Innovative Methods in the In-situ Determination of Design Parameters on Heterogeneous Sites Subject To Ground Treatment Using Deep Impact Compaction

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ABSTRACT

Demographic shifts are forcing more frequent development of sites having heterogeneous sub-surface characteristics with unsuitable and variable settlement potential. Delineation of ground conditions at these sites is often based on testing at a limited number of locations. While the means of determining soil parameters from specific test results are well established they are of limited use without sufficient information on the spatial variability and heterogeneity of the site. Consequently, recommended ground treatment methodologies and subsequent inferred soil parameters used for design purposes are likely to be conservative. Innovative technologies have been developed that assist in the determining spatial variations across heterogeneous sites that enable the formulation of more cost effective and realistic foundation design models.

Case studies are presented where the ground treatment on some heterogeneous sites with deep impact compaction and in-situ testing has been enhanced using innovative technologies such as continuous impact response technology (CIR) and Multi-channel Analysis of Surface Waves (MASW). CIR determines the soil response over the whole site to the high dynamic loads induced by each impact load and identifies localized soft areas and weak sub-surface strata that could have adverse effects on foundation performance. MASW is a non-invasive seismic method that provides a continuous 2D sub-surface profile with the ability to detect weak layers below stronger layers.

The Case studies demonstrate the use CIR and MASW technology in determining spatial variation on heterogeneous sites.

1 INTRODUCTION

The poor load-carrying properties of many non-engineered fills have been associated with their heterogeneity (Hardie 1999). Generally, most geotechnical testing methods only indicate subsurface conditions at specific locations. They cannot necessarily be relied upon to accurately reflect strata variations which may exist between test or sample locations. The soil parameters assigned to soil profiles are also generally based on the combination of in-situ test, laboratory testing and experience and are normally engineer dependent. Consequently, without adequate information on the nature and location of spatial variation on site, soil parameters assigned by engineers are likely to be conservative.

Monitoring of Impact Compaction on sites with variable subsurface conditions play a key role in the determination of soil parameters for the design and construction of structures. The performance of Impact Compaction in the treatment of heterogeneous or variable fill sites has previously relied on the geotechnical supervision and visual observation of the works and in-situ geotechnical testing at discrete locations. This approach can be inadequate as footing performance may be adversely affected by local zones deleterious or weak material within the sub-surface that does not exhibit visual heave or surface deflection during Impact Compaction and was not identified by in-situ testing at discrete locations.

We have recently applied innovative technologies such as CIR and MASW on sites subject to ground treatment using Deep Impact Compaction to assist in the identification of the spatial variation present on heterogeneous and variable fill sites. These non-invasive testing techniques provide quick and accurate on the stiffness variations in the subsurface to a depth that allows confidence in the design of high level footings.

2 CONTINUOUS IMPACT RESPONSE (CIR) TECHNOLOGY

2.1 Description

During Compaction the impact compactor drums (Figure 1) exert high dynamic loads on the sub-grade at regular intervals across the compaction area. The peak deceleration of the compaction mass is directly related to the resistance offered at contact resulting from the stiffness and shearing resistance of the material (B. Clegg 1980). As the sub-grade density and stiffness increase with compaction, the deceleration rates of the impact compactor drums also increase (Figure 2).

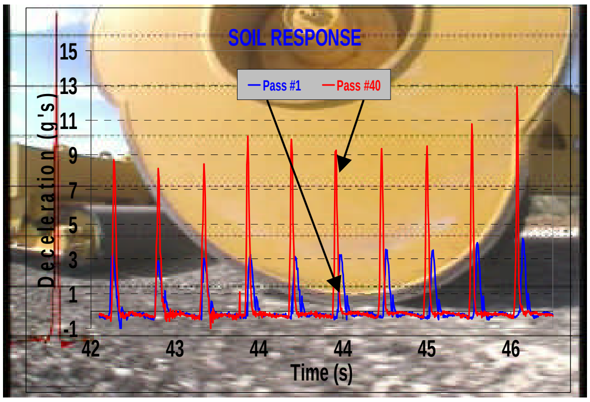
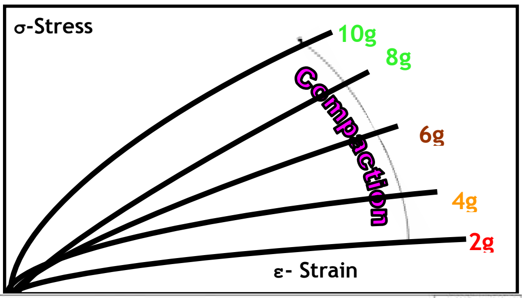


