Use of SDMT Testing for Measuring Soil Densification by Ground Improvement in Christchurch, New Zealand

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ABSTRACT: The paper illustrates, and comments on, the results of seismic dilatometer (SDMT) obtained in Christchurch, New Zealand, in combination with the results of piezocone penetration tests (CPTu). SDMTs were carried out at sites close to the Avon River in treated soils and in adjacent natural soils, in order to evaluate the effectiveness of the different ground improvement tecniques, including Rammed Aggregate Piers (RAP) and Low Mobility Grout injection (LMG). The results confirm that the DMT, as well as CPT, is sensitive to changes of stresses/density in sands and silty sands, and is therefore well suited to detecting improvements in these soils, while V_S provides less evident results.

1 INTRODUCTION

The flat dilatometer (DMT), introduced by Marchetti (1980), has been used for monitoring soil improvement by comparing DMT results before and after the treatment (Marchetti et al. 2001). Compaction is generally reflected by an increase of both the horizontal stress index K_D and the constrained modulus M_{DMT}. The seismic dilatometer (SDMT) provides both the shear wave velocity V_S and the usual DMT parameters (Marchetti et al. 2008).

The paper illustrates, and comments on, the seismic dilatometer test results obtained in Christchurch, New Zealand, in combination with the corrected cone tip resistance q_t from piezocone tests (CPTu). The initial site investigations were conducted within the scope of the Ground Improvement Trials Project for the New Zealand Earthquake Commission (EQC), the Ministry of Business, the Innovation and Employment, Housing New Zealand Corporation, Network for Earthquake Engineering Simulation (NEES), and the U.S. National Science Foundation (NSF). The study was commissioned in response to the need for ground improvement following the 2010-2011 earthquakes. SDMTs were carried out at sites close to the Avon River, in treated soils and in adjacent natural soils, in order to evaluate the effectiveness of the works. The ground improvement methods investigated include Rammed Aggregate Piers (RAP) and Low Mobility Grout injection (LMG). Further testing was carried out as part of commercial developments in and around Christchurch CBD.

2 USE OF (S)DMT FOR MONITORING SOIL DENSIFICATION

Several researchers have investigated the use of the DMT for detecting benefits of soil improvement.

Schmertmann et al. (1986) reported a large number of before/after CPTs and DMTs carried out for monitoring dynamic compaction at a power plant site (mostly sand). The treatment increased substantially both the cone resistance q_c and the constrained modulus M_{DMT}. The increase in M_{DMT} was found to be approximately twice the increase in q_c.

Jendeby (1992) reported before/after CPTs and DMTs carried out for monitoring the deep compaction produced in a loose sand fill with the "vibrowing". He found a substantial increase of both q_c and M_{DMT}, but M_{DMT} had a greater increase, (nearly twice), a result similar to the previous case.

Pasqualini & Rosi (1993), in monitoring a vibroflotation treatment, noted that the DMT clearly detected the improvement even in layers marginally influenced by the treatment, where the benefits were undetected by CPT.

All the above results suggest that the DMT is sensitive to changes of stresses/density in the soil and therefore is well suited to detect the benefits of the soil improvement (in particular increased σ_h and increased D_R).

An interesting consideration by Schmertmann et al. (1986) is that, since treatments are often aimed at reducing settlements, it would be more rational to base the control and set the specifications in terms of minimum M_{DMT} rather than of minimum D_R.

3 SITE INVESTIGATIONS AND GROUND IMPROVEMENT WORKS

The Ground Improvement Trials Project was designed with the aim of investigating new land strengthening methods for the reconstruction process of Christchurch, New Zealand, which was strongly damaged by liquefaction effects due to the 2010-2011 earthquake sequence. In this respect, the techniques being investigated include:

- Rapid Impact Compaction (RIC): rapid ground compaction using a hydraulic ram attached to a digger;
- Rammed Aggregate Piers (RAP): drilling into the ground, filling the holes with gravel, and then compacting the gravel with a hydraulic ram;
- Low Mobility Grout (LMG): injecting a cement-based grout into the ground under pressure to form a series of underground pillars;
- Horizontal Soil Mixing (HSM): directional drilling beneath a structure to mix cement into the soil and create horizontal beams.

The following paragraphs provide more details about the site investigations and the RAP and LMG works realized close to the Avon River. All the considered piezocone (CPTu) and cross hole (CH) tests were downloaded from the Canterbury Geotechnical Database (2012). Fig. 1 indicates the four trial sites considered for the present study: Site 3 (Wainoni), Site 4 (Wainoni), Site 6 (Bexley), and 121 Bower Avenue. The information was plotted on the DBH Residential Foundation Technical Categories map, produced by CERA (2012) for guidance on the repair or rebuilding of building foundation systems, and into the land damage from future earthquakes.

