Optimising seismic resilience assessments – Part II. Integrating geophysical and geotechnical investigations

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ABSTRACT

In a country frequently shaken by earthquakes, understanding the risk to infrastructure from seismic shaking is a vital part of any construction project. With no single technique able to fully capture the seismic hazard in an area, a case study is presented displaying the strength of integrating surface geophysical techniques, targeted intrusive geotechnical investigations, and geological context to provide a comprehensive site-specific seismic hazard assessment.

Shear wave velocity profiles were undertaken across a 30ha New Zealand Port Facility to analyse the port's seismic resilience and identify where ground improvements may be required. Shear wave velocity (Vs) profiles were measured at 79 locations using the non-invasive Multichannel Analysis of Surface Waves (MASW) method. The shear wave velocity profiles obtained were constrained using pre-existing invasive data from boreholes and CPTs and interpreted within the Port's geological setting. From these results, a pseudo-3D map of subsurface stratigraphy across the port was produced, identifying the extent, depth, and thickness of reclamation fill and geological layers. Variations in Vs were mapped across the site. Results from the MASW survey were used to select the optimal locations for five additional seismic CPT investigations, the results of which reinforced the findings of the non-invasive investigation.

Overall, the use of surface geophysical methods allowed investigation to depths not achievable by CPT alone and enabled data collection in areas where invasive studies were not permitted. The combination of surface geophysics and targeted geotechnical investigations allowed for a comprehensive and robust assessment of seismic risk across the Port.

1 SEISMIC RISK AND HAZARD ASSESSMENTS

Earthquakes pose a considerable risk to infrastructure in New Zealand, making understanding the vulnerability of a site to seismic shaking intrinsic to building design, risk management and mitigation. This is reflected in the revised National Seismic Hazard Model, released by GNS in October 2022 (GNS Science, 2022), which includes the time-averaged velocity of shear seismic waves in the uppermost 30m of the subsurface (Vs30) as a fundamental parameter. While the Ministry for Business, Innovation and Employment (MBIE) is yet to decide how the revised NSHM will be incorporated into building codes, it is clear that investigations of shear wave velocity in the shallow subsurface is going to become required for any new construction sites.

The NZS1170.5:2004 incorporating Amendment 1 (Standards NZ, 2016) lists a hierarchy of seven method options for how to undertake seismic site classifications, of which invasive geophysical methods and non-invasive geophysical investigations rank first and second, respectively. Invasive geophysical methods such as seismic cone penetration tests (sCPTs) provide direct measurements of in-situ shear wave velocities, however there are many situations where such tests may be impractical, provide insufficient data, or become cost-prohibitive for certain projects. This could include sites with space constraints, where drilling is not permitted, or large sites with heterogeneous subsurface conditions. In such conditions, surface geophysical methods can provide an alternative source of data or complement and extend the information provided through invasive techniques.

In this paper, a case study is presented of an approximate 30-hectare port site that needed to be assessed for seismic resilience by geotechnical engineers. While existing boreholes and CPT data were available in certain areas of the site, new site investigations were required to provide insights in areas with a dearth of information. In this case, the geotechnical team decided to employ surface geophysical testing to obtain in situ shear wave velocity measurements, as well as to determine the most productive locations for conducting further invasive testing. Using this approach, any areas of concern identified from surface information could specifically be targeted with invasive tests, providing an efficient and cost-effective investigation compared to the typical approach of undertaking a large number of invasive investigations at predetermined locations to hopefully identify any areas of concern within the boundary of the site.

2 NON-INVASIVE GEOPHYSICAL ASSESSMENT OF SHEAR WAVE VELOCITY

The MASW technique is one of several surface geophysical methods that are available for measuring the shear wave velocity profile at a site. Given that shear waves are usually very low in amplitude, they are often difficult to measure directly. MASW has thus become a popular technique for such applications due to surface waves having typically high amplitude components, with the Rayleigh wave the most commonly utilised. For a detailed explanation of the MASW technique, the reader is referred to Foti et al (2018).

