differs among tool models and is also adjustable using different lengths of isolator joints. The receivers are spaced 1.0 m apart on currently available tools in the standard setup.

2.2 Data Acquisition

The logging tool is deployed using wireline cable down to the test depth(s) of interest in an open borehole, i.e. uncased at the test depth of interest. At each test depth, the tool is held in a stationary position while data acquisition takes place. Test depths are hereafter referred to as "stations" and the distance between stations as "station spacing". As the receiver spacing is 1.0 m, a station spacing of 1.0 m is in theory sufficient to provide full velocity coverage from the bottommost to topmost station. Smaller or larger station spacings, such as 0.5 m or 2.0 m, are sometimes used, dependent on project-specific requirements. Data acquisition is typically performed starting at the bottom of the borehole and progressing uphole station-by-station.

When activated, the dipole transmitter excites multiple wave types in the borehole environment, including a refracted P-wave and a flexural (surface) wave, which are recorded at the two receivers. The transmitter can be fired in two opposite, horizontal directions, namely positive and negative, orthogonal to the tool long axis to generate flexural waves with two opposite polarities.

Data acquisition consists of performing several acquisition cycles at each station. Every acquisition cycle comprises three transmitter activations (or shots), whereby the transmitter fires sequentially in the positive, negative, positive horizontal directions. These three activations are used to record three different modes: (1) the S1-wave and (2) S2-wave modes corresponding to the two opposite polarity flexural waves and (3) the P-wave mode associated with the refracted P-wave. In other words, each acquisition cycle results in one S1-wave shot record, one S2-wave shot record, and one P-wave shot record, where a shot record consists of a near receiver trace and a far receiver trace, i.e. a trace pair. Performing multiple acquisition cycles per station thus produces multiple shot records per mode.

In addition to recording data where the transmitter is actively fired, it is also beneficial to acquire regular background noise measurements for characterizing environmental noise. This can be useful for setting up appropriate filters during data processing.

2.3 Data Processing

Derived values of v_p and v_s are determined from arrival times ("picking") of the waves of interest at the near and far receivers and using the known receiver distance to compute the interval velocity. A derived velocity represents the average velocity of the ground between the two receivers. It is often presented at the mid-point between the two receivers. Picking is performed for each of the three modes separately. Where applicable, the average of the S1- and S2-wave velocities is treated as the S-wave velocity v_s.

The recorded data containing the signals of interest (refracted P-wave for P-wave mode, flexural waves for S-wave modes) may be affected by several factors which can influence the signal quality on the traces, including but not limited to:

- Ground conditions – some types of ground attenuate or distort signal more strongly than others
- Borehole conditions – signal levels generally decrease in larger size boreholes or boreholes with irregular geometry such as surface roughness (rugosity) or cavitation
- Metocean conditions – adverse weather conditions and strong currents can introduce environmental noise on the recordings
- The specific logging and drilling setups used may influence how some types of noise are transmitted to the logging tool in the borehole
- Other borehole logging parameters such as water depth, drill string depth, and borehole depth - these impact how far the logging tool is positioned from certain sources of noise.

Consequently, the recorded traces will vary in their suitability for picking (or "interpretability").

The interpretability of the data has a direct influence on the overall uncertainty of the derived values of v_p and v_s.

3 CONFIDENCE CLASSIFICATION

3.1 Confidence Criteria

3.1.1 Overview

The confidence classification scheme proposed here provides a framework for assessing recorded traces acquired using P and S suspension logging tools for their interpretability. No additional qualification is required for a competent P and S suspension logging data processor to use the classification scheme.

The scheme considers four key criteria for assigning a confidence class to the presented P-wave, S1-wave, and S2-wave velocities for each station. Each criterion is weighed equally to safeguard the simplicity of the classification process.

The four criteria can be subdivided into two main subclasses, namely shot criteria which are assessed on individual trace pairs per mode and station criteria assessed on multiple trace pairs per mode per station. The first three criteria are shot criteria: (1) first arrival visibility, (2) noise impact, and (3) polarized behaviour of S1-wave and S2-wave trace pairs. Technically, polarized behaviour considers two trace pairs as defined in Section 2.2; this is further clarified in Section 3.1.4. The final criterion is (4) velocity repeatability which is a station criterion. The criteria are described in the section below.

Based on these criteria, one of four confidence levels can be assigned per mode per station: high, medium, low, and insufficient. The levels correspond to confidence classes C1 to C4. To qualify for a particular confidence class, all criteria requirements for that confidence level must be met or exceeded, i.e. applicable for equal or higher confidence level. An overview of the confidence classes and their requirements are provided in Table 1 below.

