Predicting select geotechnical sediment properties at a carbonate site through inversion of 2D post-stack multichannel seismic data

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ABSTRACT: This paper describes a seismic inversion workflow used to predict geotechnical sediment properties for a carbonate site on the continental shelf offshore Western Australia. The subsurface profile at the study site is composed of carbonate sediments ranging from muds to sands, with zones of variable cementation, thus providing complex conditions with which to test the workflow. A 2D high frequency post-stack multichannel seismic data set was used as input for the inversion. Geoacoustic measurements made on intact sediment samples using bender elements within a triaxial apparatus were used to (1) understand relationships between acoustic (P-wave velocity and acoustic impedance) and geotechnical properties and (2) build a site-specific background acoustic impedance model which was incorporated into the inversion process. Geotechnical property predictions were spatially mapped across a selected 2D section of the subsurface; the quality of the predictions was evaluated by comparing with ground-truth data from an adjacent geotechnical borehole.

1 Introduction

The offshore wind industry is rapidly maturing with a substantial number of wind farms now fully operational, the majority located offshore Western Europe and China. Ambitious plans are in place for increased development in these and other regions of the world for the coming decades (International Energy Agency, 2019). Australia, being home to a vast offshore wind and wave energy resource, is planning similar development of offshore renewable energy infrastructure including wind farms along the coast of Western Australia and south of the Gippsland region of Victoria. Key to the geotechnical engineering success of these projects is a well-planned and executed site investigation, followed by a site characterisation process that makes optimal use of the data collected, deriving maximum information regarding site conditions.

Offshore site investigation and geotechnical characterisation techniques commonly employed today are best-suited for oil and gas projects (for which they were developed) where the investigation is tailored to a limited number of infrastructure locations over a relatively modest seabed footprint. However, in the case of offshore wind farms, projects may consist of hundreds of turbines spread across an area on the scale of tens to hundreds of square kilometres. Thus spatially extensive (e.g. geophysical) data become increasingly attractive for site characterisation purposes if valuable quantitative information can be drawn from them. This requires a multi-disciplinary approach where insights from the different geo-disciplines are harmonised to achieve the most informed understanding of seafloor and subsurface conditions.

Such integrated site characterisation workflows are in active development in academia and industry. To date, a large body of the published literature in this area is based on offshore sites in and around the North Sea region where much of the existing wind farm development has occurred. The offshore environments encountered around Australia have proven to be challenging frontiers for geotechnical engineering, dating back to the first offshore oil and gas infrastructure constructed on the North West Shelf of Western Australia in the 1980s (Khorshid, 1990). This is due in large part to the prevalence of carbonate sediments, which exhibit unique physical properties and engineering behaviour, as detailed in Watson et al. (2019). Thus geotechnical engineering solutions, beginning with site characterisation efforts, must be designed with an appreciation for and understanding of these challenging environments.

A valuable tool available to aid development and implementation of integrated site characterisation workflows is the constantly increasing body of high quality open-source scientific software packages, including those especially designed for geoscience and geoengineering applications. The ability to tailor these packages for use with existing site data is an increasingly promising prospect.

These complimentary factors provided the impetus for the work presented here—where the application of a quantitative seismic inversion workflow to a site investigation data set collected offshore Western Australia is demonstrated. A series of open-source software packages were utilised in this workflow, implemented using the Python scripting language.

2 Background

2.1 *Offshore site investigation & characterisation*

Geophysical and geotechnical site investigation data are routinely used together during the site characterisation process (Birchall, 2012; Cauquil, 2012; Thomas, 2017). Initially, spatial information from the geophysical survey is used to plan the layout of infrastructure, and if time allows, fine-tune the geotechnical survey by identifying specific areas of complex seabed conditions which must be further investigated. In a geotechnical engineering context, seismic data are often used in a purely qualitative manner. Seismic sections are visually inspected and interpretations about the geological structure of the subsurface relevant to geotechnical engineering, such as the identification of sediment layer boundaries, potential obstructions (e.g. boulders), top of bedrock, etc., are made.