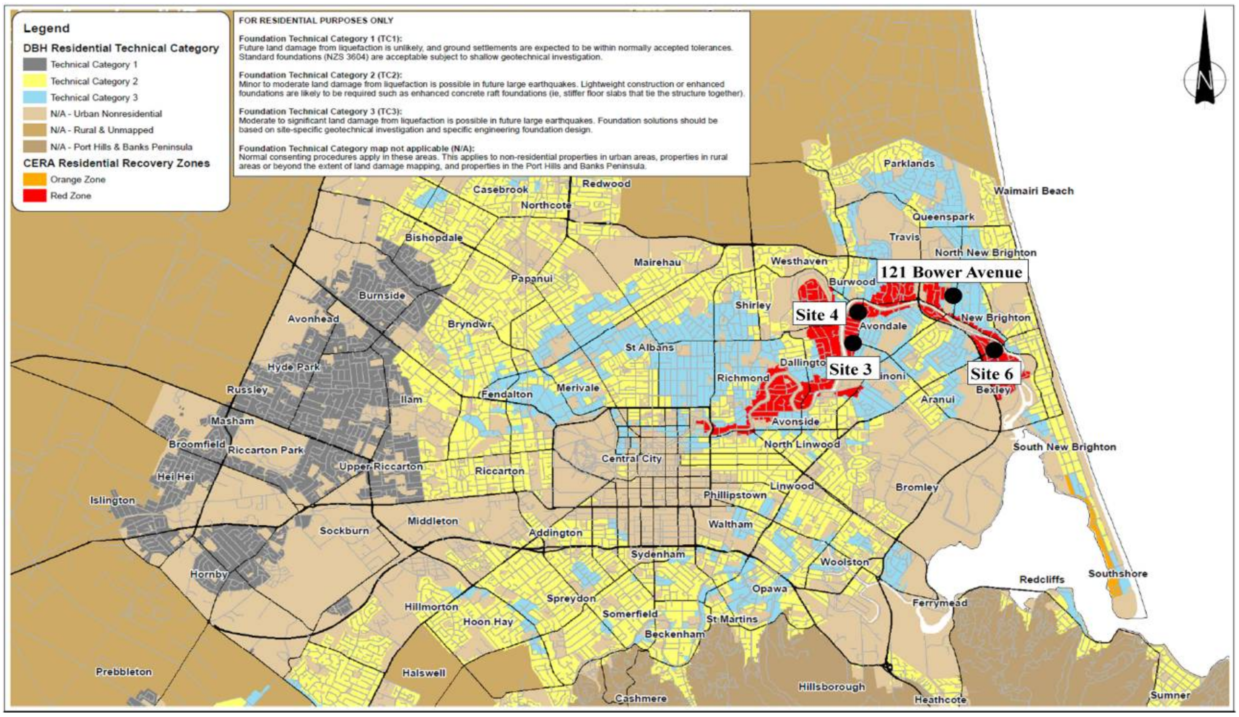

Fig. 1. DBH Residential Foundation Technical Categories (CERA 2012) with location of the four trial sites of study.

3.1 *Site 3 (Wainoni)*

An intense site investigation was performed at Site 3 (Wainoni), RAP Spacing Trial Area – 2 Brezees Road, and it consists of several CPTu tests prior and after installing the RAP columns in the ground improvement area. In particular, post installation CPTu's were carried out at different temporal intervals, in order to verify the effectiveness of the works with time, and in distinct locations, in order to evaluate the efficacy of the RAP columns with the geometry. In contrast, SDMTs were realized only after the construction of the Rammed Aggregate Piers, and consequently the SDMT test in the natural soil was performed outside the RAP area.

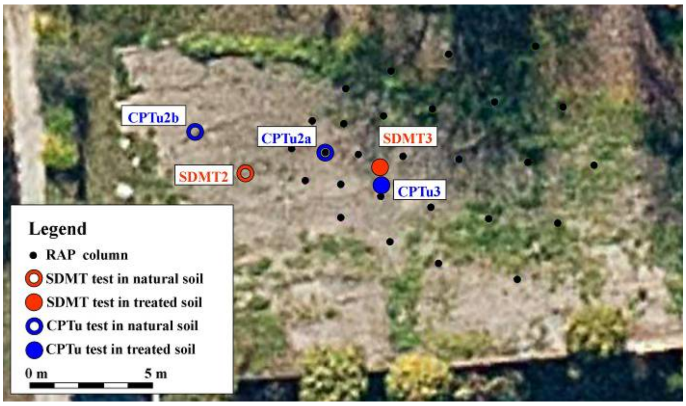

Fig. 2. Site investigation and RAP works realized at Site 3, RAP Spacing Trial Area – 2 Brezees Road.

Because the focus of this study is the comparison of CPTu and SDMT results before and after the soil improvement, the paper includes only the CPTu tests closest to the SDMTs. In this respect, Fig. 2 shows the location of the considered investigations in natural soil (SDMT2, CPTu2a and CPTu2b) and in treated soil (SDMT3 and CPTu3), centered in the RAP area, and the geometry of the ground improvement at Site 3. The RAP trial spacing in the area of interest is roughly 1.5 m, while the RAP columns reached 4.0 m depth.

Fig. 3 summarizes the profiles with depth of the SDMT parameters, in terms of material index I_D (indicating soil type), constrained modulus M_{DMT}, and horizontal stress index K_D (related to stress history/OCR), obtained using common DMT interpretation formulae (Marchetti 1980, Marchetti et al. 2001), as well as shear wave velocity V_S and the corrected cone resistance q_t from CPTu. Site 3 is mainly composed of sands and silty sands, which show significant improvement after treatment as measured by M_{DMT} and K_D from the(S)DMT and q_t from the CPT(u) within the depth range from 2.0 to 4.0 or 5.0 m depth. In contrast, little improvement is observed at greater depths, as expected, recognizing that the RAP columns are only 4.0 m depth. On the other hand V_S profiles show a smaller increase after treatment within the same depths of interest.