A typical investigation set up for MASW involves an active spread of 24 or more geophones (receivers), spaced in a straight line at equal intervals dependent on the depth of investigation desired. The geophones are mounted either on spikes in the ground, or on a weighted land streamer, to ensure that they remain level and with sound ground contact throughout the measurements. A sledgehammer or drop-weight is used as a seismic source, with at least two shot locations used either side of the active spread. (Fig. 1). Once multichannel field records have been gathered, dispersion curves are extracted from each record and inverted to obtain a 1D vertical profile of shear wave velocity at the midpoint of the active spread. With the acquisition of multiple 1D Vs profiles in an area, appropriate interpolation methods can be used to obtain a 2D or 3D map of shear wave velocity variations across a site.

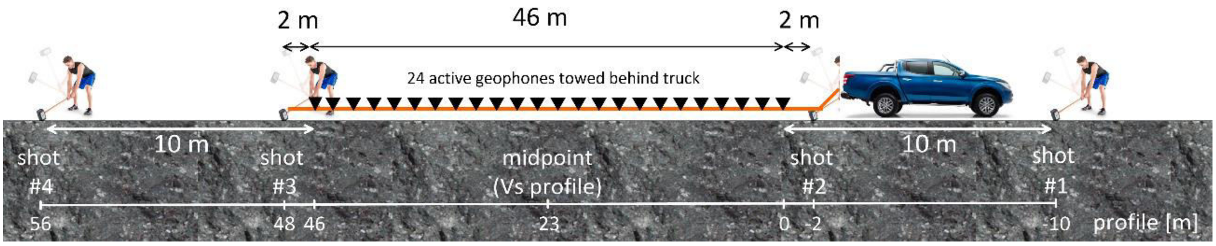

Figure 1: Geophysical site setup for the MASW investigation at the Port. A landstreamer towing 24 active geophones at a 2 m inter-geophone spacing was towed by a truck around the Port. Four shot points per profile location were taken at 2 m and 10 m away from the outermost geophones on either side of the active geophone spread.

3 A PORT CASE STUDY

In this case study, geotechnical and geophysical investigations were undertaken across a port area of around 30 hectares, to assess the site for seismic resilience. Development of the port had occurred in many stages since the 1950's, with the site located on reclaimed land consisting of wood, domestic waste, sand, and boulders. A desk study of the area's geology and records from previous invasive testing suggested that below the fill the site was likely underlain by sequences of recent estuarine deposits and marine sediments, beneath which lay a gravel formation. In some localized areas of the site, a terrestrial sediment layer could be expected between the estuarine deposits and the underlying gravel.

Given the variation in fill composition and sequence thicknesses across the reclaimed land, it was expected that near-surface shear wave velocity profiles would vary across the site, along with the associated seismic risk. Considering the size and complexity of the site, MASW was selected as the most suitable tool to investigate and quantize these variations. Being non-invasive and cost-efficient, a comprehensive array of MASW measurements could be undertaken across the entire Port site without interrupting regular operations, while keeping investigation costs within budget. By combining the results of the MASW investigation with those of previously conducted invasive tests, the aim was to provide a pseudo-3D map of the shear wave velocity of geological layers, and their thickness, across the site. A further output of the investigation was to map the depth of groundwater across the site by analysing P-wave data, however this is not focused on in the present paper.

To investigate shear wave velocity variations across the Port site, a total of 79 MASW profiles were collected. Profiles were spaced to give the best practical coverage across the whole site (Fig. 2), with the majority of data acquisition undertaken at during the night to reduce seismic noise levels and not interfere with regular port operations. The MASW setup is detailed in Figure 1, and consisted of 24 geophones mounted on a land-streamer at 2m spacing. This setup was towed behind a vehicle, with the smooth and efficient shifting of the equipment between profile locations allowing for all acquisition to be completed within a 7 day period. At each profile location, shots were acquired at 2m and 10m offsets at either end of the array, using a 6kg sledgehammer as a seismic source. These offset distances were selected as they provided the largest frequency range in measurements. By measuring shots off both ends of the array, it was possible to verify that the underground layering at the profile site was horizontal, as this a fundamental assumption in the methodology. To account for any potential background seismic noise from port operations or wind, between 5 and 19 individual shots were stacked at each offset. Ambient background noise records were also acquired and saved for later analysis.