Figure 1: Peak Impact Drum Decelerations

Figure 2: Illustration-Deceleration with Compaction



The CIR technology measures the deceleration rates of the impact drum assembly and records the location co-ordinates with integrated GPS technology (Figure 3). The measured g-values indicate the average sub-grade stiffness over the CIR zone of influence.

The recorded g-values and correspoding co-ordinates are imported onto the site plans and colours are assigned to the range of g-values measured across the site (See Figure 4). The CIR plots indicate the varying degrees of sub-grade stiffness across the site. Lower g-values on the CIR plot typically indicate weaker sub-surface materials.

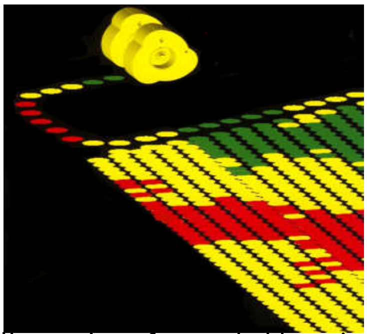


Figure 3: Illustration of recorded locations

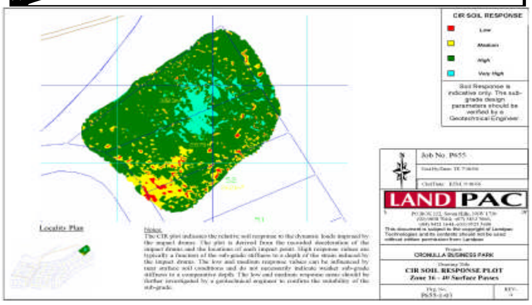


Figure 4: Example of CIR Plot

2.2 CIR-Zone of Influence

The CIR zone of influence is governed principally by the depth to which strain is induced in the sub-grade by the high dynamic loads exerted by the impact drum assembly. This depth is a function of the size and type of the Impact compactor used and the sub-grade stiffness.

To evaluate the depth of the CIR zone of influence, a correlation analysis was conducted between the measured g-values and 30 Cone Penetration tests (CPTs) at a site at Kurnell in Sydney that was subject to Impact Compaction. This site required densification of very loose and loose sands to depths of 5.5 metres and was compacted to refusal using a Landpac 3-sided (135kJ Kinetic Energy) Impact Compactor. The CIR system was applied at regular intervals during the impact compaction works and the locations of the recorded g-values were determined using differential GPS. The CPTs extended to a depth of 6m and the locations of each CPT were recorded by a registered surveyor.

The g-values after compaction refusal (zero compaction induced settlement) at the CPT locations and averaged CPT cone resistance values to varying depths were used for the correlation analysis. The correlation coefficients (r) and coefficients of determination (R^2) are given in Table 1.

Table 1: Correlation Analysis Results

	Depth (metres)					
	0-1m	**0-2.0m**	**0-2.5m**	**0-3.0m**	**0-4.0m**	**0-5.0m**
Correlation Coefficient (r)	0.5	0.8	0.6	0.3	0.04	-0.12
Coefficient of Determination (R^2)	25%	64%	36%	9%	0.16%	1.4%

Table 1 indicates that there is a significant relationship between the CIR g-values and the soil strength to a depth of 2 to 2.5 metres. Although the compaction strain induced in the sub-grade by the high dynamic impact loads extends beyond 2.5m depth (Figure 5) the relationship between the measured CIR g-values and CPT cone resistance values was not significant beyond 2.5m depth.