The improvement of the soil properties is reflected also by the ratio M_{DMT}/q_t, the lateral earth pressure coefficient K_0 and the relative density D_R within the shallower layers, as represented in Fig. 4. K_0 profiles were evaluated from (S)DMT for freshly deposited sands according to Baldi et al. (1986), while D_R values were obtained from (S)DMT according to Jamiolkowski et al. (2003) and from CPT(u) to Robertson (2009). Fig. 4 illustrates that (S)DMT overestimates D_R. A possible reason is that K_D is affected by both the stress history and the relative density, while q_c has a direct correlation with the relative density (Lee et al. 2011). It should also be noted that Fig. 4 couples CPTu2b with SDMT2, assuming that q_t profiles from CPTu2a and CPTu2b (natural soil) are quite similar, as shown in Fig. 3, and that CPTu2b is closer to SDMT2 in terms of position and geotechnical profile.

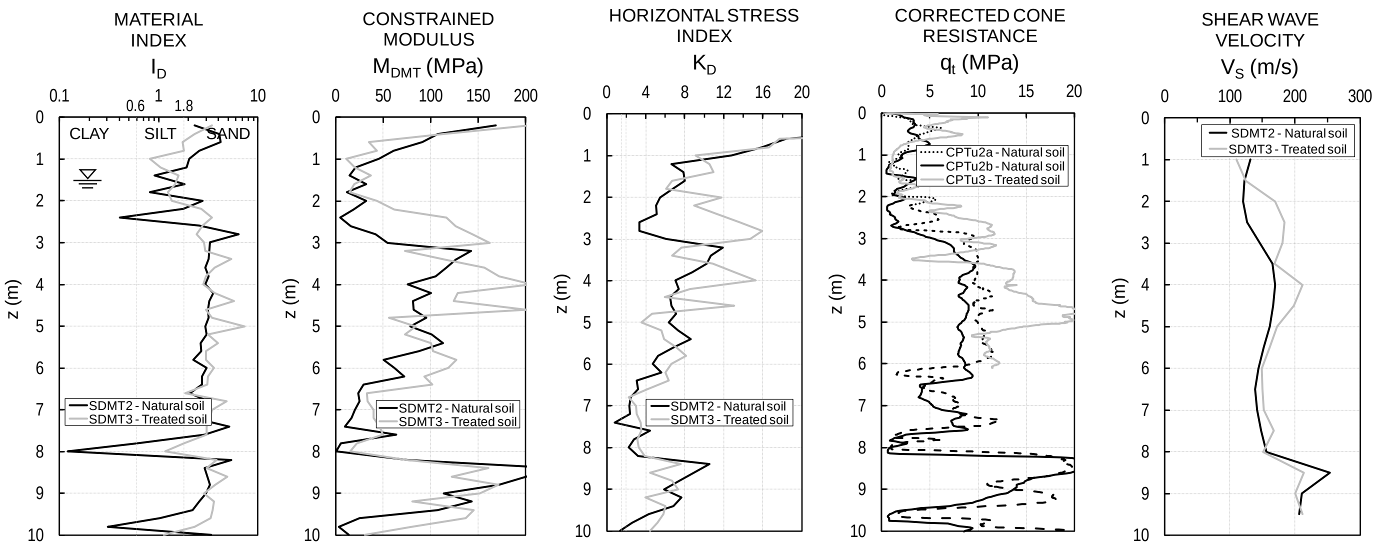

Fig. 3. SDMT and CPTu results in natural and treated soils at Site 3, RAP Spacing Trial Area.

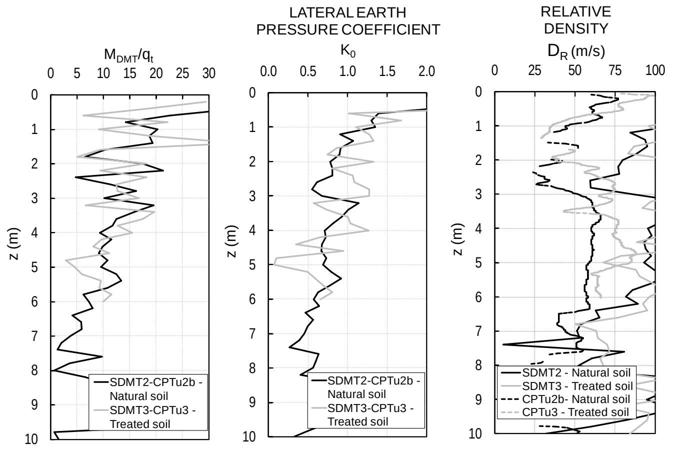

Fig. 4. M_{DMT} /q_t, K_0, and D_R profiles from SDMT and CPTu interpretation at Site 3, RAP Spacing Trial Area.

3.2 *Site 4 (Wainoni)*

3.2.1 *T-Rex Testing Area 1-2*

As for Site 3, a large site investigation was carried out at Site 4, T-Rex Testing Area 1-2 – Avonside Drive. Fig. 5 indicates the tests considered for this site in natural soil (SDMT5, CPTu5a, CPTu5b and CH5) and in treated soil (SDMT2, CPTu2 and CH2), located at the border of the RAP area, and the geometry of the ground improvement. Rammed Aggregate Piers were installed at T-Rex Testing Area 1-2 with a trial spacing of about 1.5 m and a RAP column depth of 4.0 m.

