Assessment of empirical soil property correlations for New Zealand soils

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Background and motivation

- Soil properties can be obtained by: laboratory testing, in-situ investigations, and correlation-based methods

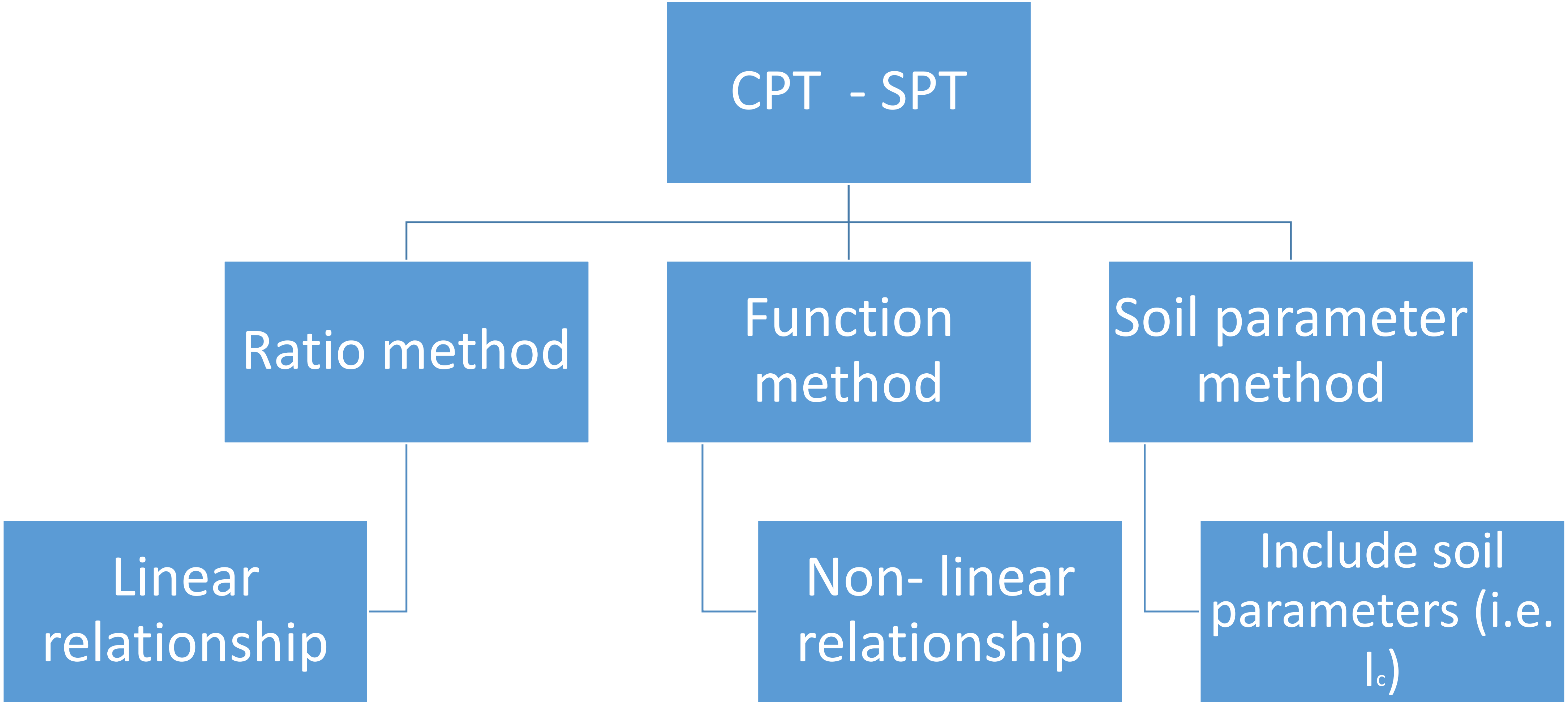
- Various correlations have been developed to estimate soil properties using in-situ methods from databases collected in different countries or regions.

- No data or limited data for New Zealand soils

- Assess the applicability and reliability of existing empirical correlations for New Zealand soils

- Develop empirical correlations based on New Zealand databases

Literature review



SPT-CPT correlations

- Category 1

Ratio of CPT tip resistance and SPT blow count

Source	Soil type	n ratio
Schmertmann (1970)		$n=(q_c/N)$
	Silt, sandy silt and slightly cohesive silt-sand mixture	0.2
	Clean, fine to medium sand and slightly silty sand	0.35
	Coarse sand and sand with little gravel	0.5
	Sandy gravel and gravel	0.6
Robertson et al. (1986)		$n= (q_c/p_a)/N_{60}$
	Sensitive fine grained	0.2
	Organic material	0.1
	Clay	0.1
	Silty clay to clay	0.15
	Clayey silt to silty clay	0.2
	Sandy silt to clayey silt	0.25
	Silty sand to sandy silt	0.3
	Sand to sandy silt	0.4
	Sand	0.5
	Gravelly sand to sand	0.6
	Very stiff fine grained	0.1
	Sand to clayey sand	0.2

SPT-CPT correlations

- **Category 2**

correlations of CPT tip resistance , SPT blow count $\frac{q_c\, ,q_t/p_a}{N_{60}}$ **and soil behaviour type index, Ic （Robertson and Wride 1998)**

