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Using Multi-Channel Analysis of Surface Waves and Cone Penetrometer Tests to delineate an in-filled palaeochannel during routine investigations – A Christchurch Earthquake Case Study

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ABSTRACT: The major events of the Canterbury Earthquake Sequence (CES) caused significant land and building damage in Christchurch between September 2010 and December 2011. The extensive damage necessitated detailed ground investigations and liquefaction hazard assessments to inform repair and rebuild options. Relying solely on intrusive testing to provide sufficient information for ground characterisation, risk assessments and design is often costly, particularly for large sites, and can be limited by site access. Combining traditional intrusive methods with non-intrusive geophysical investigations has proven to be an economical and time-saving approach and can aid in delineating abrupt changes in ground stratigraphy.
This paper presents a case study site where a combination of Multi-channel Analysis of Surface Waves (MASW) profiles and Cone Penetrometer Tests (CPTs) were used to outline the extents of an in-filled palaeochannel. The contrasting land and building damage at the site is described, together with the importance of a detailed desktop study. The MASW and CPT results are correlated with observations of damage, and the effectiveness of combining the two investigation techniques is highlighted.

1 BACKGROUND

The four major earthquakes and aftershocks of the Canterbury Earthquake Sequence (CES) between 4th September 2011 and 23rd December 2011 caused significant land and building damage. This has led to an estimated rebuild industry of NZ$40 billion (Potter et al 2015). There were around 15,000 residential houses and properties with severe damage from liquefaction and lateral-spreading related phenomena (Kaiser et al 2012).

The late Quaternary (Holocene-age) near surface geology of the Christchurch area is made up of coastal and marine deposits (Christchurch Formation) and fluvial deposits (Springston Formation) (Brown et al 1995). The variability in depositional environments since the last glaciations has led to significant lateral and vertical variability in the near surface, including numerous buried palaeochannels. The loose, water saturated, and uniformly graded sand and silt units within the Christchurch and Springston Formations are susceptible to liquefaction (e.g. Brown et al 1995). Differential behavior of the near surface soils caused extensive damage during the CES (Kaiser et al 2011).

Significant effort during the rebuild has therefore been put into ensuring that adequate geotechnical investigations are undertaken to quantify liquefaction potential and to support the design of resilient foundations and ground remediation strategies. Relying solely on intrusive investigations, in particular boreholes and cone penetrometer tests (CPTs), can be costly and sometimes logistically difficult in developed residential areas with limited access. An appropriate combination of intrusive testing and non-intrusive geophysical methods can often provide cost effective and detailed ground characterisation in areas with variable ground stratigraphy and difficult access.

Geophysics has been used to support intrusive investigations at a large number of complex sites in Christchurch. This paper describes one case study that highlights many of the advantages associated with this approach. The study site had considerable variability in ground conditions and there was significant but 'localised' land and building damage. A combination of geophysical methods and CPTs were used to delineate the structure of an in-filled palaeochannel crossing the site, to evaluate site ground conditions, to explain the observed land and building damage, and to inform development options. The investigation provided a more cost effective and timely ground investigation compared to alternative traditional intrusive investigations.

2 THE SITE AND NATURE OF DAMAGE

The site is located at Cresselly Place, St Martins Christchurch, within a 'point bar' of the Heathcote River (see Figs 1 & 2 below).

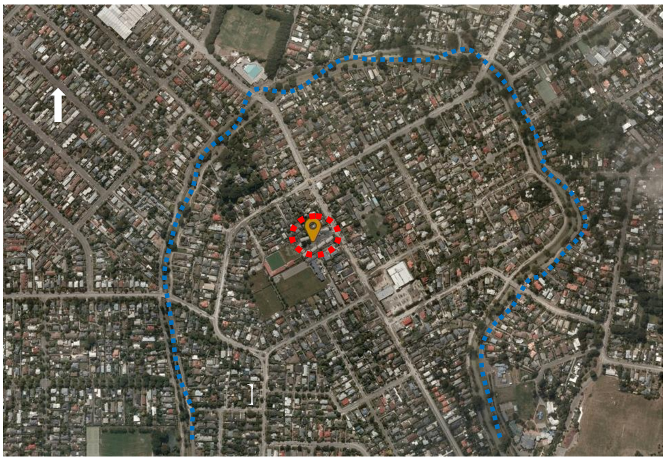

Figure 1 – Site location and relation to Heathcote River (blue dashed line). Image background from LINZ Crown Copyright Reserved.