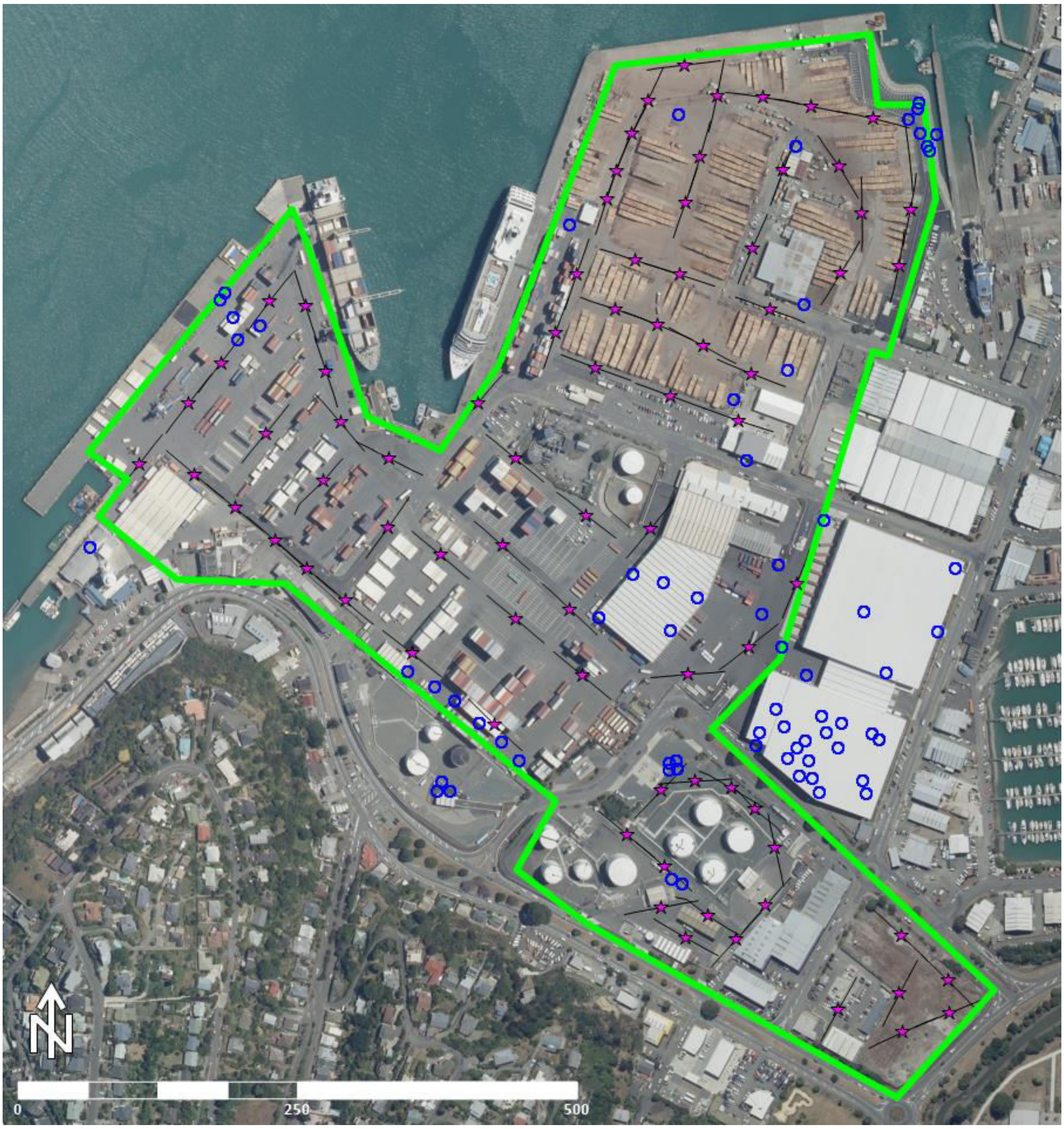

Figure 2: Location of acquired MASW profiles across the Port site. The centre of each geophone spread, where the 1D Vs profiles were acquired, are shown as pink stars, while the length and direction of each active seismic spread are shown as corresponding black lines. Blue circles depict the locations of previous CPT investigations.

4 GEOPHYSICAL DATA PROCESSING AND OUTPUTS

Alongside good data acquisition protocols, quality data processing procedures are vital to obtaining meaningful and accurate geophysical results and interpretation. To convert the raw seismic data to a final shear wave velocity profile, three main steps are required (Fig. 3):

1. Quality assurance: In this case, seismic data from all four shot locations at each profile site were analysed to ensure that the horizontal layering assumption required for MASW was fulfilled (i.e. shots at the same offset either end of the array had the same arrival times). All profiles fulfilled this criteria, with

no profiles having to be discarded. In addition, the frequency spectrum of the measured ambient seismic noise at each location was assessed.

2. Dispersion spectra analysis: For each shot location, the dispersion spectra is calculated from the raw seismic data via Fourier transform. From each spectrum, the fundamental mode (the mode of vibration with the lowest propagation velocity) is identified and the dispersion curve is picked. This is a critical step in the processing, with care required to correctly identify the fundamental mode from higher modes to avoid over-estimating Vs. In this case study, mode-splitting or mode-kissing, where various modes are merged together, was observed at many of the profile locations (e.g. Fig. 3). This was most likely an artefact of the hard-cap asphalt layer covering the Port, on top of which the seismic data were acquired. In cases displaying mode-splitting, careful signal muting was used to avoid picking portions of dispersion spectra that were a mixture of different modes. Of the 79 acquired MASW data sets, only one was discarded due to severe mode-splitting meaning picking the fundamental mode was not possible.
3. Inversion of the dispersion curve into a layered earth Vs model: Starting models for the inversion were built incorporating the results of previous CPT and borehole data close (<50m) to the profile sites, with layer thicknesses constrained during the inversion to match the results of existing invasive testing. A maximum of 30 inversion iterations were run, with layer parameters varied between iterations until an acceptable match was found between the theoretical dispersion curve from the layered model and the measured dispersion curve. Acceptable model error was assessed in the form of the root-mean-squared (RMS) error between the starting model and all the layered models tested during the inversion.