- Jefferies & Davies (1993) & Lunne et al. (1997)

$$\frac{q_c/p_a}{N_{60}} = 8.5\left(1 - \frac{I_c}{4.6}\right)$$

- 60% energy efficiency
- 195 SPT-CPT data pairs
- fine-medium sand trace silt
- Mud rotary boreholes
- 2 m spacing

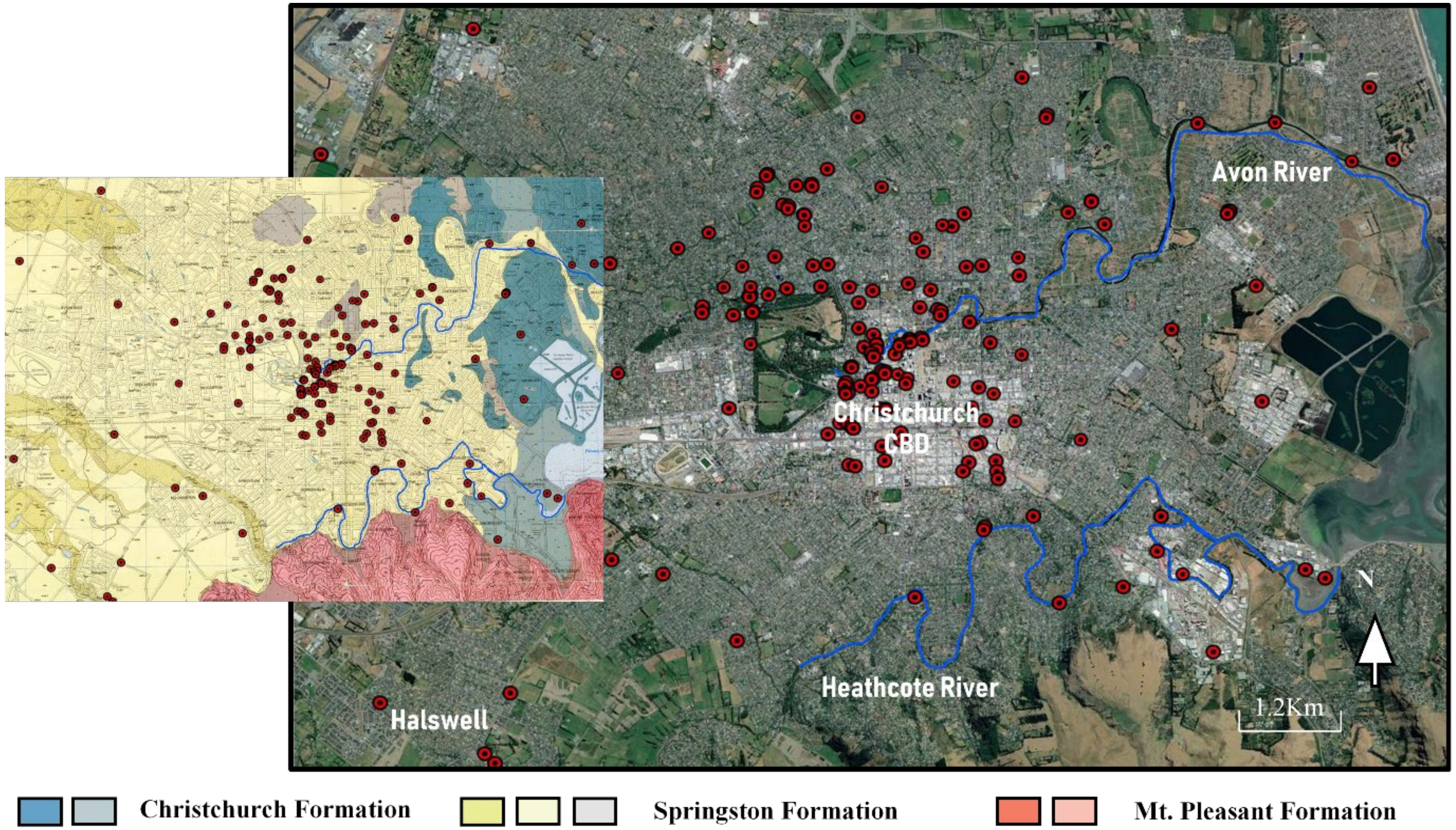
- Robertson (2012)

$$\frac{\left(\frac{q_t}{p_a}\right)}{N_{60}} = 10^{(1.1268-0.2817I_c)}$$

- update for Lunne et al. correlation
- may be overestimated for highly sensitive fine-grained soils

Christchurch database

- Map of 199 BH-CPT location pairs in greater Christchurch area, New Zealand. The surficial geologic map (Brown & Weeber 1992) for this area is inset at left.