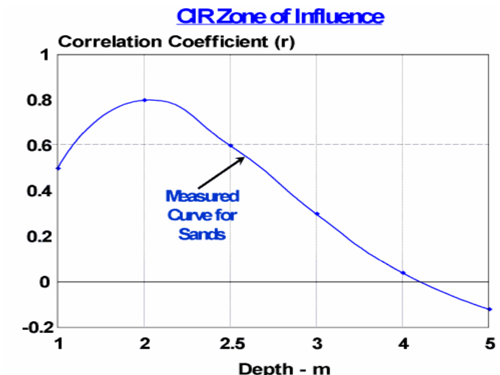


Figure 5: Correlation Curve

3 MASW TECHNOLOGY

3.1 Description

The MASW test can provide a 2-D stiffness profile over whatever investigation length and depth is desired. For the test, an impact source generates surface waves that disperse through the area of interest. The geophones, placed at known locations, typically 1m apart, record the vertical movement vs time of the ground perpendicular to the impact source and a shot record is produced as illustrated in Figure 6 (Park and Miller 2004).

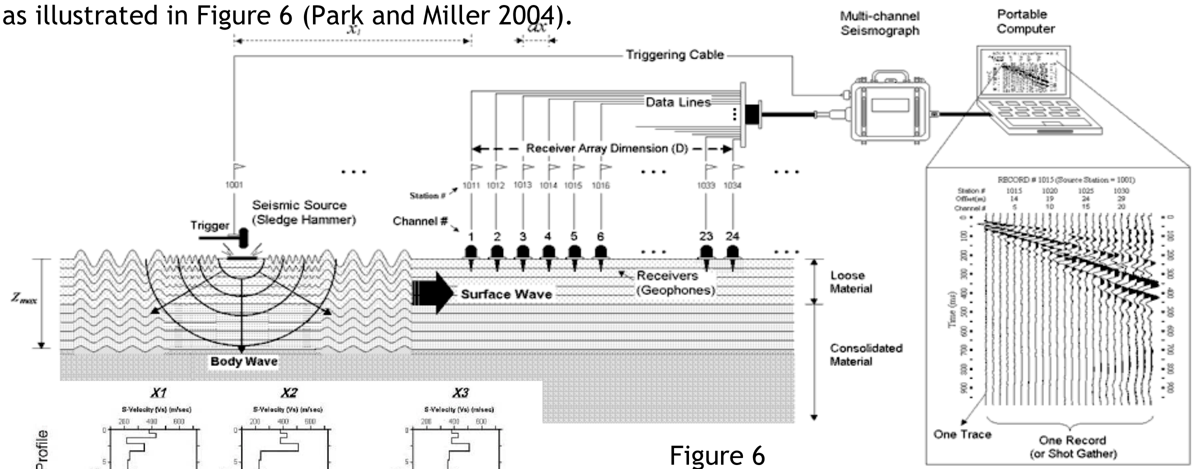


Figure 6

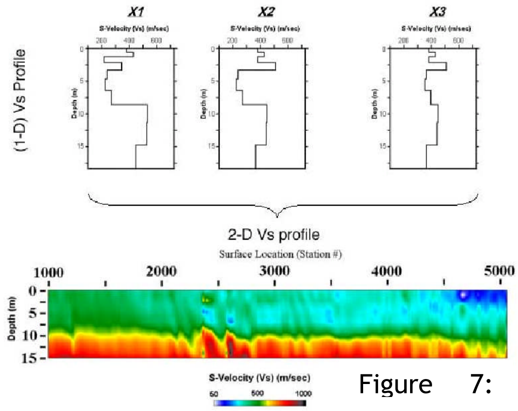


Figure 7:

This shot record is processed digitally using specialist software using a fast Fourier Transform after which, dispersion curves can be picked representing the fundamental Rayleigh waves. The dispersion curves are used in an inversion analysis that provides 1D stiffness profiles. A model within up to 20 variable thickness layers is used for the inversion analysis. Multiple 1D stiffness profiles can be used to produce a 2D stiffness profile of the survey line as illustrated in Figure 7 (Parl and Miller 2005). The stiffness is typically represented as shear wave velocity but with the use of an assumed Poisson's Ratio and Bulk Density the Shear Modulus and Young's Modulus can be calculated. The MASW differs from more conventional seismic methods such as refraction and reflection in that it can locate weak layers beneath strong layers.