During the subsequent geotechnical survey, in situ tests such as piezocone penetrometer tests (PCPTs) and sampling boreholes, followed by laboratory testing, provide quantitative geotechnical information. This information can then be analysed in conjunction with the seismic data interpretations to characterise the subsurface in geotechnical terms, assessing continuity of sediment layers and assigning layer (unit) properties, identifying cemented regions, etc.

The ability to extend beyond the qualitative use of geophysical data and extract quantitative information is an attractive proposition. The discrete, one-dimensional ('1D') information obtained from geotechnical data is still critical to the site characterisation process, but when used together with the spatial geophysical data in an integrated manner, can lead to the best understanding of geotechnical conditions.

2.2 *Novel quantitative data integration workflows*

Quantitative data integration approaches using geophysical and geotechnical data have been in development for some time. Quantitative characterisation of the seafloor has been an area of study for several decades, including development of swept-frequency subbottom profilers such as the Chirp system for such purposes (Schock, 1989; Panda et al., 1994; Stevenson et al., 2002). Characterisation of the subsurface has also been an area of active study, including the linking of acoustic and geotechnical parameters (Hamilton, 1970; Haynes et al., 1993; Richardson et al., 1997; Lyu et al., 2021), and *in situ* test data such as PCPT measurements (e.g. Nauroy et al., 1998).

More recently, seismic inversion techniques have become an area of particular interest. Originally developed for hydrocarbon prospecting, seismic inversion techniques have recently been adapted for use with higher frequency site investigation seismic data sets (e.g. Vardy, 2015; Chen et al., 2020; Karkov et al., 2022). The acoustic impedance inversion technique of Vardy (2015) was incorporated into the integrated site characterisation effort for the TNW Wind Farm Zone offshore the Netherlands (Norwegian Geotechnical Institute, 2022). Published project documents and accompanying data sets from this and other projects (e.g. Fugro Netherlands Marine B.V., 2020) made available by the Netherlands Enterprise Agency show that these techniques are being actively adopted in industry. Other aspects of these data integration workflows include the application of geostatistical and machine learning techniques (e.g. Forsberg et al., 2017; Sauvin et al., 2019; Cai, 2022). The variety of work to date demonstrates a diverse pool of potential solutions from which to select, adapt, and apply to a given site investigation data set.

2.3 *Seismic inversion considerations*

Seismic inversion is a general term encompassing a broad range of different techniques, but generally means the estimation of physical subsurface material properties from a set of remotely collected seismic data. There are a variety of seismic inversion approaches for quantitative characterisation of the near-surface (summarised in Vardy et al., 2017), one of which is acoustic impedance inversion. Acoustic impedance (Z) is the product of P-wave velocity (V_P) and bulk density (ρ_b) and is a physical property of subsurface sediment and rock. A change in acoustic impedance across an interface produces a seismic reflection which is observable in the seismic data. The amplitude of the reflection is determined by the reflection coefficient (RC) of the interface, calculated for a normally incident P wave using Equation 1 (Dix, 1952):

$$RC = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_{b2} V_{P2} - \rho_{b1} V_{P1}}{\rho_{b2} V_{P2} + \rho_{b1} V_{P1}} \qquad (1)$$

where Z_1, ρ_{b1}, and V_{P1} are acoustic impedance, bulk density, and P-wave velocity of the upper layer, respectively, and Z_2, ρ_{b2}, and V_{P2} are those of the lower layer.

Acoustic impedance inversion is performed using a post-stack seismic data set, where each seismic trace is representative of the response to the normally incident (vertically propagating) portion of a spherical acoustic wavefront (P wave). Two components needed to perform (absolute) acoustic impedance inversion are the seismic wavelet, which is an estimate of the seismic signal produced by the source, and a background acoustic impedance model. The background acoustic impedance model is also termed the low frequency model as seismic data do not have a low enough frequency component to capture general trends with increasing depth in the subsurface (Barclay et al., 2008). Relative acoustic impedance inversion, which does not require the incorporation of a background model, can be performed to estimate relative changes in acoustic impedance across the subsurface. This provides valuable stratigraphic information but does not result in the absolute sediment property values needed for geotechnical characterisation.