Base dataset

❑ Borehole

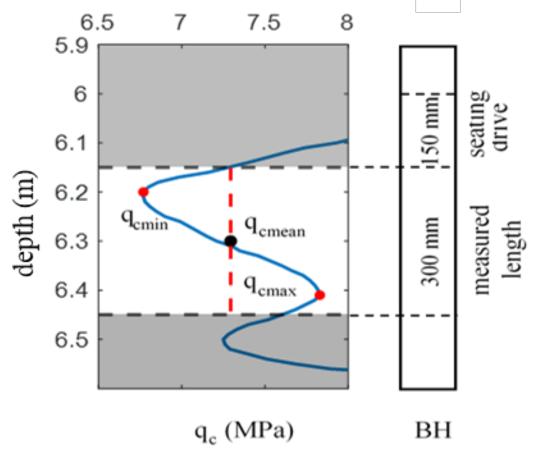
- Mud rotary, Direct-push dual tube and rotary sonic
- Distance between CPT soundings and borehole greater than 12 m removed

❑ SPT

- Hammer efficiencies from calibration 48% to 102% corrected to 60% energy efficiency
- N = 0 and incomplete tests (drive length less than 450 mm) removed
- N_{60} grater than 50 removed
- Gravel data removed
- Locations effected by heave and artesian water effects removed

❑ CPT

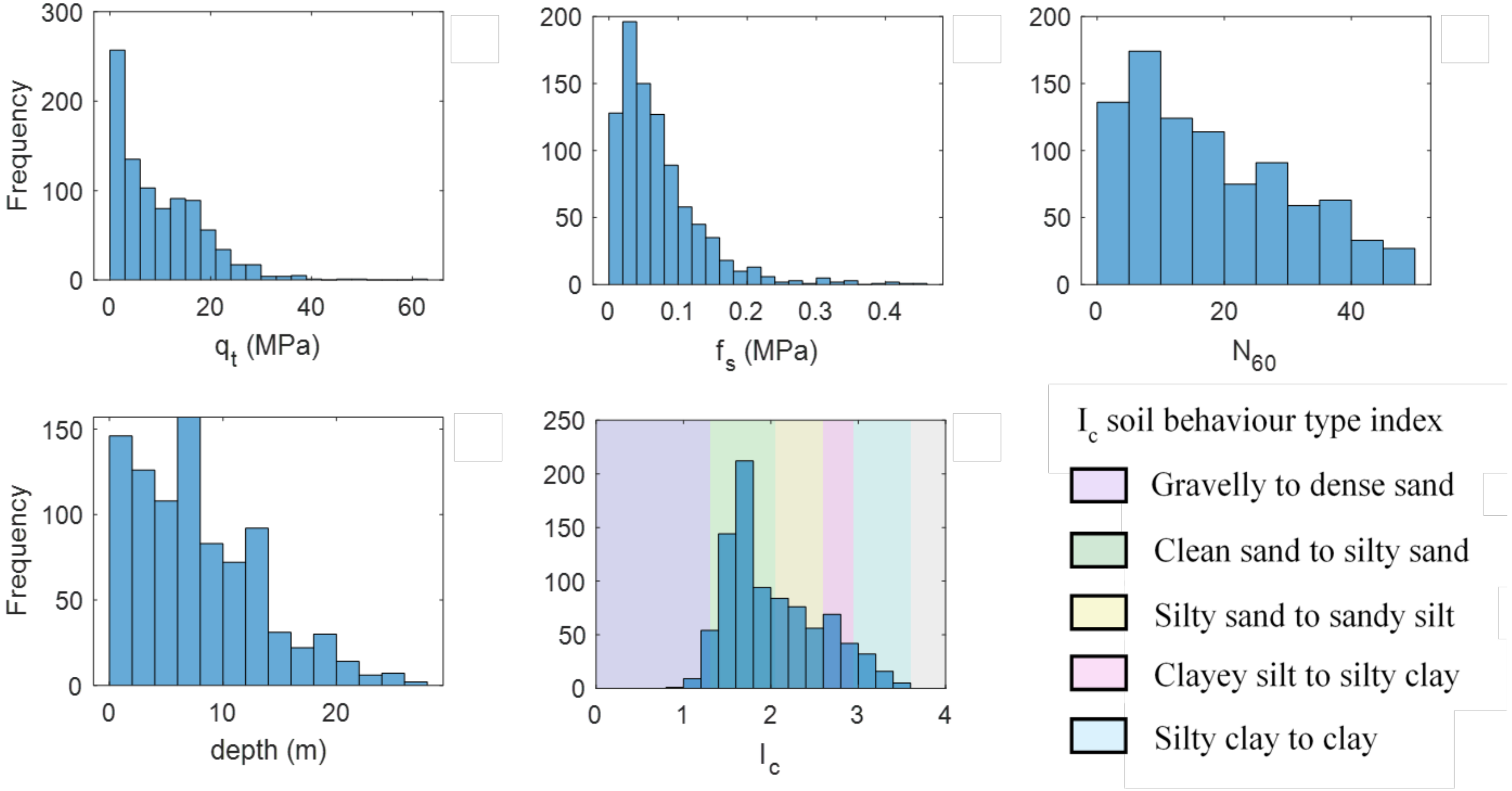
- CPT variables less than 0 removed
- Mean CPT variables over SPT test range
- Points with excessive CPT variables with SPT range removed



Attribution of a representative CPT parameter value to the SPT interval

Base dataset summary

- 896 SPT-CPT data pairs



Histograms of measured SPT and CPT parameters for the base dataset: q_t, f_s, measured SPT N_{60}-value, midpoint depth and I_c