Table 1. Confidence classification for PSSL trace data

Class	Confidence Level	First Arrival Visibility	Noise Impact	Polarized Behaviour*	Velocity Repeatability
C1	High	Clear	No or low	Excellent	Within limit, high pick quantity
C2	Medium	Identifiable	Moderate	Clearly visible	Within limit, high pick quantity
C3	Low	Not identifiable to identifiable (semblance picking possible)	High	Partially visible	Within limit, medium pick quantity
C4	Insufficient	Not identifiable (semblance picking impossible)	Obstructive	Not visible	Exceeds limit or inadequate pick quantity

Notes
***Applicable for S-waves only**

3.1.2 First Arrival Visibility

Using the first arrival, i.e. the first instance of signal on the trace, for velocity derivation is generally the most reliable feature for arrival time picking. Latter parts of the trace may be affected by interference from other waves or reflected modes. As the first arrival corresponds to the energy travelling directly from the source along the borehole wall to the receiver, it is less affected by such interference. First arrival visibility can be assessed as follows:

- **Clear –** first break is clearly visible
- **Identifiable –** first break is not clearly visible, but the first peak/trough or inflection point thereafter clearly is
- **Not identifiable to identifiable (semblance picking possible)** – the first peak/trough or inflection point is barely visible or not visible at all; in cases where there is no visibility, the near and far traces have sufficient likeness to permit semblance-based picking
- **Not identifiable (semblance picking impossible)** – first break, first peak/trough, and first inflection point are all not identifiable and the likeness between near and far traces is not sufficient for semblance-based picking

3.1.3 Noise Impact

Any acoustic response that is not part of the signal of interest is defined as noise. Rather than viewing noise purely in terms of its amplitude (such as in signal-to-noise ratio), it is evaluated on its overall impact in trace processing. More specifically, noise may be high amplitude but have low impact, assuming the noise doesn’t cause the trace to saturate excessively, if the noise frequency content is significantly different than the signal frequency range.

As a common example, the S-wave geophones are also sensitive to the refracted P-wave generated in the borehole. In a typical soil response, the shear wave signal may contain frequencies up to 1000 Hz, whereas the lower limit of the P-wave signal is ~3000 Hz. In such a situation, it is straightforward to apply a low-pass filter, thus the noise impact is low. For noise impact, the following assessments are possible:

- **No or low** – there is no noise or noise is easily filterable with no signal loss or distortion
- **Moderate** – raw data can be processed without filtering but strongly benefit from applying filters; filtering may result in some signal loss or distortion
- **High** – raw data cannot be processed due to noise and noise is in similar frequency range as signal; filtering results in detrimental signal loss or distortion but resultant signal is still usable for picking
- **Obstructive** – raw data cannot be processed due to noise and filtering does not result in discernible signal for picking.

3.1.4 Polarized Behaviour

The polarized behaviour criterion applies exclusively to the shear wave data, where the S1- and S2-wave traces should be equal in amplitude but opposite in behaviour due to the opposite transmitter directionality used in acquiring these two modes. This involves comparing a single S1 shot with a single S2 shot, so therefore is treated as a shot criterion.

The evaluation is typically performed between S1 and S2 shots from the same acquisition cycle as a matter of practical convenience, however this is not a requirement. Any S1 shot can be compared to any S2 shot from the same station. Small time shifts between the S1 and S2 traces due to slight variations in the tool's triggering mechanism are disregarded. The assessment specifically compares traces from the same receiver, i.e. S1-near with S2-near and S1-far with S2-far. When near and far traces have different assessments, the less favourable assessment applies. Polarized behaviour can be assessed as follows:

- **Excellent** – S1 and S2 traces show perfectly opposite behaviour at equal amplitudes from first arrival onwards
- **Clearly visible** – S1 and S2 traces show largely equal amplitude and opposite behaviour, notably on the first arrival and soon thereafter
- **Partially visible** – S1 and S2 traces may demonstrate polarized behaviour at some points from first arrival onwards but not consistently
- **Not visible** – no discernible polarized behaviour can be observed between the S1 and S2 traces.

A minimum of one picked trace per mode is required to determine the level of polarized behaviour. If only S1-wave or S2-wave data are pickable on a station, polarized behaviour cannot be assessed, and a default assessment of "not visible" applies. In cases where multiple picks exist for one S mode and only a single pick exists for the other S mode, the single picked trace may be used to establish the level of polarized behaviour on the multiple picked traces.