In order to create an accurate background acoustic impedance model, knowledge of the subsurface conditions independent of the seismic data must be obtained, most commonly through the geotechnical survey. Depending on the level of geotechnical information available, this background model may vary from an approximate trend in acoustic impedance with depth, to a more detailed, unit-specific configuration. Different methods of background model creation have been investigated by the authors, for example the method presented in O'Neill et al. (2023). Based on these investigations, it has been found that the incorporation of detailed characterisation work in the building of the background model (subsequent to a carefully executed initial processing of the seismic data) will result in more accurate output from the seismic inversion process. The quantitative workflow developed for this study, including the position of the background model within the overall process, is illustrated in Figure 1.

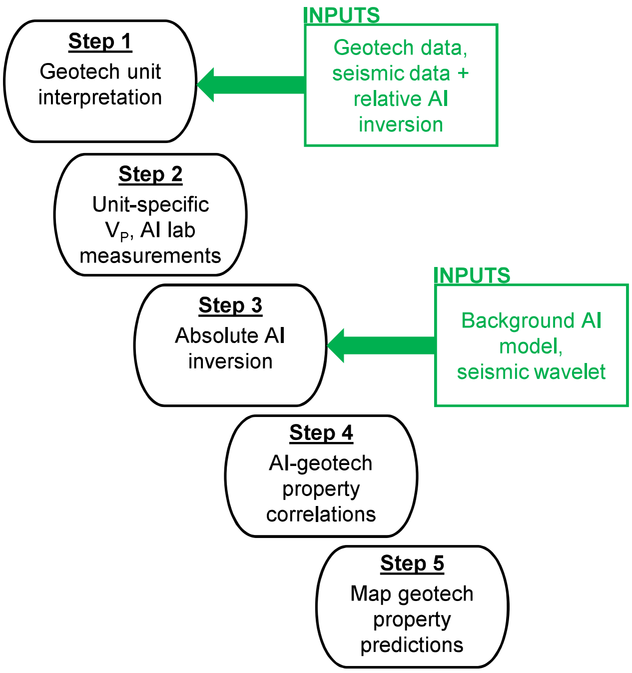

Figure 1. Quantitative seismic inversion workflow used in this study (AI = acoustic impedance).

As indicated, seismic inversion is a valuable tool for quantitative site characterisation, however it is not a standalone solution. Geological, geotechnical, and geophysical expertise regarding site conditions are still critical to the overall characterisation process. Geotechnical data are also a necessity.

3 Western Australian offshore site study

3.1 *Site conditions & geotechnical subsurface characterisation*

The offshore site examined in this study is located on the northern continental shelf of Western Australia in approximately 170m water depth. A post-stack 2D multichannel seismic data set was acquired at the site. For demonstration purposes, an approximately 40m-wide by 30m-deep subsection of a 2D seismic line was selected for this paper—representative of an area relevant to an intermediate-depth monopile installation. A geotechnical sampling borehole and PCPT profile are in close proximity to the line, at offset distances of approximately 14 and 23m, respectively. The seismic subsection used in this analysis, with superimposed geotechnical data, is shown in Figure 2a.

Using the information presented in Figures 2a and 2b, seven geotechnical units were interpreted within the subsurface profile, detailed in Table 1. The first boundary is the seafloor, clearly observable in the seismic section as a strong, positive amplitude reflection. Subsequent boundaries were interpreted by matching reflections in the seismic amplitude data with changes in sediment type as observed in geotechnical borehole samples and variations in *in situ* PCPT cone tip resistance measurements. A relative acoustic impedance inversion was also performed to assist in this process, allowing for better visualisation of units and the determination of low-to-high, or high-to-low contrasts in acoustic impedance across each unit boundary.

As is commonly encountered at offshore sites on the Western Australian continental shelf, several layers of cemented material were identified in the subsurface profile. Post-depositional cementation in offshore carbonate sediments can range from light cementation between grains to hard continuous, rock-like layers (e.g. calcarenite). For sites on the Western Australian continental shelf, sub-aerial exposure is one cause of this, with some shelf areas exposed during the last glacial maximum (~20 000 years ago) when sea level was approximately 125m lower than present (Heap and Harris, 2008). However, the subsurface materials in the depth of interest at the selected study location are not believed to have been sub-aerially exposed. Identification of cemented layers and their extents is a key aspect of geotechnical engineering in the region and has a large influence on the selection of foundation solutions.