The horizontal resolution of the MASW method is related to the number of channels used to acquire a dispersion curve that provides a 1D stiffness profile. Typically, if good quality shot record can be acquired the number of channels used can be reduced to 12 (generally at 1m spacing) with 1D profiles generated every metre if necessary to help identify a subsurface feature.

4 CASE STUDIES

4.1 Infrastructure Development on Heterogeneous Shallow Landfill

4.1.1 Site Description

The site located at Tugun on the Gold Coast, Queensland had about 4m of landfill over naturally occurring loose to dense sand. The landfill was reported to have been placed 20 to 40 years ago and consisted predominantly of inert waste material with small amounts of biodegradable waste.

It was proposed to build a desalination plant at the site and consideration was given to the in-situ ground improvement of the landfill material using Impact Compaction. A trial was conducted using impact compaction with a Landpac three sided 135 kJ Kinetic Energy machine.

To monitor the effect of the in-situ ground improvement pre and post MASW, CIR and Settlement Monitoring were conducted.

4.1.2 Pre and Post MASW Testing

Pre and post MASW testing consisted of three 70m long lines (A, B and C), spaced 10m apart and are presented below:

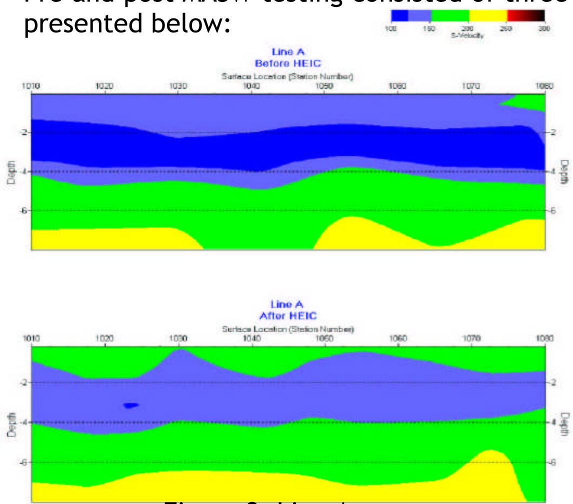


Figure 8: Line A

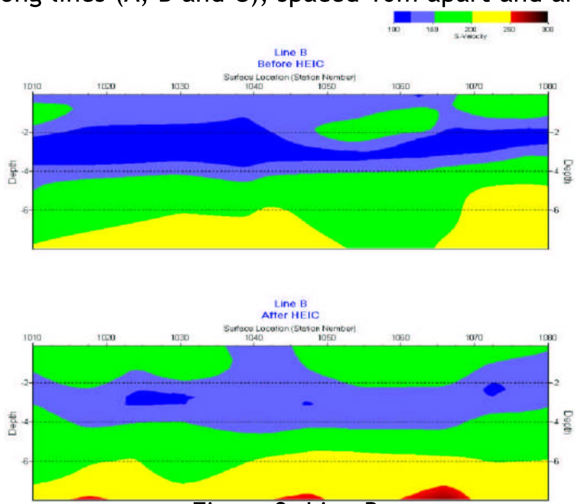


Figure 9: Line B

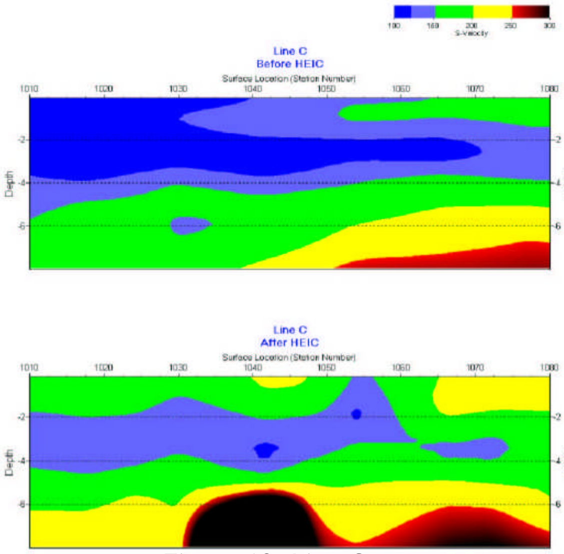


Figure 10: Line C

Line: A. (Figure 8) The pre-compaction plot shows relatively weak material (Vs<150m/s) from the surface with very weak material (Vs<120m/s) from 2-4m. The lower underlying material (Vs<200m/s) is likely to represent the natural sand. The post compaction test shows a significant increase in shear wave velocity over the top 4m with the virtual elimination of the very weak layer from 2 to 4m depth.