Figure 2 – Site detail (note building locations). Image background from LINZ Crown Copyright Reserved.

The site experienced land damage in the form of ground settlement and ground cracks which were recorded by the Earthquake Commission (EQC, a Crown Entity) and its partners (CGD, 2016). A desktop review highlighted a global settlement pattern indicating a potential in-filled channel crossing the site, based on LiDAR data from the Canterbury Geotechnical Database (CGD) (Figs 3 & 4).

Building D, which appeared to straddle the edge of the channel, showed significant hogging (Fig 5). Building C sagged towards the middle, which correlates with its location near the centre of the in-filled channel. There was also up to 40 mm lateral stretch across Building D foundations and veneer around the inferred channel boundaries. Damage observed around other buildings also supported the hypothesis of the in-filled channel shown on Figure 4.

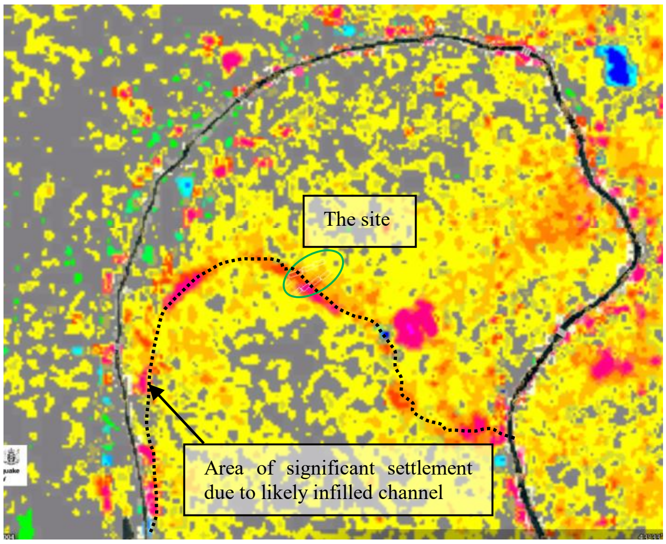

Figure 3 – LiDAR vertical movement (no tectonic component) from CES events between 4th September 2010 and 23rd December 2011. Sourced from CGD (2016).

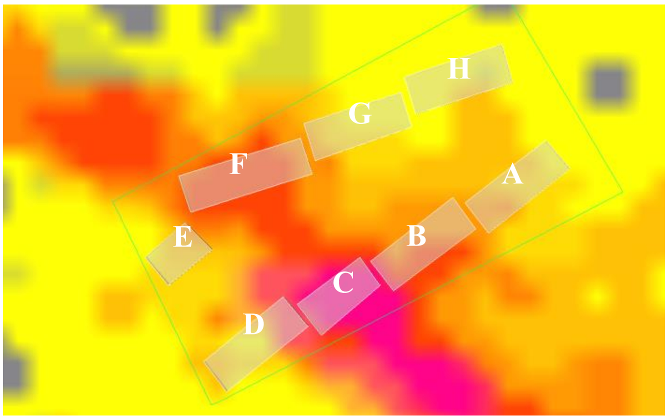

Figure 4 – LiDAR Vertical Movement from CES (site detail with building locations).

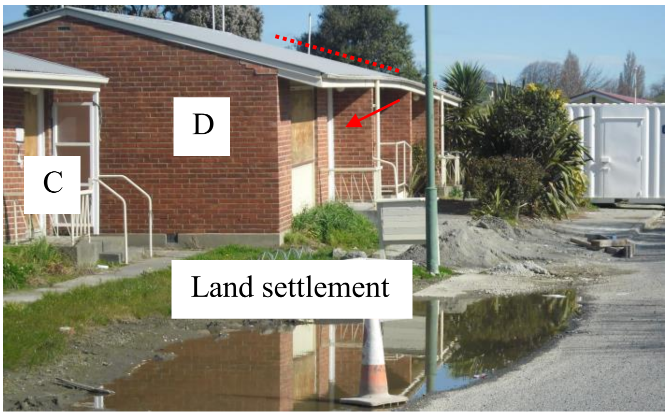

Figure 5 – Building D differential settlement (view roof line). Building 'broken' around dotted line.