Table 1. Units identified at the study site

Unit	Material description
1	Carbonate silty sand
2	Carbonate sandy silt
3	Slightly cemented carbonate muddy sand
4	Carbonate sandy mud
5	Moderately cemented carbonate muddy sand
6	Carbonate muddy sand/sandy mud
7	Interlayered carbonate silty sand and calcarenite

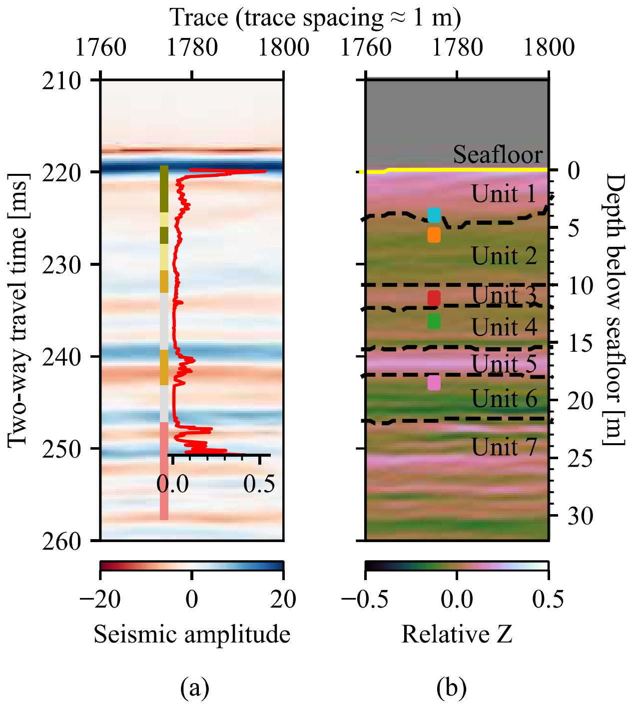

Figure 2. a) Seismic subsection with superimposed geotechnical data; coloured bar displays borehole sediment classifications (green = silty sand, yellow = sandy silt, orange = muddy sand with cementation, grey = muddy sand/sandy mud, pink = interlayered uncemented/cemented material) and red line plots normalised net cone tip resistance. b) Relative acoustic impedance inversion output showing interpreted geotechnical units; coloured markers indicate sample locations selected for laboratory testing (results shown in Figure 3).

3.2 *Laboratory V_P testing & assembly of background acoustic impedance model*

In order to aid creation of the site-specific acoustic impedance background model, a series of V_P and bulk density measurements were made on selected borehole samples using bender elements within a triaxial apparatus. Intact borehole samples from Units 1 through 4 and Unit 6 were selected for testing. The cemented nature of sediments within Units 5 and 7 made it difficult to recover high quality intact samples; the material collected from these cemented strata was fractured and discontinuous, and thus was unsuitable for trimming into triaxial specimens. Taking reliable acoustic measurements within cemented material remains an existing challenge and is an area for future investigation. Because of the absence of laboratory measurements in cemented sediments for this study, inversion results in the cemented units are not expected to accurately capture *in situ* conditions.

Once trimmed and placed into the triaxial cell, each specimen (TX-1 through TX-5) was subjected to a series of anisotropic effective stress states, the starting stress being representative of *in situ* conditions present at the depth from which each sample was recovered. A lateral earth pressure coefficient (K_o) of 0.4 was selected for testing, consistent with industry practice (Carter et al., 2000). Once primary consolidation was achieved at each stress increment, a series of V_P measurements were made using bender elements mounted within the end platens. The measured V_P values were then multiplied by bulk density of the specimen to compute acoustic impedance. The results of the laboratory testing are presented in Figure 3 (each data point represents the mean value computed over a series of approximately 20 measurements, i.e., 20 P wave transmissions and recordings).