Fig. 6 summarizes the profiles with depth of the SDMT parameters, in terms of material index I_D, constrained modulus M_{DMT}, and horizontal stress index K_D, as well as shear wave velocity V_S in comparison with V_S profiles from CH tests, and the corrected cone resistance q_t from CPTu. The T-Rex Testing Area 1-2 is mostly a non homogeneous sand and silty sand site, as interpreted by CPTu logs in natural soil (CPTu5a and CPTu5b). Moreover, this RAP panel settled more than 113 mm during the blast test performed for the Ground Improvement Trials Project, while the best RAP panel settled only 67 mm. This may explain, at least in part, the fact that M_{DMT} and K_D seem even to decrease after the treatment. It can be also noted that SDMT5 in untreated soil was located some distance away from the treated ground and may not be as representative of the true conditions at the treated site.

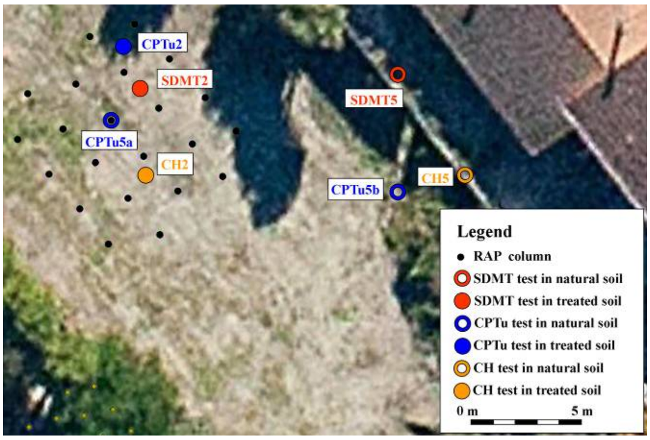

Fig. 5. Site investigation and RAP works realized at Site 4, T-Rex Testing Area 1-2 – Avonside Drive.

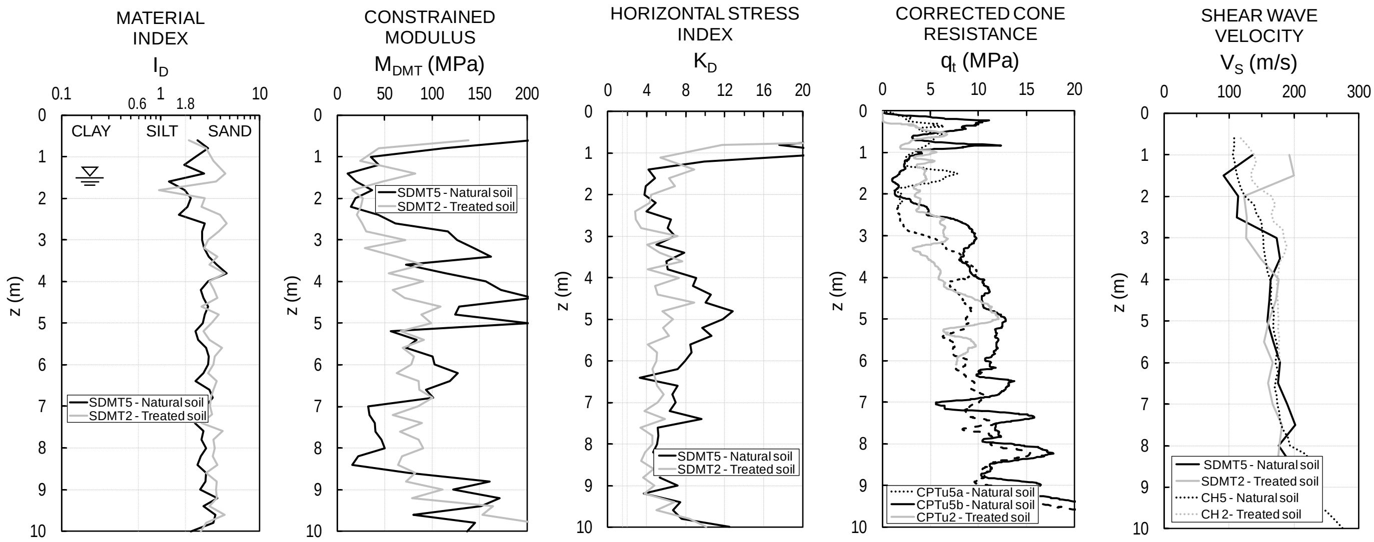

Fig. 6. SDMT and CPTu results in natural and treated soils at Site 4, T-Rex Testing Area 1-2.

3.2.2 *RAP Spacing Trial Area*

At Site 4 another location, namely RAP Spacing Trial Area – Avonside Drive, was thoroughly investigated. Fig. 7 indicates the tests considered for this site in natural soil (SDMT6 and CPTu6) and in treated soil (SDMT7 and CPTu7), located at the border of the RAP area, and the geometry of the ground improvement. Rammed Aggregate Piers were installedat the RAP Spacing Trial Area with a trial spacing of about 2.0 m and a RAP column depth of 4.0 m. Fig. 8 summarizes the profiles with depth of the SDMT and CPTu parameters, while Fig. 9 plots the ratio M_{DMT} /q_t, the lateral earth pressure coefficient K_0, and the relative density D_R, obtained by coupling (S)DMT and CPT(u) data.