3 SITE INVESTIGATION METHODS

3.1 *Desktop review and site walkover*

Prior to proposing geotechnical and geophysical investigations, a desktop review and site walkover was undertaken. The review indicated that damage at the site was likely related to changes in ground stratigraphy from a historical channel. The in-filled channel hypothesis contrasted earlier investigations, which proposed lateral spreading as the cause of land and building damage. It is noted that Cresselly Place is at least 300m from the nearest bank of the Heathcote River and previous studies probably did not have the benefit of reviewing the CGD global settlement data, which shows ground settlement occurred along a lineament, interpreted here to be a palaeochannel feature.

3.2 *Site Investigations*

A combination of eight CPTs and four MASW survey lines were undertaken in 2013 to delineate the extents of the in-filled channel and soil stratigraphy across the site. The investigation locations are shown on Figure 6, and include an additional seismic CPT and machine drilled borehole undertaken by others in 2015 (CGD, 2016).

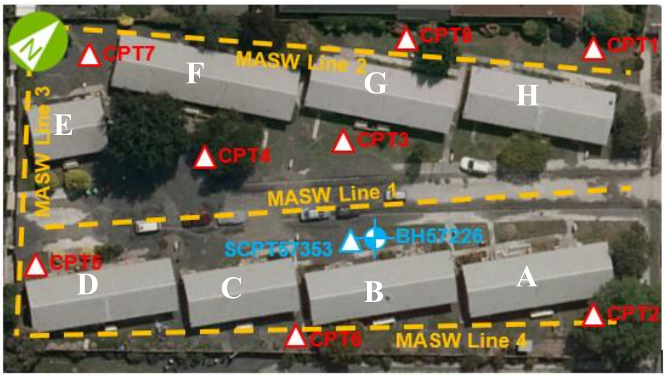

Figure 6 – Extent of investigations undertaken.

A staged approach was adopted with MASW soundings completed first and used to plan the distribution of the CPT positions.

3.3 *MASW*

MASW is a geophysical technique that uses the dispersive nature of surface waves to model the shear-wave velocity (Vs) versus depth of the subsurface (Park et al 1999). The propagation velocity model of the recorded surface waves is inverted to find the Vs velocity model that best fits the observed propagation velocity pattern (Park et al 1999).

MASW shot records were collected at 5m spacing along the survey lines using a 24 channel towed seismic array with 1m geophone spacing and a source offset of 10m. The field records were processed using the Kansas Geological Survey software package SurfSeis4©. The velocity data was interpolated into two dimensional Vs profiles for the MASW lines.

The orientation of the MASW survey lines (Fig 6) was planned to optimise coverage across the site and to identify any abrupt changes in Vs.

3.4 *Cone Penetration Tests (CPTs)*

Eight CPTs were undertaken with positions based on results from geophysical testing and site access constraints along the northern and southern site boundaries. The CPTs targeted the middle and edges of the inferred channel, as well as ground outside the channel. The CPTs were conducted to 18m depth, near the top of the Riccarton Gravels Formation, which underlies the Springston Formation. The CPTs were not extended into the Riccarton gravels to minimise potential issues with artesian flow.

3.5 *Liquefaction Assessment*

A liquefaction hazard assessment was undertaken based on Idriss and Boulanger (2008), and Zhang et al (2002). The aim of the assessment was to identify the soil layers that could have liquefied during the major earthquakes of the CES and the likely magnitude of settlement. For this paper, back-analysis of the 22 February 2011 Mw6.2 earthquake has been re-run based on Boulanger and Idriss (2014) to highlight contrasting liquefaction potential at either ends of the inferred channel.

4 RESULTS

4.1 *CPT Results*

A summary of the CPTs is presented on Figures 7 and 8 indicating normalized cone penetration resistance (Qt) and Soil Behavior Type Index (Ic) with depth. The results indicate the following:

- The logs of CPT1 and CPT2, at the eastern end of the site with less observed settlement, show dense sands and gravelly sands from 3m to 4m depth extending to at least 10m depth. This relatively thick dense layer is generally absent in all other CPTs at shallow depth.
- The logs of CPT4 and CPT6 located in the 'middle' of the inferred channel, show soils with relatively low Qt cone resistance to minimum 14m depth. Organic layers are also interpreted between 11m and 13m depth in CPT6.
- Other CPTs show varying ground conditions, with the medium dense to dense layer only encountered in thin layers and generally not as strong as in CPT1 and CPT2.

Based on the CPT results, it can be inferred that CPT1 and CPT2 are outside the infilled channel, CPT4 and CPT6 are in the channel, and the rest are probably in transition zones. The CPT results therefore support the hypothesis that there is a historical channel and the nature of land and building damage is directly related to variability in ground conditions.