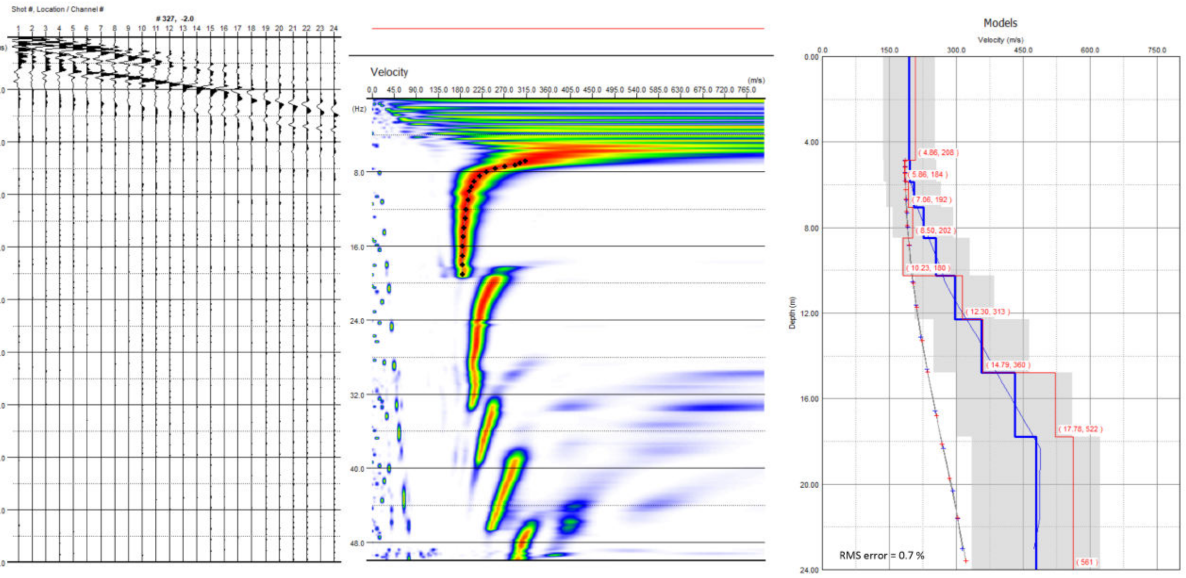

Figure 3: Example of MASW data. Left: seismic record as acquired in the field; Middle: dispersion spectrum with dispersion curve (DC) of fundamental mode picked; Right: A best fit layered-earth Vs model (red), along with the starting model (blue), and the picked and calculated DCs. This example shows clearly the mode splitting in the dispersion spectrum as observed on many of the data sets.

Following these three processing steps, 1D shear wave velocity profiles with depth were successfully obtained at 78 locations across the Port site, providing information on shear wave velocity variations between the depths of 3 to 25m below ground level. The depth reached with the MASW investigations varied across the Port site, as would be expected due to the unique variations in the subsurface composition resulting from the reclamation process.

In addition to providing shear wave velocity profiles at each location, such as in Figure 3, maps of the average shear wave velocity for different depth intervals were produced for the Port site, as shown in Figure

4. To produce the contour map, time averaged shear wave velocities were calculated for different depth intervals at each profile site, based on Equation 1 below:

$$Vs,d = \frac{\sum H_i}{\sum {}^{H_i}/_{V_i}} \quad (1)$$

where H is the thickness of a layer (i) and V_i the shear wave velocity of that same layer.

Maps were then produced using both Kriging and Inverse Distance methods to interpolate Vs between MASW profile locations, giving a spatial visualisation of shear wave velocity variations across the site. As an example, from Figure 4 it can be seen that shear wave velocities in the uppermost 10m of the subsurface are comparatively higher in the Southwest, and lower in the Northeast, respectively, when compared to other areas of the Port.