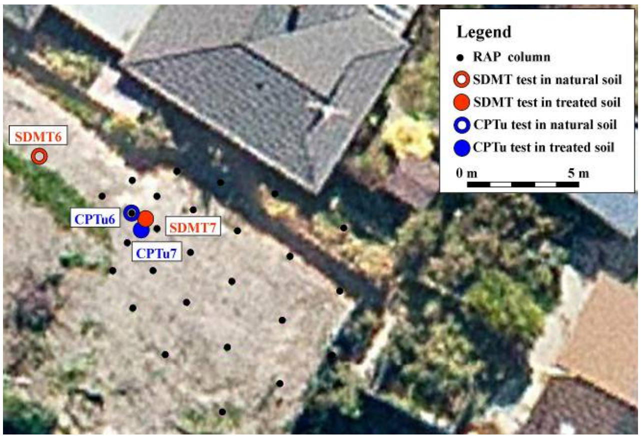

Fig. 7. Site investigation and RAP works realized at Site 4, RAP Spacing Trial Area 1-2 – Avonside Drive.

The RAP Spacing Trial Area is mainly composed of sand and silty sand deposits which show a slight increase in the soil properties within the first 3 m, moving from natural to treated soil. Then, the corrected cone resistance q_t, and the relative density D_R, grow consistently up to 6 m depth, while the (S)DMT parameters M_{DMT} and K_D, coupled with M_{DMT} /q_t and K_0, detect an increase mostly limited to between 3.0 and 4.0 m depth. This aspect could be due to a sort of variability of the subsoil outside the RAP area, where CPTs are not available. As for Site 3, the shear wave velocity V_S shows a smaller increase within the same depths of interest.

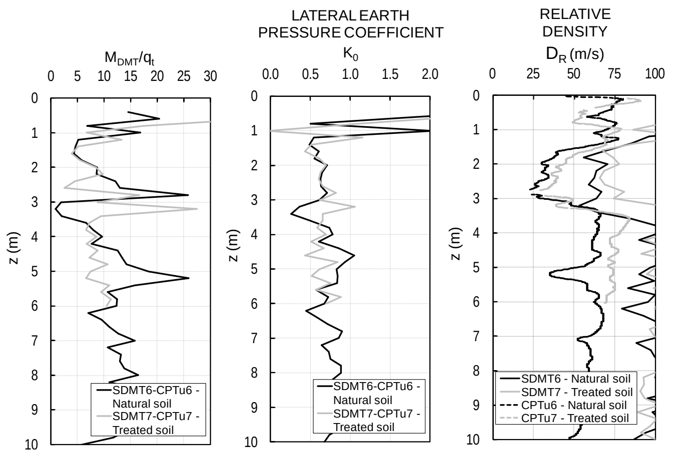

Fig. 9. M_{DMT} /q_t, K_0, and D_R profiles from SDMT and CPTu interpretation at Site 4, RAP Spacing Trial Area.

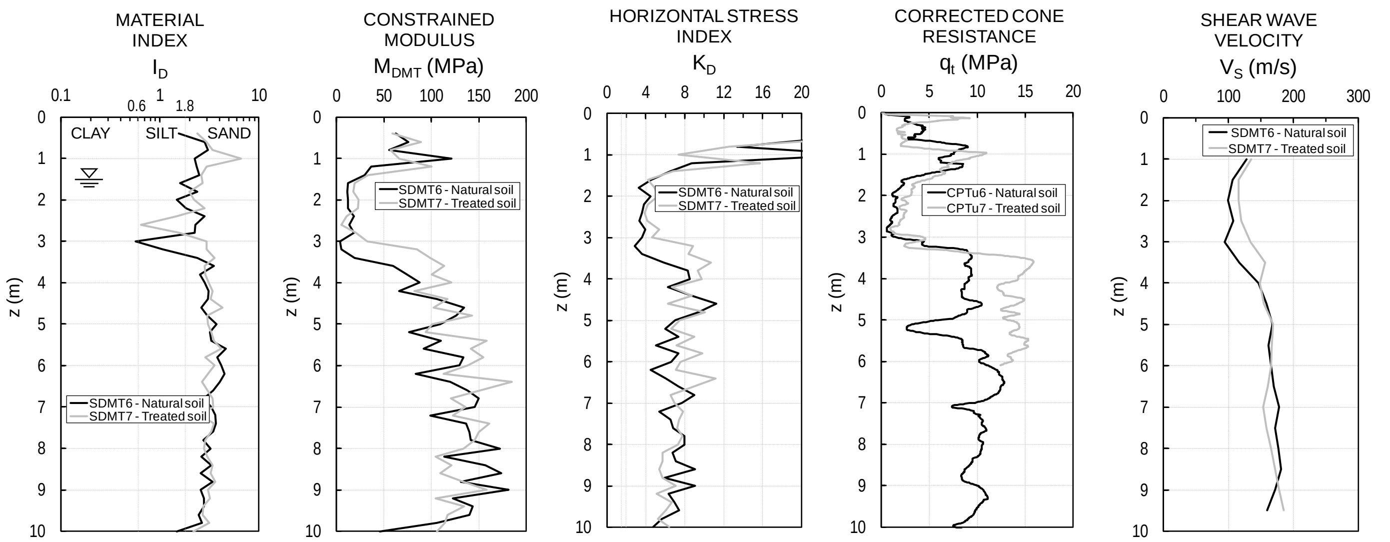

Fig. 8. SDMT and CPTu results in natural and treated soils at Site 4, RAP Spacing Trial Area.