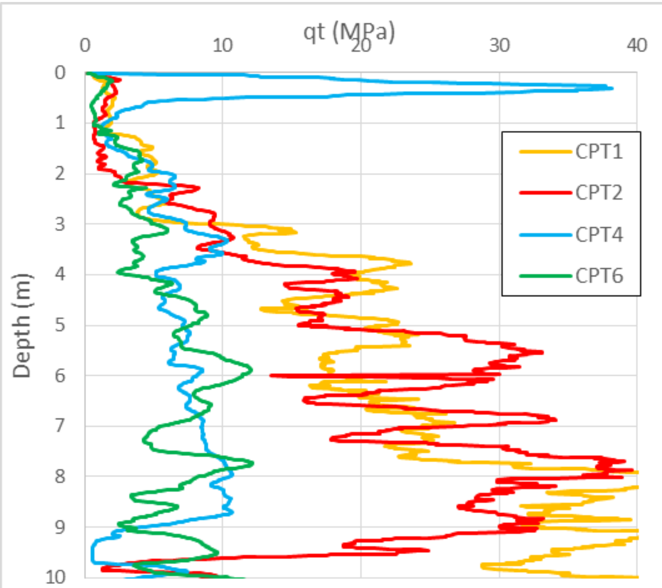

Figure 7 – Normalised cone resistance Vs depth (upper 10m profile and only CPTs 1, 2, 4, 6 shown for clarity).

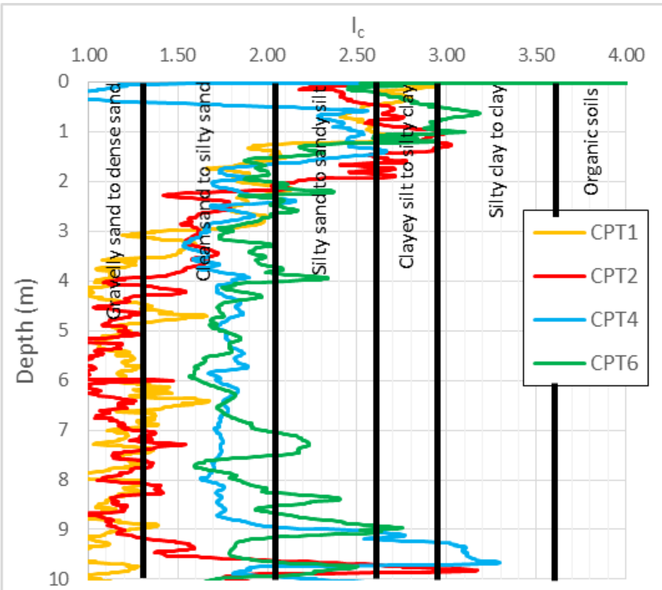

Figure 8 – Soil Behaviour Type Index (Ic) Vs depth (upper 10m profile and only CPTs 1, 2, 4, 6 shown for clarity).

4.2 *Liquefaction Assessment Results*

The liquefaction assessment results for CPTs 1, 2, 4, and 6 are presented in Figures 9 and 10 for the upper 10m profile. The results show the following:

- CPTs 1 and 2, at the eastern end of the site with less settlement, show no liquefiable layer below 3m depth to at least 10m. The assessed liquefaction settlement is generally less than 50mm.
- CPTs 4 and 6, located in the middle of the inferred channel, have potentially liquefiable layers from below the groundwater table to at least 10m depth. The assessed liquefaction induced settlement is generally more than 150mm.

The results of the liquefaction assessment were consistent with site observations. Areas where more liquefaction induced settlement was observed were assessed to have thicker calculated liquefaction layers and larger magnitudes of calculated free field settlement. The liquefaction assessment also supports the hypothesis of a historical channel and that the nature of observed damage is directly related to variability in ground conditions.