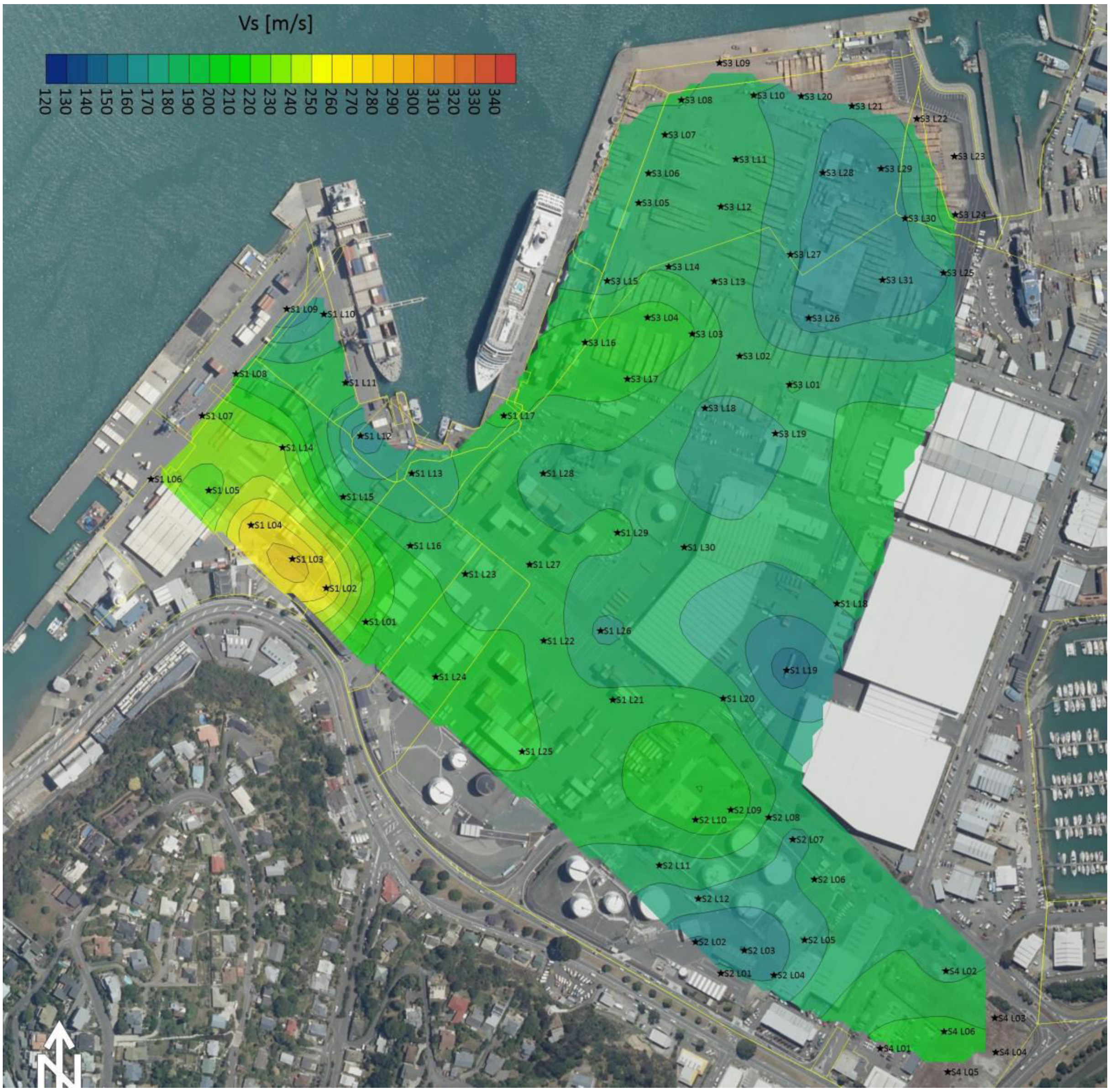

Figure 4: Kriging interpolation contour map of the time averaged shear wave velocity over the first 10 mbgl across the Port site. Black stars indicate the location of MASW profiles used in the interpolation. Yellow lines outline the boundary of reclaimed land.

5 INTEGRATING INVASIVE AND NON-INVASIVE INVESTIGATIONS

As described above, the use of existing invasive data (CPTs and boreholes) when it is available greatly helps to increase the robustness of the MASW data processing procedure. In the Port example, geological interpretations from the pre-existing invasive tests were also able to be matched to the Vs profiles obtained from the MASW investigations. This allowed for the mapping of the thickness and depth of geological layers across the Port site including across areas where invasive testing was not possible. From the general geological sequence found in boreholes together with the observed Vs step changes in the MASW inversion models, the following Vs value ranges were identified for the four different lithologies across the Port site:

1.	Reclamation Fill	≈ 110 – 220 m/s (average 165 m/s)
2.	Estuarine Deposits/Marine Sediments	≈ 150 – 250 m/s (average 190 m/s)
3.	Alluvium	≈ 210 – 330 m/s (average 265 m/s)
4.	Underlying Gravel	≈ 280 – 500 m/s (average 395 m/s)

The non-invasive MASW results were also of use in calibrating shear wave velocity estimates based on CPT data to the local site conditions. In this case, while estimates of Vs based on existing CPT data (McGann et al., 2015; and Barounis et al., 2019) generally agreed with the velocity trends with depth found via MASW, the estimated Vs values were generally lower using the CPT method than MASW. It was concluded that CPT correlations based on Christchurch soils (alluvial sands/silts) were not applicable to the marine and reclamation environment of the Port. The geotechnical team thus adapted the correlation used by Hegazy and Mayne (1995) to estimate Vs from CPT data and extended the Vs estimates obtained down to 30 m depth by using the Boore et al. (2011) correlation. The resulting shear wave velocities obtained using the Hegazy and Mayne (1995) approach were found to generally agree well with the measured MASW shear wave velocities.