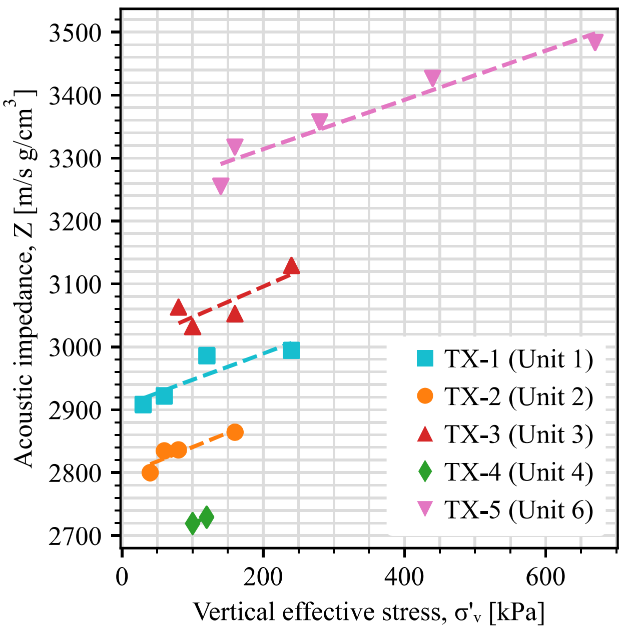

Figure 3. Laboratory acoustic impedance triaxial measurements. Dashed lines represent (assumed) linear increase in acoustic impedance with increase in vertical effective stress.

As shown in Figure 3, the sediment types tested exhibit a consistent trend of increasing acoustic impedance with increasing effective stress, but are translated vertically along the acoustic impedance axis. This supports the need to create a unit-specific background acoustic impedance model. For the present study, the model was constructed by assigning the acoustic impedance-effective stress relationships shown in Figure 3 to their corresponding interpreted units (shown in Figure 2b). Vertical effective stress was estimated across the profile—then within each unit, acoustic impedance values were assigned using the linear relationships presented visually by the dashed lines in Figure 3 (computed using linear least squares regression). The resulting acoustic impedance background model is shown in Figure 4a. As laboratory measurements were not available for Units 5 and 7, a relationship between acoustic impedance and vertical effective stress was assumed.

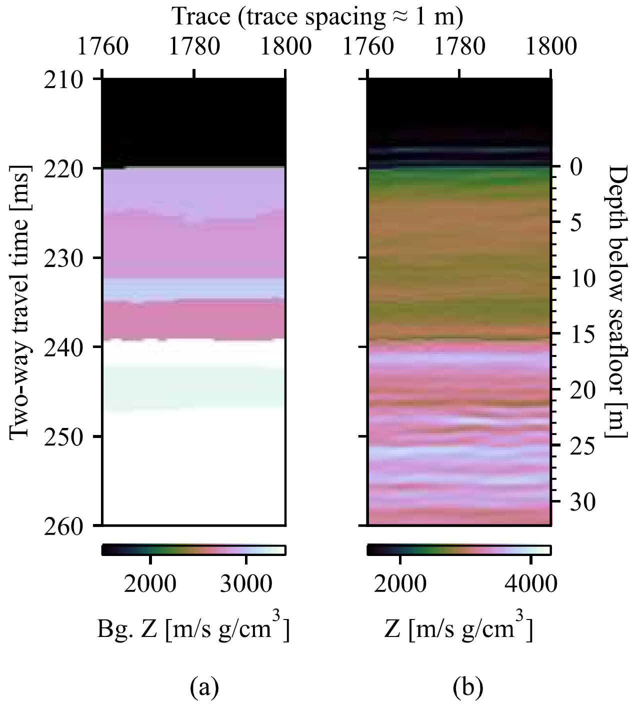

Figure 4. a) Unit-specific acoustic impedance background model and b) absolute acoustic impedance inversion output.

3.3 *Absolute acoustic impedance inversion*

As discussed in Section 2.3, with the background acoustic impedance model established, absolute acoustic impedance inversion can be performed. The other necessary component is an estimate of the seismic wavelet which is a time series representation of the signal emitted by the source during the offshore seismic survey. This was computed from the seismic data using a Fourier analysis technique, and was calibrated using geotechnical ground-truth data.

The inversion computations were performed using the open-source PyLops library (Ravasi and Vasconcelos, 2020). The PyLops post-stack acoustic impedance inversion module implements a linear operator based on the convolutional forward model, wherein the seismic wavelet is convolved with reflectivity values computed from the acoustic impedance model using Equation 1. The resulting output is a deterministic least squares solution (i.e. a single deterministic best fit). Further detail describing the inversion process used in this study can be found in O'Neill et al. (2023). The output acoustic impedance model solution for the section considered in this study is shown in Figure 4b.