3.3 *Site 6 (Bexley)*

As for Site 3 and 4, a thorough site investigation was carried out at Site 6, RAP Spacing Trial Area - Wairoa Street. Fig. 10 indicates the tests considered for this site in natural soil (SDMT2 and CPTu2) and in treated soil (SDMT1 and CPTu1), centered in the RAP area, and the geometry of the ground improvement. Rammed Aggregate Piers were at a trial spacing of about 1.8 m at the test location, with a RAP column depth of 4.0 m. Fig. 11 summarizes the profiles with depth of the SDMT and CPTu parameters, while Fig. 12 plots the profile of the additional parameters evaluated by coupling DMT and CPT data. Site 6 is essentially composed by sands, which identify a significant increase in M_{DMT}, K_D, q_t and D_R moving from natural to treated soil, between 1.2 and 4.2 to 4.8 m depth. In contrast, the change in these parameters often becomes null or negative at greater depths. V_S follows a similar trend, but exhibits a smaller increase within the same depths of interest. On the other hand the change in soil properties is not clearly reflected by the M_{DMT}/q_t, while K_0 detects higher values for a few thin layers of treated soil.

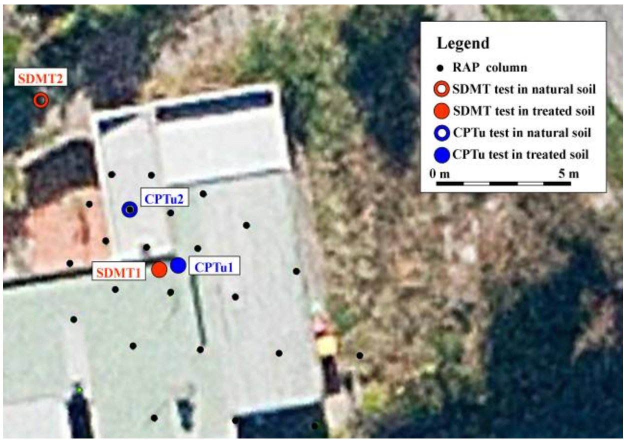

Fig. 10. Site investigation and RAP works realized at Site 6, RAP Spacing Trial Area - Wairoa Street.

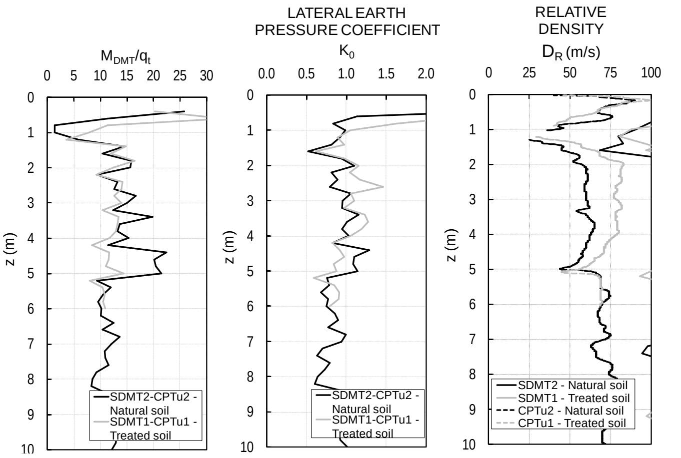

Fig. 12. M_{DMT}/q_t, K_0, and D_R profiles from SDMT and CPTu interpretation at Site 6, RAP Spacing Trial Area.

3.4 *121 Bower Avenue*

Finally, at 121 Bower Avenue Low Mobility Grout (LMG) works were constructed, reaching 4.0 m depth for the LMG injections. As shown in Fig. 13, several CPTu, CH and SDMT tests were carried out in natural soil (CPTu2n, CPTu3n, CH1n, CH2n, CH3n, SDMT4) and treated soil (CPTu2i, CPTu3i, CH1i, CH2i1, CH2i2, CH3i, SDMT1, SDMT2, SDMT3). Fig. 14 summarizes the results of the SDMT3, SDMT4, CH3n, CH3i, CPTu3n and CPTu3i tests, while Fig. 15 plots the profile of the additional parameters evaluated by coupling (S)DMT and CPT(u) data. Bower Avenue is mainly a sand and silty sand site, where the LMG injections do not appear to provide clear results in terms of soil densification. In situ test data, including V_S values from SDMT, show a small increase of the soil properties for the treated soil relative to the natural soil, within the first 4.0 m depth. This trend is slightly more emphasized by CPTu, which provides an additional contribution for the ground improvement at greater depth.

Fig. 13. Site investigation and RAP works realized at 121 Bower Avenue.