3.1.5 Velocity Repeatability

As PSSL data are susceptible to noise which may be misconstrued as signal during processing, there is significant added value in processing multiple trace pairs per mode per station to verify derived velocities are repeatable. This best practice is analogous to logging repeat passes for continuous borehole geophysical logs such as natural gamma and full wave sonic or performing multiple measurements at each test depth for other stationary tests such as borehole seismic and formation pressure testing. Ideally, a minimum of three shots per mode are picked per PSSL station to ensure a high degree of certainty in the repeatability of the derived velocities.

P-wave and S-wave velocity repeatability are treated separately. For the assessment of S-wave velocity repeatability, all computed S1-wave and S2-wave velocities for the station are included in the analysis.

The velocity repeatability for each wave type is considered acceptable, or "within limit", when the percentage difference Δ between the maximum velocity v_{max} and minimum velocity v_{min} for the station is less than the velocity repeatability limit. The percentage difference Δ is calculated by:

$$\Delta = \frac{v_{max} - v_{min}}{v_{max}} \cdot 100 \qquad (1)$$

The applicable velocity repeatability limit is a function of v_{max} as defined in Table 2. The repeatability limit values have been determined based on experience, noting that higher velocity waves typically (1) have sharper features permitting more precise picking on multiple traces and (2) are generally less affected by low frequency environmental noise common in marine settings. By analysing many data sets in varying lithologies, it was concluded pickable data's repeatability error typically lies within these ranges.

Table 2. Velocity repeatability limits

Maximum Wave Velocity [m/s]	Repeatability Limit
$v_{max} < 500$	10%
$500 \leq v_{max} < 1500$	5%
$v_{max} \geq 1500$	3%

In addition to checking the velocity repeatability is within limit, the total number of picked shots or picked unique stacks per mode is also considered as part of the velocity repeatability criterion. Guidance regarding stacking data, including dense stacks, is covered in more detail in Section 3.2.3 below. Combining these elements, the possible assessments for the velocity repeatability criterion are as follows:

- **Within limit, high pick quantity** – velocity repeatability condition satisfied; at minimum, three picked shots and/or stacks
- **Within limit, medium pick quantity** – velocity repeatability condition satisfied; at minimum, two picked shots and/or stacks, or one picked dense stack
- **Exceeds limit or inadequate pick quantity** – velocity repeatability condition not satisfied, and/or at most one picked shot or one picked non-dense stack.

3.1.6 Example Trace Assessments

In Figures 1 to 3, a few examples are provided of assessed trace pairs to demonstrate the first arrival visibility, noise impact, and polarized behaviour criteria. In each figure, near traces are presented on the left and far traces on the right. P-wave, S1-wave, and S2-wave data are indicated in green, orange, and blue, respectively. Where shots have been filtered, the unfiltered data have been presented on top and filtered data on bottom; the type of filters used are indicated in the figure caption. Picked arrivals are indicated with a dashed vertical line.

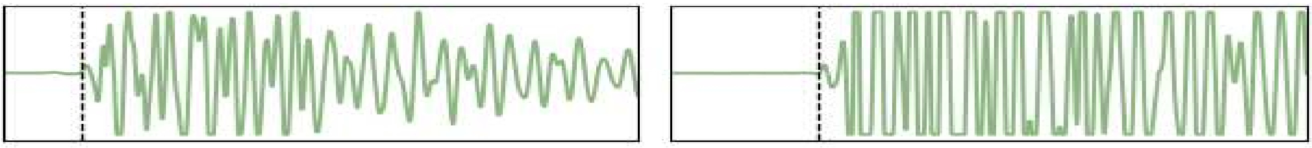

Figure 1 – P-wave shot (unfiltered); near and far traces show clear first arrival visibility and no/low noise (high confidence); overall shot confidence is high