Lines: B & C. (Figure 9 and 10) The post compaction tests show a similar result to Line A with a significant improvement over the top 4m and the virtual elimination of the very weak (Vs<120 m/s) layer. The effect of the impact compaction, as recorded by the increase in shear wave velocity by the MASW, will be significantly less primary settlement of the landfill material under an applied load from the proposed development.

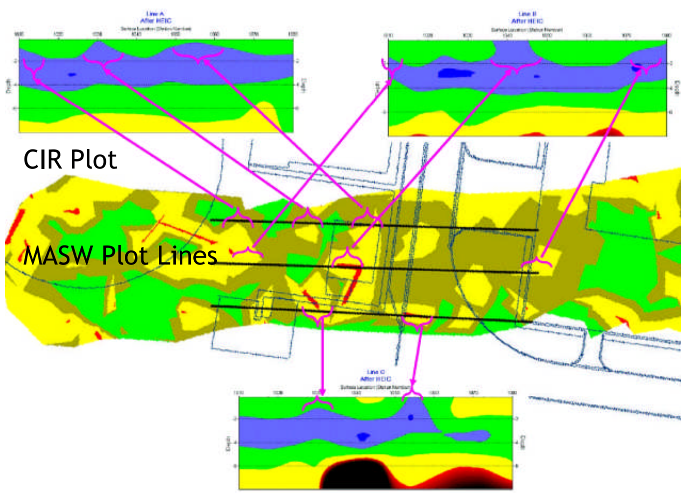


Figure 11: CIR and MASW

4.1.3 CIR Monitoring

The CIR plot from this site is shown in Figure 11. The areas of weak sub-grade on this plot (Figure 11) appear to correlate reasonably well with the lower shear velocity zones observed on the post-MASW sections.

The CIR monitoring and MASW testing indicated that significant increases in strength were achieved in the landfill material and underlying natural sands with the use of Impact compaction.

Localised areas with weaker sub-surface material that would adversely affect footing performance were identified with the corresponding use of CIR and MASW technology.

4.2 Industrial Development on "Uncontrolled Variable Fill"

4.2.1 Site Description

A portion of the site located at Yatala on the Gold Coast, Queensland had 1 to 4m of uncontrolled sandy clay/clayey sand fill overlying natural silty clay and extremely weathered sandstone. A previous geotechnical report suggested the area was filled in two stages with the upper half being placed under controlled conditions and the lower layer having been placed some time earlier in an uncontrolled manner. In-situ ground treatment was performed with a Landpac three sided 135 kJ Kinetic Energy machine.

4.2.2 CIR Monitoring

The CIR monitoring during the ground treatment identified several areas with a low to medium sub-grade response (Figure 12). Test pits were excavated at these locations and weak clay well above its optimum moisture content was discovered below the stiffer upper layer. These areas were removed and replaced with suitable material and compacted with impact compaction.

The remediated areas were then re-tested with CIR monitoring and MASW testing to assess the bearing suitability for high level footings.