Clean, fine to medium sand and slightly silty sand identified from sampling

- Category 1

Schmertmann correlation: 491 SPT-CPT data pairs

Robertson correlation: 499 SPT-CPT data pairs

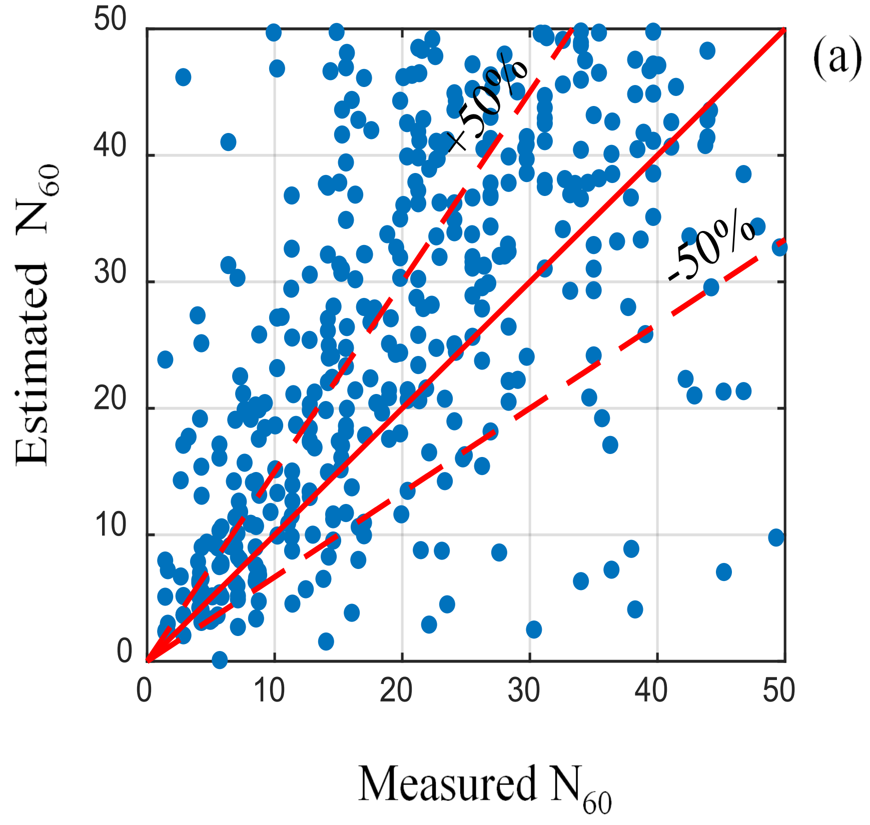
Clean sand to silty sand corresponding to I_c values

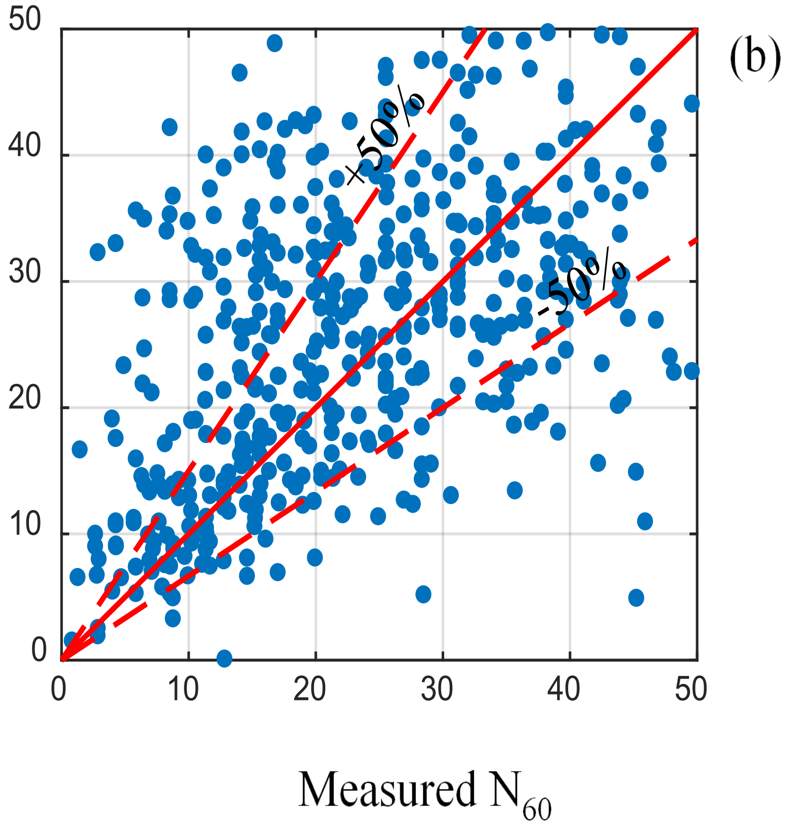
- Category 2

896 SPT-CPT data pairs

Assessment results

- **Category 1**





- Beyond the ±50% limits
  Schmertmann correlation: 55%
  Robertson correlation: 40%

- R^2
  Schmertmann correlation: 0.24
  Robertson correlation: 0.38

Comparison of the measured N_{60} and estimated N_{60} using: a) Schmertmann (1970) Correlation for 491 SPT-CPT datapoints; b) Robertson et al. (1986) Correlation for 499 SPT-CPT datapoints.