Based on the inversion output, acoustic impedance values for the subsurface range from approximately 2200 to 4000m/s g/cm^3, with values in the uncemented sediment units ranging from approximately 2200 to 3400m/s g/cm^3. Although similar in appearance to the relative acoustic impedance model presented in Figure 2b, the values displayed in Figure 4b are now estimates of the *in situ* sediment properties. Because acoustic impedance is not a sediment property commonly used in geotechnical engineering, it is not built-in to the geotechnical site characterisation and design process. Thus the final step in the workflow was to convert estimated acoustic impedance values to physical geotechnical sediment property 'predictions'.

3.4 *Sediment property prediction*

In order to convert acoustic impedance values to geotechnical sediment characterisation properties, relationships between the two must be established. For this study, relationships were developed using a combination of multi-sensor core logger (MSCL) measurements made on shallow piston core samples and traditional geotechnical laboratory measurements. A series of 21 piston core samples were collected across the site, having a maximum sample depth of approximately 5m below seafloor. V_P and attenuated gamma density (analogue of bulk density) measurements were made at 1-cm intervals along the cores. Following MSCL testing, the cores were then subsampled for determination of geotechnical characterisation properties, including particle size distribution parameters, Atterberg limits, and carbonate content.

Measurement results are presented in Figure 5 together with additional carbonate sediment data compiled from the literature from other world regions. The bulk density versus acoustic impedance plot shows an increase in bulk density with increase in acoustic impedance. This is expected as bulk density is a component of acoustic impedance. The median grain size (D_{50}) measurements show an increase in acoustic impedance with increasing D_{50}. The greater spread in the D_{50} data is attributed to the fact that there is a weaker physical link between a single particle size distribution parameter (e.g. D_{50}) and acoustic impedance. An example of this is the possibility for two significantly different sediment types (with different acoustic impedance values) to have approximately the same D_{50} value.

Two methods were used to establish the relationships presented in Figure 5. Because of the greater number of data points in the bulk density plot, a statistical technique was implemented. To quantify the spread in data points across different values of acoustic impedance, low estimate (LE), best estimate (BE), and high estimate (HE) lines were computed by first defining eight acoustic impedance ranges ('bins'). Within each bin, linear least squares regression was used to first find the line of best fit (BE line), then a search algorithm was implemented to find y-intercepts of lines at which 10 and 90 percent of the data points fell below (constrained to the same slope as the BE line). The centre points of each of these lines, positioned at the bin centres, were then connected thus establishing the LE, BE, and HE lines shown in the upper plot of Figure 5. Because of the reduced number of data points in the D_{50} relationship, LE, BE, and HE lines were estimated by eye and manually assigned.