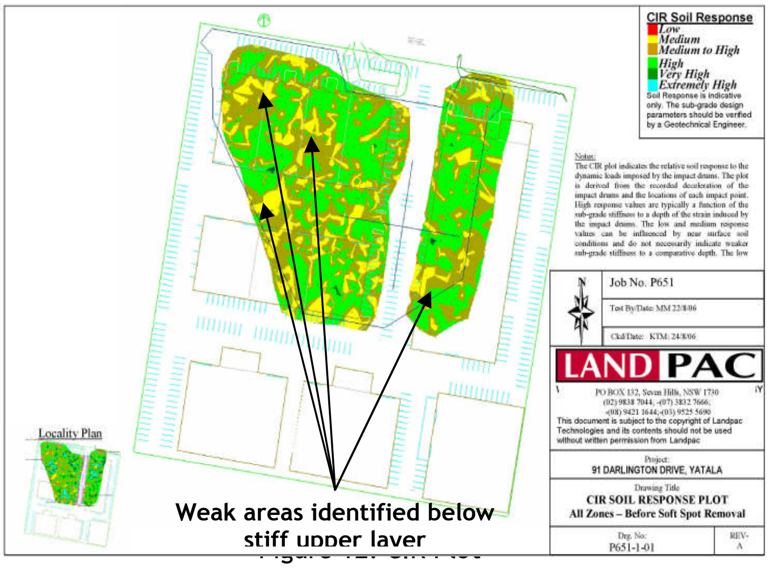


Figure 12: CIR Plot

4.2.3 MASW Testing

Two MASW survey lines are presented below after the ground treatment had taken place:

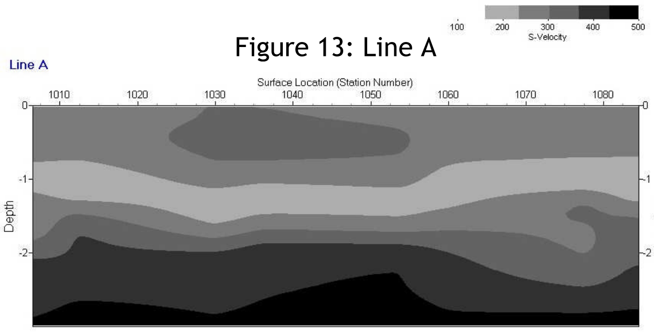


Figure 13: Line A

Line A: (Figure 13) This line shows there is about 1.5m of fill, the top half of which is stiffer than the bottom half. This is consistent with the 2 staged filling of the site. The low velocity layer is between 150 and 240 m/s.

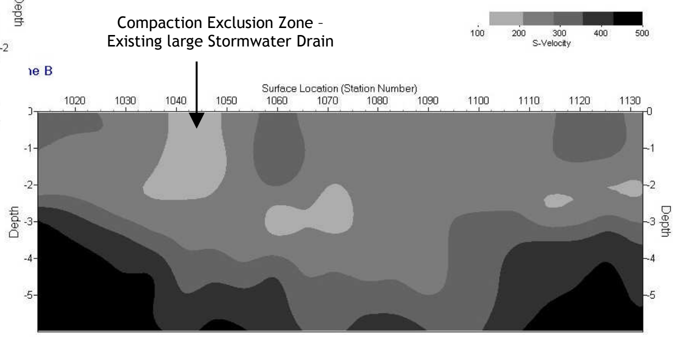


Figure 14: Line B

Line B: (Figure 14) This line was located perpendicular to an original creek that was filled. The fill depth varies from 4m in the centre to 2m to the east. The presence of an existing underground stormwater drain within an impact compaction exclusion zone can clearly be seen between approximate Ch 1040 - 1050.

4.3 Industrial Warehouse development on a Heterogeneous site

4.3.1 Site Description

The site located at Eagle Farm, Brisbane was developed as a distribution warehouse with high level footings and slab-on ground construction. The subsurface consisted predominantly of 1-2m of un-engineered gravely clay fill over a 1-2m thick weak clay layer over a 2-4m thick very loose or loose clayey sand stratum. Groundwater was recorded at approximately 2m below the surface.