Assessment results

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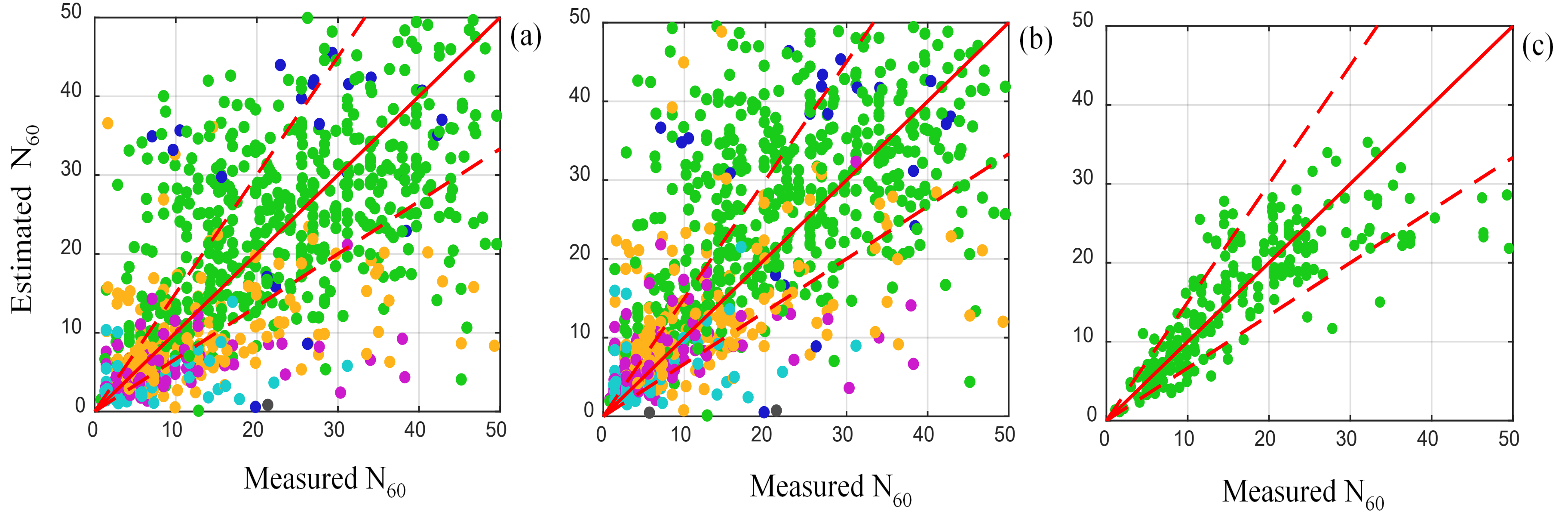
Category 2



- Organic soils-clays $I_c > 3.6$
- Silty clay to clay $2.95 < I_c \leq 3.6$
- Clayey silt to silty clay $2.60 < I_c \leq 2.95$
- Silty sand to sandy silt $2.05 < I_c \leq 2.60$
- Clean sand to silty sand $1.31 < I_c \leq 2.05$
- Gravelly sand to dense sand $I_c \leq 1.31$

- Beyond the $\pm$50% limits
  Lunne et al. : 47%
  Robertson : 47%
  Jefferies and Davies: 20%

- R^2
  Schmertmann : 0.43
  Robertson : 0.43
  Jefferies and Davies: 0.61

Comparison of the measured N60 and estimated N60 for: a) 896 SPT-CPT datapoints using Lunne et al. (1997) Correlation; b) 896 SPT-CPT datapoints using Robertson (2012) correlation; c) 195 SPT-CPT datatpoints applied in Jefferies and Davies (1993).

Reference

Zhou, H., Wotherspoon, L. M., Hayden, C. P., McGann, C. R., Stolte, A., & Haycock, I. 2021. Assessment of Existing SPT–CPT Correlations Using a New Zealand Database. *Journal of Geotechnical and Geoenvironmental Engineering*, 147(11), 04021131. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002650.

Literature review

- Summary of existing empirical CPT-V_s correlations

Reference	In-situ technique	Area	Number of data pairs	Regression function	Soil type	R^2
Andrus et al. (2007)	sCPT, crosshole, P-S suspension logging	California, Japan, South Carolina	72	$V_s = 2.27 q_t^{0.412} I_c^{0.989} z^{0.033}$	Holocene-aged deposits	0.779
			72 for Holocene-age; 113 for Pleistocene-age	$V_s = 2.62 q_t^{0.395} I_c^{0.912} z^{0.124} SF$ SF=0.92 for Holocene-age	Holocene- and Pleistocene-aged deposits	0.709
Hegazy and Mayne (1995)	sCPT, crosshole, downhole, SASW	Worldwide	323	$V_s = [10.1\,log(q_c) - 11.4]^{1.67} * \left[\frac{f_s}{q_c} * 100\right]$	General soils	0.695
Hegazy and Mayne (2006)	sCPT, crosshole, downhole, SASW	Worldwide	558	$V_s = 0.0831 Q_{tn} e^{1.786Ic} \left(\frac{\sigma'_{vo}}{P_a}\right)^{0.25}$	General soils	0.85
Madiai & Simoni (2004)	DPSH.S sCPT, crosshole, downhole	Italy	25	$V_s = 140 q_c^{0.3} f_s^{-0.13}$	Holocene fine-grained soils	0.92
			18	$V_s = 268 q_c^{0.21} f_s^{0.02}$	Holocene coarse-grained soils	0.73
McGann et al. (2015)	sCPT	New Zealand	513	$V_s = 18.4 q_c^{0.144} f_s^{0.0832} z^{0.278}$	Holocene-aged deposits	0.856
Robertson (2009)	sCPT	Worldwide	1,035	$V_s = \left[10^{1.68+0.55I_c} \left(\frac{q_t - \sigma_{vo}}{P_a}\right)\right]^{0.5}$	Holocene-and Pleistocene-aged deposits	N/A
Tun & Ayday (2018)	sCPT	Turkey	245	$V_s = 52.674\ln(q_c) + 109.29$	General soils	0.90