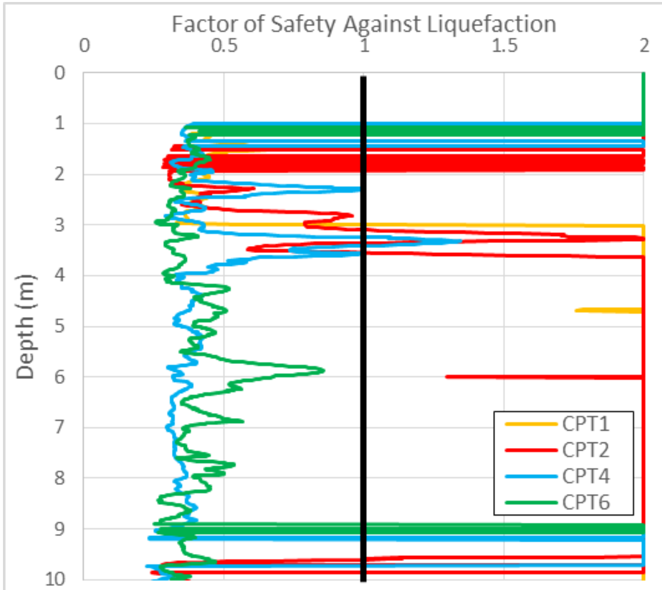

Figure 9 – Factor of Safety Against Liquefaction Vs depth (upper 10m profile and only CPTs 1, 2, 4, 6 shown for clarity).

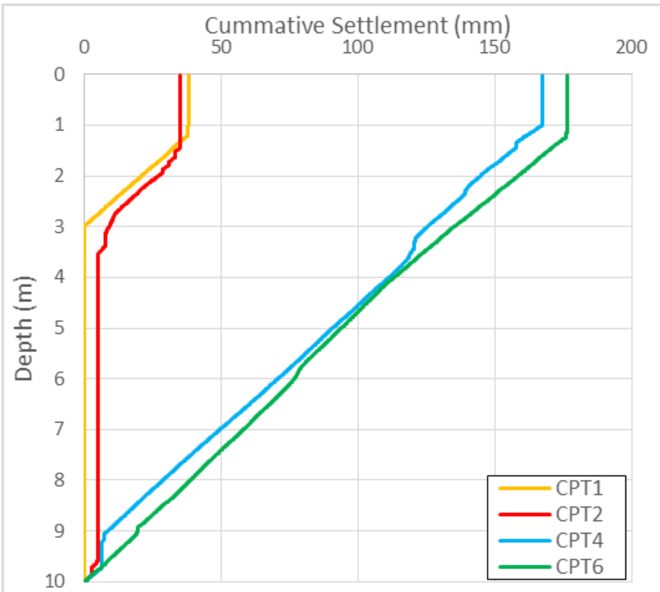

Figure 10 – Liquefaction Induced Reconsolidation Settlement Vs depth (upper 10m profile and only CPTs 1, 2, 4, 6 shown for clarity).

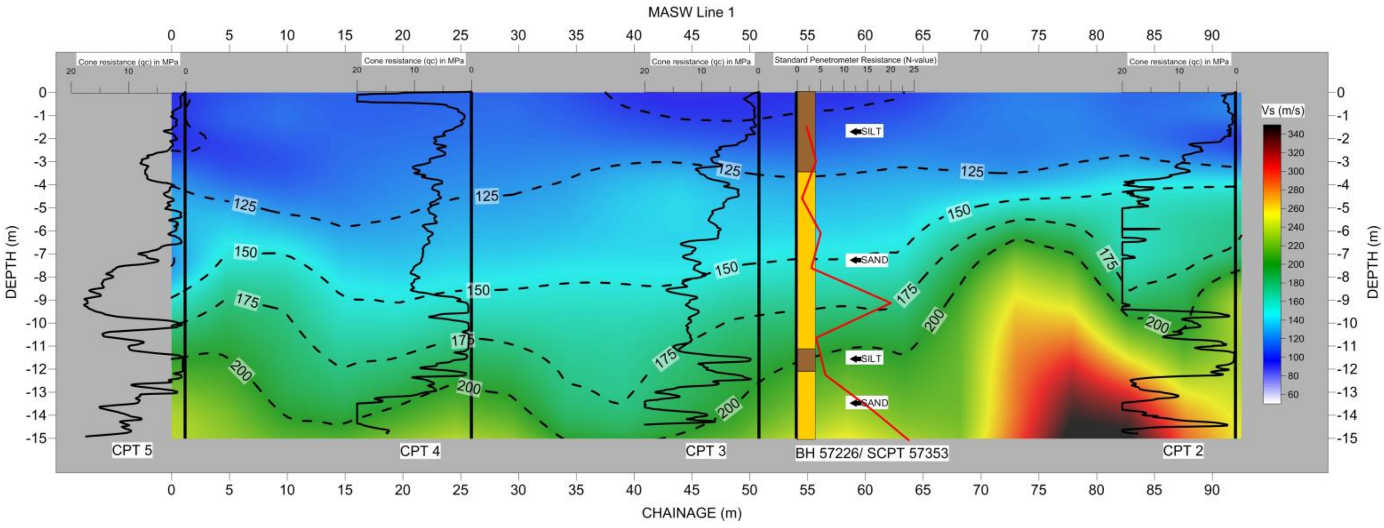

Figure 11 – MASW Line 1 plot superimposed with results of intrusive investigations.