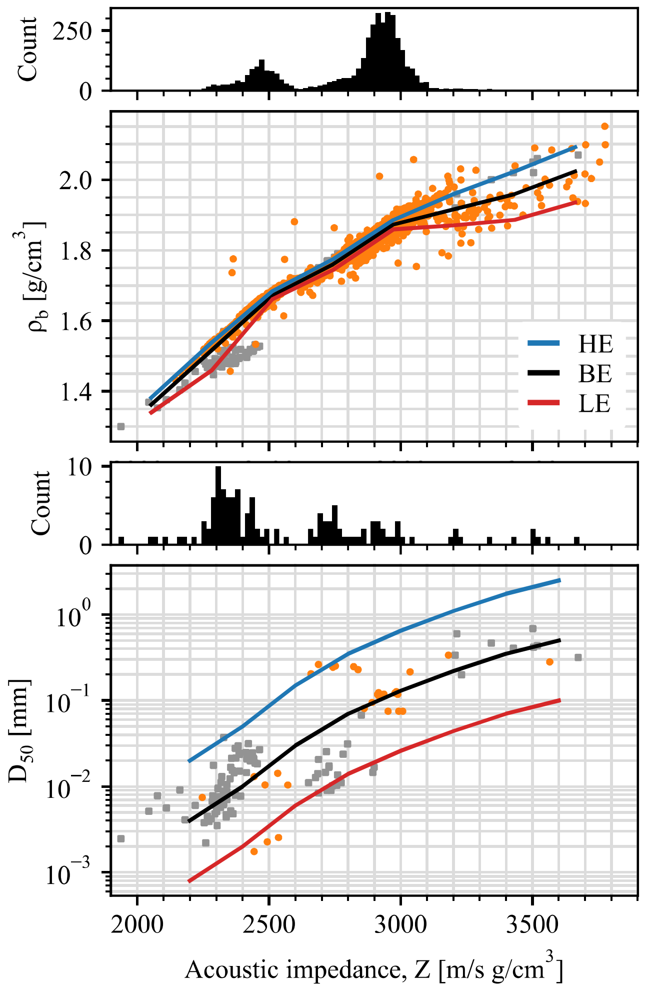

Figure 5. Relationships between two geotechnical sediment characterisation properties and acoustic impedance. Orange data points are from the study site, grey data points are from the literature (Shumway, 1960; Johnson et al., 1977; Hamilton and Bachman 1982; Richardson et al., 1997; Richardson and Briggs, 2004). Histograms are provided above each plot showing number and distribution of data points.

These lines were then used to compute sediment property predictions from the acoustic impedance output. Best estimate predictions for bulk density and D_{50} are shown in Figures 6a and 6b, respectively. Low estimate and high estimate prediction values can be similarly mapped across the section but are not shown.

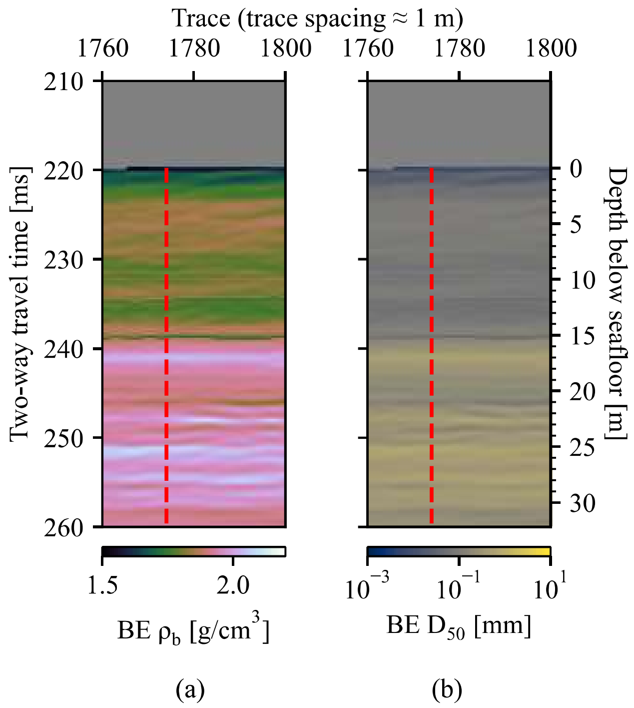

Figure 6. a) Bulk density and b) median grain size best estimate predictions mapped across the subsurface section. The red dashed line in each plot identifies the location of Trace 1774.

3.5 *Assessment of results*

In order to assess the accuracy of predictions made in the seismic inversion workflow, the results were compared with ground-truth data derived from the adjacent borehole. Trace 1774 was selected for comparison as it is the closest in proximity to the borehole, with an offset distance of approximately 14m. Computed bulk density and median grain size LE, BE, and HE predictions for Trace 1774 are plotted together with measurements made on samples from the adjacent borehole in Figure 7.

As can be seen in Figures 7a and 7b, the sediment property predictions are in good agreement with a majority of the ground-truth data. The greater variability in the D_{50}-acoustic impedance correlation is captured in the wider LE-to-HE band in Figure 7b. When reviewing the comparison, the lateral offset between the seismic line and the geotechnical borehole should be kept in mind, especially in the variably cemented region from a depth of approximately 22m below seafloor to the bottom of the profile (Unit 7 shown in Figure 2b) where conditions may change substantially over short lateral distances. Making accurate predictions within this zone is more challenging and was not a focus of this study. The workflow can be improved with a greater understanding of the geoacoustic properties of cemented sediments, which is needed to more accurately calibrate the seismic inversion process.