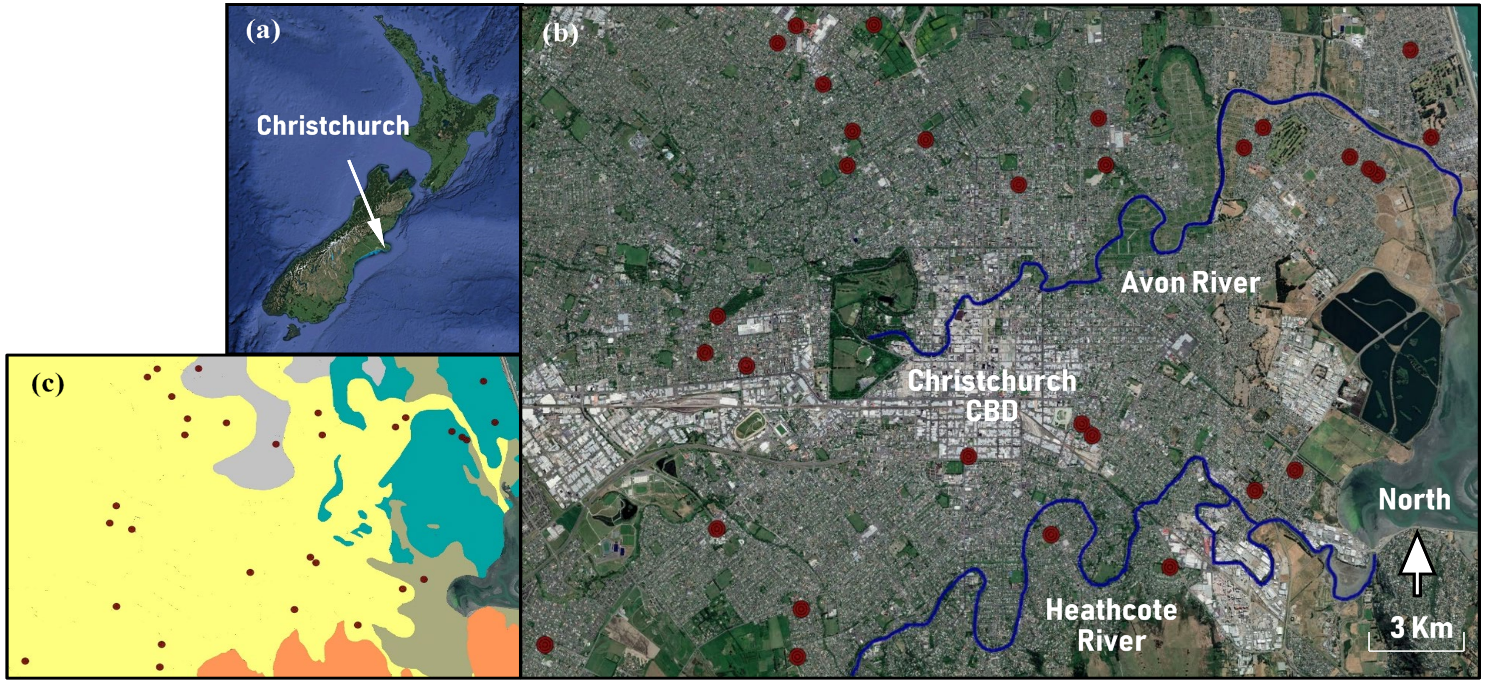
CPT-V_s correlations

- Among the empirical CPT-V_s correlations available in the literature, four commonly used correlations for Holocene-aged soils were considered:

Correlation	CPT-V_s data pairs	Soil type	Range of I_c	Range of q_c/ q_t (MPa)	Range of f_s (MPa)	Eq.
Hegazy and Mayne (2006)	558	Mine Tailings, Cohesive and Cohesionless soils	$1.0 < I_c < 4.8$	$0.1 < q_c < 50$	$0.1 < f_s < 1.3$	$V_s = 0.0831 Q_{tn} e^{1.786Ic} \left(\frac{\sigma'_{vo}}{P_a}\right)^{0.25}$
Andrus et al. (2007) Holocene-only	72	Holocene-aged deposits	$1.19 < I_c < 4.0$	$0 < q_t < 31$	N/A	$V_s = 2.27 {q_t}^{0.412} {I_c}^{0.989} z^{0.033}$
Robertson (2009)	1035	Holocene- and Pleistocene-aged deposits	N/A	N/A	N/A	$V_s = \left[10^{1.68+0.55I_c} \left(\frac{q_t - \sigma_{vo}}{P_a}\right)\right]^{0.5}$
McGann et al. (2015)	513	Holocene-aged deposits	$1.15 < I_c < 3.5$	$0 < q_c < 27$	$0 < f_s < 0.36$	$V_s = 18.4 {q_c}^{0.144} {f_s}^{0.0832} z^{0.278}$