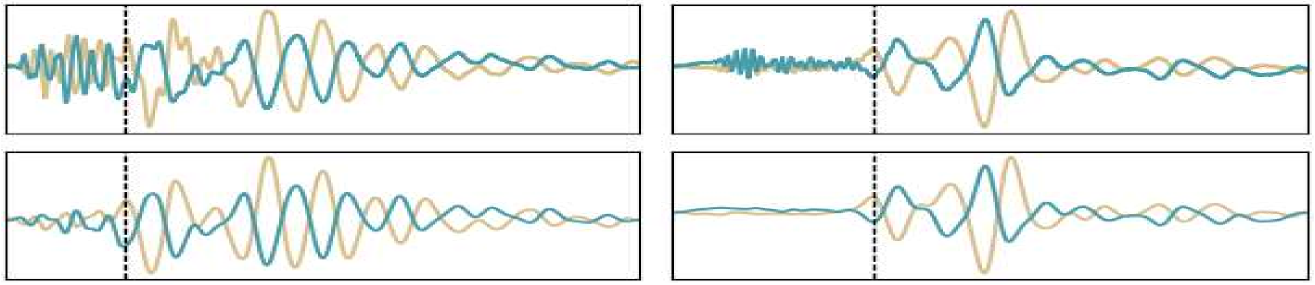

Figure 2 – S1-wave and S2-wave shots (bottom traces filtered with low pass 1500 Hz); unfiltered near trace demonstrates high frequency noise around first arrival which can be mostly filtered out with some remaining noise, i.e. moderate noise; the filtered near trace has identifiable first arrival visibility, moderate noise, and excellent polarized behaviour (medium confidence); the filtered far trace has a clear first arrival, low noise, and excellent polarized behaviour (high confidence); overall shot confidence is medium

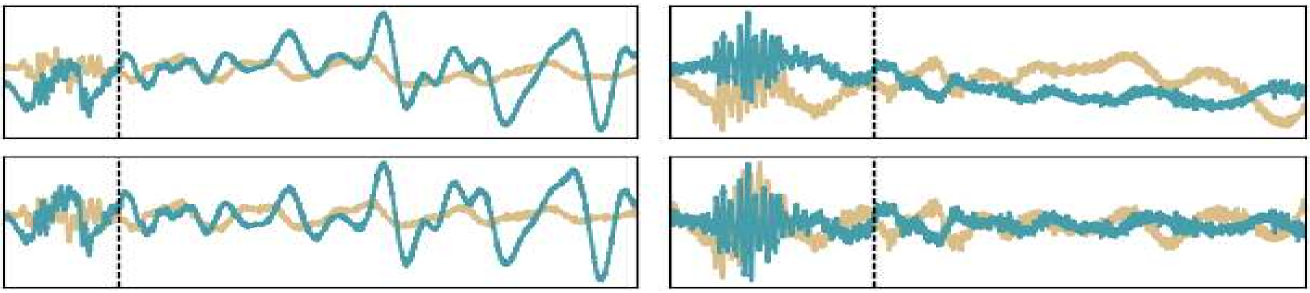

Figure 3 – S1-wave and S2-wave shots (bottom traces filtered with high pass 200 Hz); both unfiltered traces demonstrate significant noise throughout which can be somewhat filtered out with considerable remaining noise (i.e. high noise); both filtered traces have barely visible first arrivals, high noise, and partially visible polarized behaviour (low confidence); overall shot confidence is low

3.2 Usage of the Classification Scheme

3.2.1 Main Steps

A practical approach to using the confidence classification scheme involves three main steps: (1) shot scoring, (2) velocity repeatability checks, and (3) assigning confidence class.

First, shot scoring consists of performing checks for all picked shots on a station for the shot criteria: first arrival visibility, noise impact on the waveforms, and polarized behaviour of the S-waves. This leads to a score ranging from one to three per shot corresponding with low to high confidence level, respectively. To meet a certain confidence level, all applicable shot criteria requirements for the level must be satisfied or exceeded as defined in Table 1. For shot criteria on trace pairs where the near and far traces do not satisfy the same criteria requirements, the lower score of the two traces applies. The picked shot scores are averaged and rounded for the station per mode.

Then, velocity repeatability checks on all picked shots are performed for each wave type on the station as detailed in Section 3.1.5.

Lastly, the station confidence class is assigned, per mode, according to the highest class satisfied by both the average shot score and the velocity repeatability check. When a criterion in Table 1 does not meet the requirements for class C3, then class C4 (Insufficient Confidence) applies, and no velocity is presented for this mode.

As an example, a station contains three picked P-wave shots with velocities 1780 m/s, 1800 m/s, and 1800 m/s. The three shots are assessed as follows:

- Shot 1: visibility first arrival – clear, noise impact – moderate, polarized behaviour – not applicable; shot score 2
- Shot 2: visibility first arrival – clear, noise impact – no or low, polarized behaviour – not applicable; shot score 3
- Shot 3: visibility first arrival – identifiable, noise impact – moderate, polarized behaviour – not applicable; shot score 2.

Thus, the average shot score for the P-wave mode at this station is 2.33, which is rounded to 2 and corresponds to a medium confidence level shot score.

The velocity repeatability check demonstrates the picked velocities have a 1.1% percentage difference as per Equation 1 and are within the limit of 3% applicable for this velocity range (Table 2). As there are three picked velocities, the station P-wave mode is assessed as “within limit, high pick quantity” which is suitable for high confidence level.