4.3 *MASW*

The MASW results show low V_s (<100 m/s to 175 m/s) material in the upper 4m on the eastern end of the site thickening to over 10m depth near the centre of the site and then thinning towards the western end.

MASW Line 1 represents a typical west to east MASW profile across the site (Fig 11). Figure 11 includes CPTs 2, 3, 4, 5 and BH_57226 superimposed onto the plot for comparison purposes. The plots show good correlations between inferred strata based on MASW shear wave velocities and that from CPT tip resistance and borehole SPT tests. It can be inferred, based on the results, that the base of the paleochannel is coincident with shear wave velocities in the range of 170m/s to 180m/s.

It is worth noting that the MASW plot does not clearly show the weaker layers beneath stronger layers, such as in CPT5 below 11m depth (see Fig 11). While this is not critical for this study, care should be taken when interpreting MASW plots with V_s inversions. In such cases, it is recommended to review the raw shear wave velocity data and inversion modeling parameters if relying on the strength of specific layers for engineering purposes.

4.4 *Implication of results and observed damage*

A comparison between MASW and CPT profiles, borehole records, and the nature of observed damage shows the following:

- The MASW plots generally correlate well with CPT profiles and show the depth to the dense sandy layer. This is interpreted to be the base of a historical infilled palaeochannel.
- The nature of observed land damage is directly related to variability in ground stratigraphy. More settlement was recorded towards the western end of the site in locations similar to those identified on CPT and MASW plots with less dense sands and silts.
- Building damage can be explained based on building locations in the inferred channel profile. Building D straddled the low V_s part of the channel profile and transition zones while Building C was in the middle where larger magnitudes of settlement could be expected based on ground stratigraphy.
- Ground cracks recorded at the site appear to coincide with areas of sudden changes in ground stratigraphy based on MASW plots.

A combination of MASW and CPTs can therefore be effectively used to delineate sudden changes in ground stratigraphy and inform likely future land and building damage in liquefaction prone areas.

5 CONCLUSIONS

This case study at Cresselly Place highlights the potential for MASW to identify in-filled channels and abrupt changes in ground stratigraphy, which can have a significant influence on future land and building damage particularly in liquefaction prone areas.

At Cresselly Place, it was demonstrated that MASW findings correlated with CPTs, boreholes, and observed damage. MASW, with the ability to collect more data points at relatively low cost, can therefore be used in forensic and routine site investigations to produce 2D profiles between intrusive investigation points.

At Cresselly Place, it was possible to complete MASW lines in some areas where even small CPT rigs could not access. The versatility of the system has been successfully adopted for numerous site investigations in Christchurch.

Finally, the desktop review found critical information on the site, the advantage of which when planning site investigations cannot be overstated. At Cresselly Place, without the benefit of global vertical settlement data, CPTs supplemented with one or two boreholes could have been considered appropriate for the redevelopment. However, CPTs and boreholes on their own could not have provided a complete explanation for the differing ground conditions, and may have led to conservative rebuild and remediation strategies based on unknown risks.

6 RECOMMENDATIONS

The following should be noted when utilising MASW (and any other non-intrusive investigation technique) for ground characterisations in the course of a geotechnical investigation:

- MASW investigations should be combined with intrusive investigations such as CPTs or boreholes, to allow for physical sampling and geological correlation of V_s variations.
- A staged approach should be adopted where practicable, to allow preliminary findings from MASW to be used to inform targeted and more expensive intrusive investigations.
- MASW may not be appropriate for some subsurface conditions, and may be limited in its ability to model high jumps in V_s (i.e. soil to bedrock), V_s inversions (i.e. gravels to marine silts), and sharp vertical changes in V_s (i.e. steeply dipping channel edges or fault planes). Engineers should consult with a qualified geophysicist to identify limitations specific to a site, and alternative solutions.

7 ACKOWLEDGEMENTS

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