Christchurch database

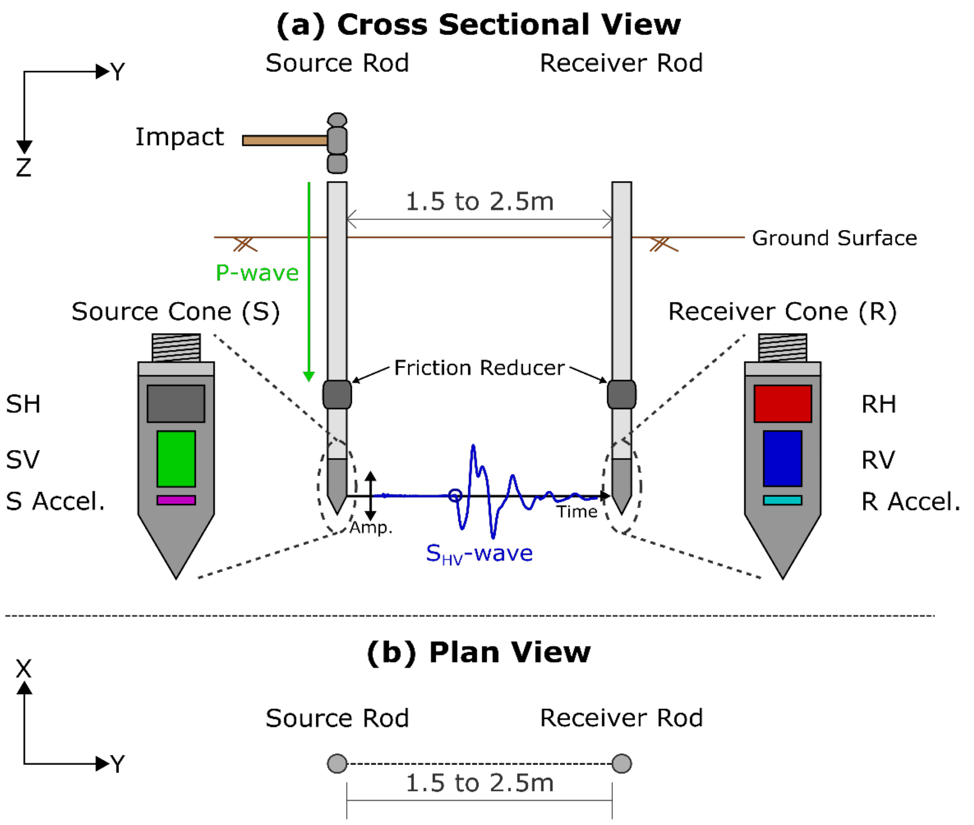
- Map of 31 DPCH-CPT pairs in greater Christchurch area, New Zealand.



Maps Data: Google Earth, © 2021 Google, Image © 2021 TerraMetrics, Image © 2021 Maxar Technologies

Christchurch Formation	Springston Formation	
Dune and beach sand	Fluvial sand, silt and loess	Mt. Pleasant Formation
Peat swamp	Alluvial Gravel at depths > 3 m	

DPCH method



Schematic of the DPCH test: a) cross-sectional view and b) plan view (after Cox et al. 2019)