Finally, the confidence class is assigned according to the highest class satisfied by both the average shot score and the velocity repeatability criterion. In this case, class C2 (medium confidence level) applies.

3.2.2 Filtering

Filtering of traces is possible within this confidence classification scheme and is accounted for in the noise impact criterion. As per general best practice, applied filters should aim to maximize noise reduction while preserving signal as best as possible. The raw acoustic data should not be unnecessarily or excessively filtered.

3.2.3 Stacking

The classification scheme accommodates the use of stacking. Stacking of two or more shots helps remove random noise, i.e. noise not correlated to the PSSL source. Stacks should be performed selectively, where only traces which will contribute positively to the stack are selected for inclusion. Blind stacking, where all traces in a station are blindly added without scrutiny, is discouraged. Stacks in which five or more shots are included are referred to as dense stacks.

Generally, high confidence data do not require stacking, and the stacking of low or medium confidence data does not usually raise the resultant confidence class. There are two reasons for this. Firstly, trace behaviour is often dictated by ground conditions rather than noise, so stacking does not significantly improve traces for interpretation. Secondly, a typical PSSL station may consist of only five to ten active shots. If traces have relatively low noise, stacking up to ten usable shots will have a limited effect on reducing noise. Conversely, stacking can be useful when applied on marginally insufficient confidence data. If noise levels are relatively high, signal quality may be increased to acceptable levels for a higher confidence.

For assigning confidence class, the picked stacks should be unique. This means the picked stacks do not share the same shot data within the stacks. For a station with five shots, one stack containing shots 1, 3, and 5, and another stack containing shots 2 and 4 would both be considered unique. If both stacks contained shot 3, for example, then they would not be considered unique. The uniqueness condition ensures the velocity repeatability criterion is checked on independent sets of data.

In the context of the velocity repeatability criterion, picked stacks are treated the same as picked shots for the most part, i.e. one picked shot and two picked stacks count the same as three picked shots. Thus, the repeatability criterion remains an important facet in classification even when stacking. As stacking may not sufficiently remove noise, stacked data can still be misinterpreted, resulting in incorrect derived values of velocities. Repeatability checks reduce the likelihood of this. In consideration of challenging trace data, an additional allowance is made for the assessment “medium pick quantity” corresponding to the low confidence level, such that a single picked dense stack is also acceptable. In such situations, it is not feasible to interpret traces using individual shots or non-dense stacks, such as (noisy) data acquired in coarse, gravelly soils. Under such circumstances, the classification allows for a single, dense stack to be used for presented data, albeit at low confidence as there is no direct confirmation of repeatability made.

4 DISCUSSION AND CONCLUSION

Confidence classification assesses the interpretability of acoustic traces acquired during P and S suspension logging. The confidence class can be an important consideration for utilizing the velocity data, such as when comparing P and S suspension logging wave velocities with other measurements or as input for deriving design parameters; for example, users may choose to assign more weight to higher confidence velocities. The confidence classification presented here is not a substitute for uncertainty assessment of presented values of v_p and v_s according to ISO (2008) or similar. Uncertainty assessment should take into account additional factors such as borehole geometry and aspects of the measurement physics.

Other classifications exist (e.g. Porbaha et al., 2005), however these consider an overall family of criteria, rather than assessing each criterion individually as in the scheme defined here. A family of criteria may be suitable for providing a general impression of trace quality, however it is not comprehensive as recorded traces may not properly fit into any of the families.

The presented confidence classification scheme can be implemented in a straightforward way using basic office processing software, though efficiency gains can be achieved through a bespoke software solution. In terms of presentation, the confidence class can be presented on borehole geophysical logs, for example through color-coding of the derived velocities or through additional data channels defining the confidence class for each test depth. Alternatively, the confidence class can be presented in tabular format with supplementary information such as filters and stacks used.

Future work may include automating the process and potentially adding more quantitative criteria. Moreover, additional insight resulting from continued use of the classification scheme may lead to further refining of the criteria assessments presented here. The scheme has already been applied extensively on offshore site investigations performed by Fugro and confidence classes have been assigned to over 3000 stations successfully.

AUTHOR CONTRIBUTION STATEMENT

J. Burgers: Conceptualization, Data curation, Investigation, Methodology, Writing - original draft. **P. Maas**: Data curation, Funding acquisition, Methodology, Project administration, Writing - reviewing and editing. **J. Buist**: Formal analysis, Investigation, Software. **J. Peuchen**: Supervision, Writing - reviewing and editing.

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