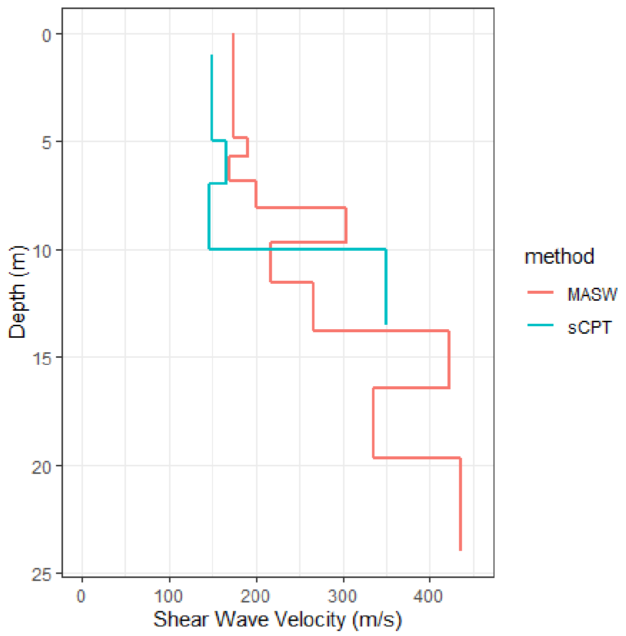

Figure 5: Comparison of Vs profiles obtained by MASW and sCPT, at locations approximately 50m apart, at the Port. sCPT data measured by RDCL.

One limitation of the MASW technique is that the vertical resolution of the obtained Vs profiles is approximately ± 0.5 m for shallow layers and increases to approximately ± 1.0 m with increasing depth. This is reflected in the fact that the measured MASW shear wave velocity profiles trends generally agreed better with intrusive data at shallower depths (3-12 mbgl) than for deeper soil layers (> 12 mbgl). Another consequence of the resolution of the MASW method is that relatively thin layers of significantly varying Vs may not be fully resolved. In the Port example, this was likely the case for a very soft marine sediment interval found around 5-9m depth (varying across the site). This layer represented the only significant discrepancy between the measured (MASW) and calculated (CPT) V_S profiles. While the MASW inversion models did identify the layer and its decreased Vs compared to surrounding layers, it generally indicated a higher velocity than the correlated CPTs.

A significant advantage of using the non-invasive MASW technique in shear wave velocity investigations is that a general picture of the site can be gained at a relatively low cost, with results used to guide the most beneficial locations for targeted further invasive investigations. In the Port case, following the completion of the MASW investigation, five additional sCPTs were measured within the boundary of the site and were used to back-check the results from the geophysical survey. In general, the sCPT shear wave velocity models agreed well with the nearest MASW shear wave velocity models obtained (Fig. 5), with differences between the two being within the error of both methods.

6 CONCLUSIONS

In the case study presented, non-invasive MASW investigations were successfully integrated with data from pre-existing invasive investigations at a Port site to give a comprehensive and robust assessment of shear wave velocity variations across the site. Further targeted invasive tests were guided by the results of the MASW investigation, with results lending weight to the interpretations given.

With the release of the revised national seismic hazard model in 2022 and the integration of Vs30 into national building codes, the presented case study is a timely example of how non-invasive and invasive shear wave velocity investigations can be carried out in unison to provide a complete seismic assessment of a large heterogeneous site.

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