4.3.2 CIR Monitoring and MASW tests

Areas with subsurface weak clay/silty material at 2.0 to 2.5m depth were identified with the use of CIR. No surface deflection or heaving was evident on the surface during the impact compaction. MASW tests were conducted to ascertain if the depth and strength of the weak clay would adversely affect high level footing performance.

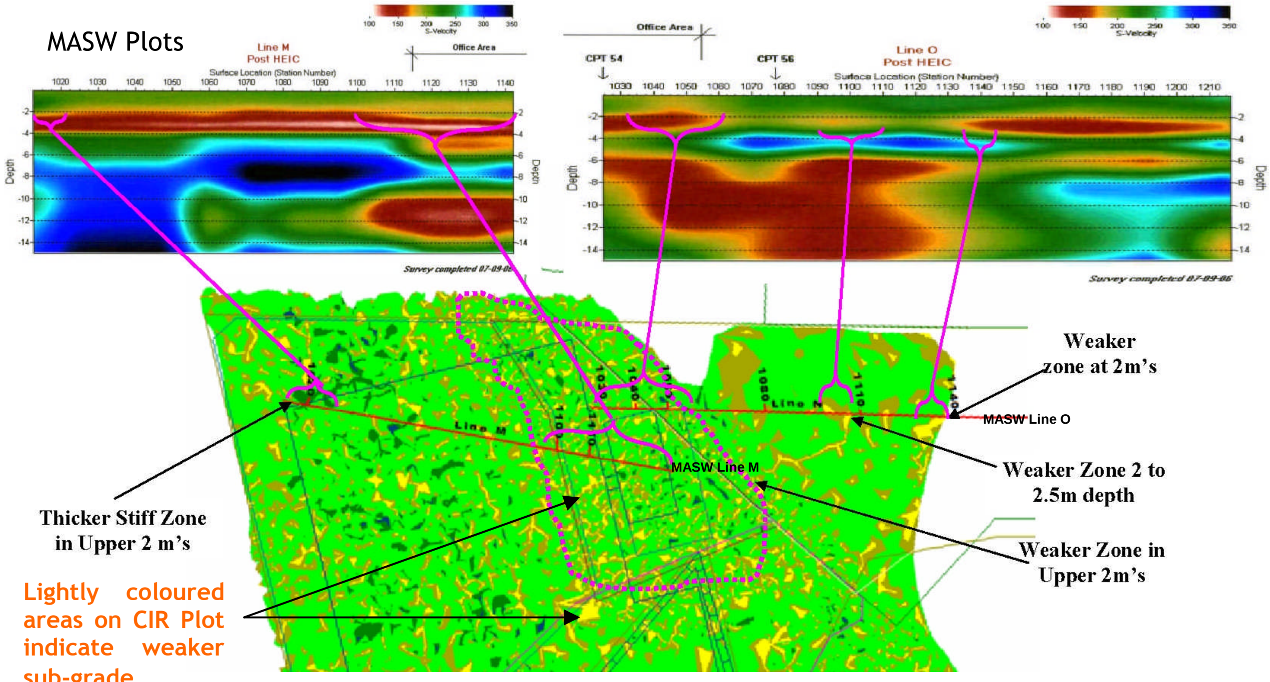


Figure 15: CIR-MASW Plots

5 CONCLUSIONS

The case studies from various heterogeneous sites show that CIR technology provides useful information on the stiffness variations across sub-grades to a depth of 2.5 metres during ground treatment using Deep Impact Compaction, identifies sub-surface weak or deleterious material and assists in the location of post compaction testing locations. It has been also shown at these sites that MASW testing can characterise various sub-surface materials using the subsurface shear wave velocity distribution in sections across the site and detect weak layers below stronger layers.

The use of CIR and MASW technology in the ground improvement of heterogeneous variable un-engineered fill sites can reduce the risk of differential settlement allowing the use of upper level footings and slab-on-ground construction and alleviates the need for removal or partial removal and replacement of un-engineered fill materials.

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