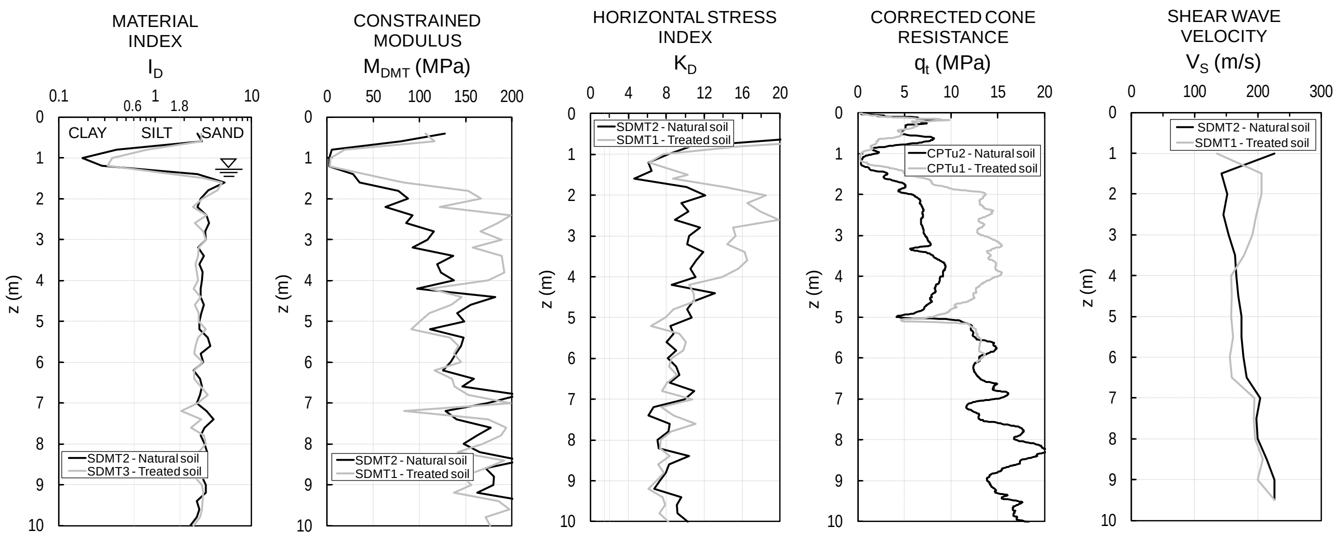

Fig. 11. SDMT and CPTu results in natural and treated soils at Site 6, RAP Spacing Trial Area.

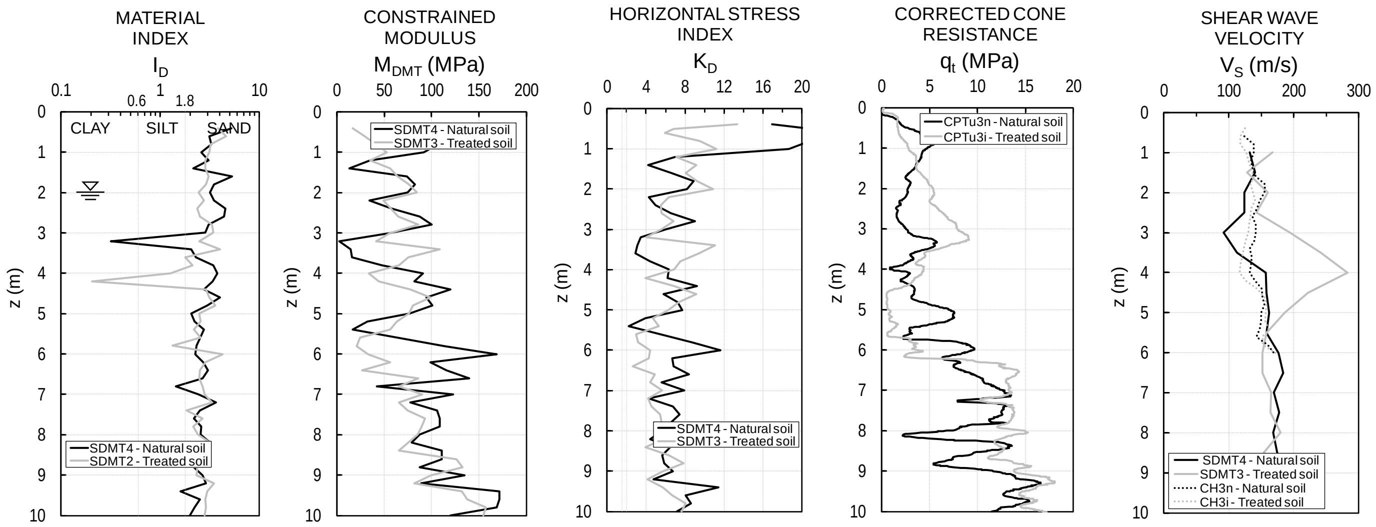

Fig. 14. SDMT and CPTu results in natural and treated soils at 121 Bower Avenue.