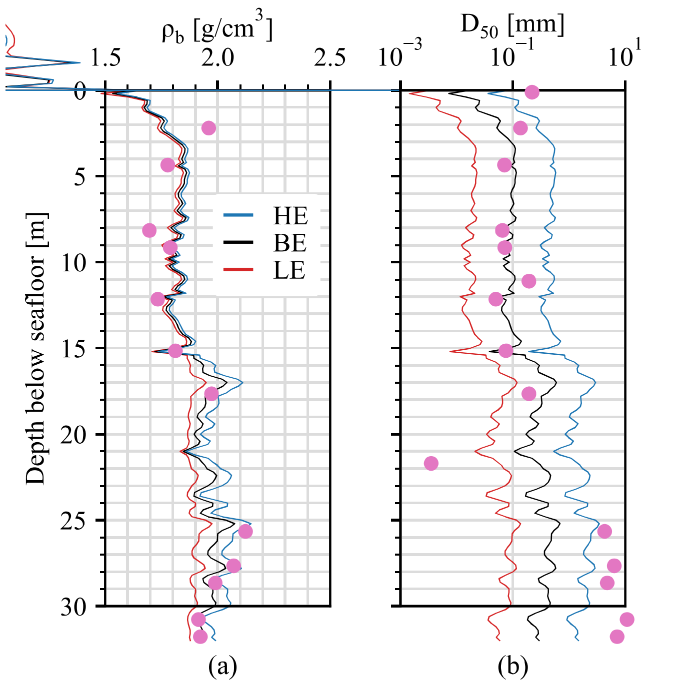

Figure 7. a) Bulk density and b) median grain size low estimate, best estimate, and high estimate predictions for Trace 1774 compared with ground-truth (pink) data points.

Although the LE, BE, and HE lines are representative of uncertainty, the only uncertainty currently quantified in this workflow is that of the correlations presented in the previous section (3.4). Quantifying uncertainty contained within other steps of the workflow, including in the inversion computation itself, is an area of current study. Furthermore, an iterative process in which 'errors' in the resulting predictions can be fed back through the inversion process is being developed. For example, this may be implemented through modification of the spatial extent of the interpreted geotechnical units followed by updating of the acoustic impedance background model. These and other aspects of the workflow are under continued development.

4 Conclusions

Through this study, the application of a novel geotechnical site characterisation workflow to a carbonate site offshore Western Australia has been demonstrated. This type of technique, which leverages the spatial extent of geophysical data, subsequently calibrated by geotechnical data, has significant utility in the context of engineering site characterisation for offshore wind farm developments.

The creation of a site-specific background acoustic impedance model from laboratory testing of retrieved samples has been shown to be an effective technique. Although not commonly included as part of the geotechnical laboratory testing programme, V_P measurements are relatively quick and simple to perform, particularly if bender elements are already being used within a triaxial apparatus for shear wave velocity measurements. The addition of V_P measurements is encouraged if a seismic inversion analysis is to be implemented as part of the site characterisation effort.

As was demonstrated here, a well-rounded approach with a confluence of knowledge from the geo-disciplines (namely geology, geophysics, and geotechnical engineering) is key to establishing the best understanding of site conditions. The expanding capabilities of digitally enabled geoengineering workflows have been supported through the increasing availability of high quality open-source software packages. As offshore wind farm and other renewable energy developments continue to proliferate globally, it is anticipated that these types of quantitative integrated workflows and their supporting tools will play a vital role in the site characterisation and engineering design process.

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The presented seismic inversion workflow was performed using a combination of open-source Python libraries and internally-developed software. Python libraries used included segyio for loading of seismic data (SEG-Y) files, pandas (McKinney, 2010) for loading and processing of tabulated data (CSV) files, NumPy (Harris et al., 2020) and SciPy (Virtanen et al., 2020) for digital signal processing and regression analyses, PyLops (Ravasi and Vasconcelos, 2020) for inversion computations, and Matplotlib (Hunter, 2007) for the creation of figures. The creators and maintainers of these libraries and the Python scripting language are gratefully acknowledged.

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