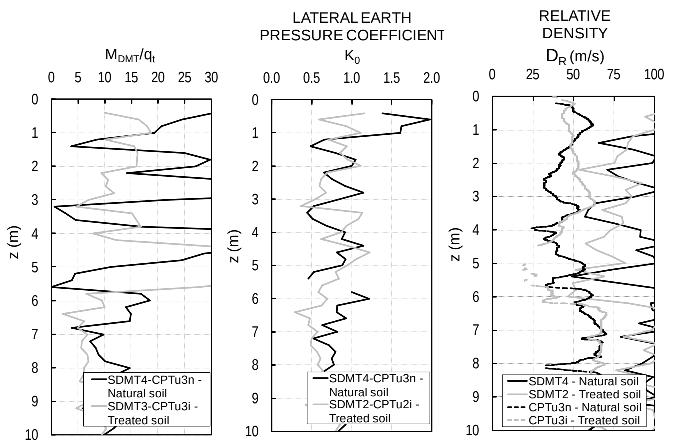

Fig. 13. M_{DMT}/q_t, K_0, and D_R profiles from SDMT and CPTu interpretation at 121 Bower Avenue.

4 COMPARISON OF THE RESULTS

Table 1 summarizes the average test results, in terms of M_{DMT}/q_t and K_0 from both the SDMT and CPTu, K_D, M_{DMT}, and V_S from the seismic dilatometer test, and q_t and D_R from the piezocone. The results include those obtained in natural and treated soil in the trial areas of Site 3 (Wainoni), Site 4 (Wainoni), Site 6 (Bexley), and 121 Bower Avenue. It should be noted that Site 4 only refers to the RAP Spacing Trial Area, due to the heterogeneity of T-Rex Testing Area 1-2.

Table 1. Summary of average tests results obtained in natural soil (NS) and treated soil (TS) in Christchurch.

Site	Depth interval (m)	M_{DMT}/q_t		K_0		K_D		M_{DMT} (MPa)		q_t (MPa)		D_R (%)		V_S (m/s)	
		NS	TS	NS	TS	NS	TS	NS	TS	NS	TS	NS	TS	NS	TS
3	2.0-4.0/5.0	11.3	15.8 (39%)	0.7	1.1 (57%)	6.2	12.5 (101%)	62.1	132.8 (114%)	5.7	12.1 (111%)	51	72 (42%)	151	184 (22%)
	5.0-6.0/8.0	-	-	-	-	3.5	4.9 (37%)	33.6	64.4 (92%)	8.3	11.4 (37%)	57	65 (14%)	145	156 (8%)
4	1.0-3.0	-	-	-	-	4.7	6.3 (34%)	18.9	33.9 (80%)	2.7	3.6 (35%)	37	45 (23%)	110	122 (11%)
	3.0-4.0	2.9	13.3 (359%)	0.4	0.7 (72%)	5.5	8.6 (57%)	41.6	91.9 (121%)	7.7	11.8 (53%)	58	71 (22%)	119	146 (23%)
	4.0-6.4	-	-	-	-	6.6	8.3 (26%)	104.4	132.8 (27%)	8.2	13.7 (68%)	57	73 (27%)	-	-
6	1.2-4.2/4.8	-	-	0.9	1.1 (19%)	9.8	14.9 (51%)	93.3	155.9 (67%)	6.5	11.7 (80%)	56	72 (30%)	151	196 (29%)
Bower Avenue	1.4-4.0	-	-	-	-	5.6	7.7 (38%)	-	-	2.8	5.6 (104%)	40	52 (29%)	133	204 (54%)
	6.4-10.0	-	-	-	-	-	-	-	-	10.9	13.9 (28%)	59	67 (13%)	-	-

A review of the data shows that the sensitivity to soil densification of K_D, M_{DMT}, and q_t is generally higher compared to the combined parameter M_{DMT}/q_t and to K_0, which do not detect a clear increase for each depth interval (roughly 50 % when detected), and to D_R and V_S values which however provide a more constant trend (on average 25 %).

Tests centred in the RAP areas (Site 3 and Site 6) show that K_D, M_{DMT} and q_t increase approximately twice as the spacing decreases from 1.8 to 1.5 m. The greater the spacing is, the lower K_D, M_{DMT} and q_t are, especially for (S)DMT parameters. On the other hand tests located at the border of the RAP area still double the constrained modulus M_{DMT}, while the horizontal stress index K_D and the corrected cone resistance q_t show an increment of about 1.5 times the value in the untreated soil.

Finally, the LMG injection did not produce any significant improvement. In fact, soil resistance and deformability often decrease, or remain the same, after the treatment, as shown by (S)DMT and CPTu parameters.

5 CONCLUSIONS

The 2010-2011 Canterbury earthquakes provided a huge dataset for the ground improvement studies that allows the analysis of soil densification methods by using in situ tests, such as SDMT and CPTu.

The results confirm that Rammed Aggregate Piers are a more effective soil improvement technique compared to the Low Mobility Grout, for the soils and depths involved.

The sensitivity of the horizontal stress index K_D, the constrained modulus M_{DMT} and the corrected cone resistance q_t to changes of stresses/density in sands and silty sands is higher for tests centred in the RAP area and for smaller spacings of the RAP columns. A less evident increase is observed for the ratio M_{DMT}/q_t and the lateral earth pressure coefficient K_0, even though such increment is not clearly identified for each depth interval, while the relative density D_R and the shear wave velocity V_S show a light increment, detected almost for all the studies cases.

Further refinements could be performed with additional in situ tests carried out as part of commercial developments in and around the Christchurch CBD.

6 ACKWNOLEDGEMENTS

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