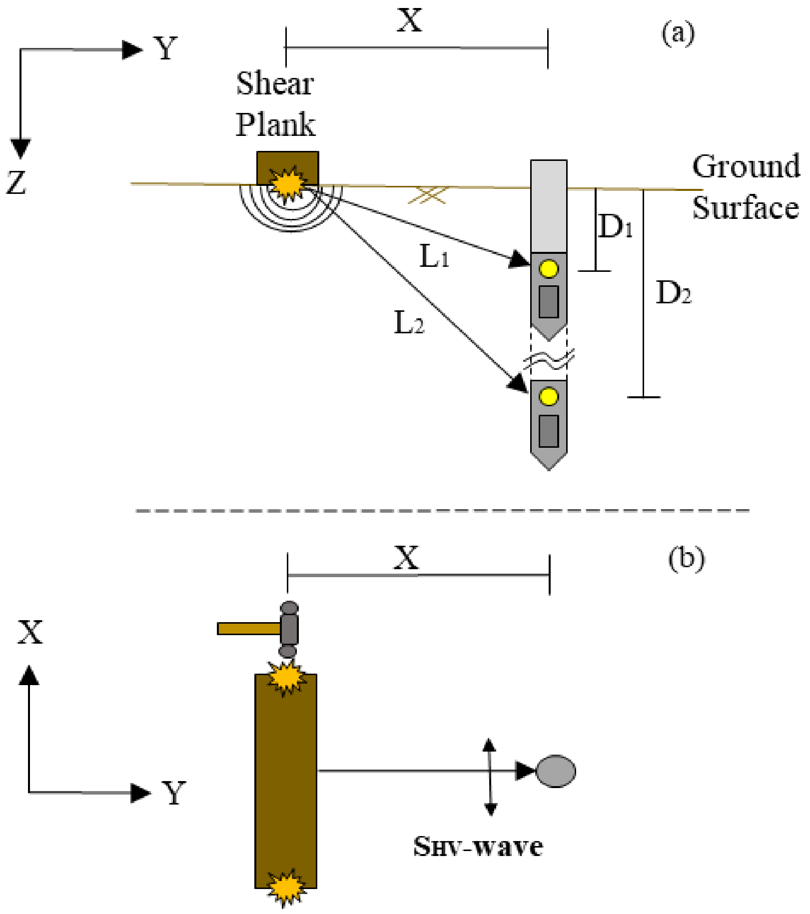
❑ Vs

- Vs representative of the soil within each 200 mm DPCH interval
- removed the measurement intervals with significant variation

❑ CPT

- CPT-based parameters recorded at 20 mm depth intervals
- arithmetic mean CPT variables over DPCH test range

sCPT method



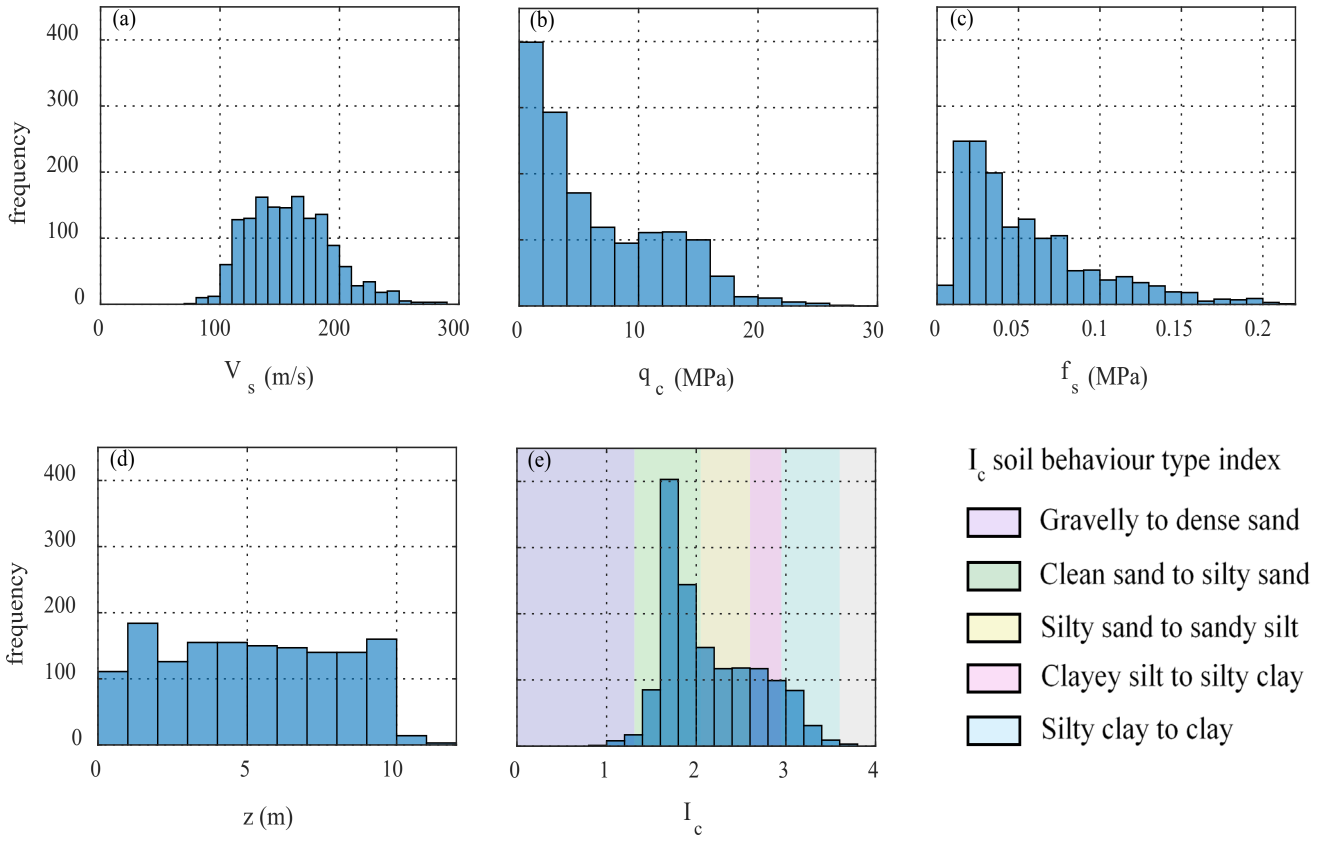
Schematic of a sCPT test a) elevation view and b) plan view (after Stolte and Cox 2019).

Different S-wave travel path assumption between sCPT and DPCH:

- ❑ **sCPT: based on vertically propagating, horizontally polarized shear waves**
- ❑ **DPCH: based on horizontally propagating, vertically polarized shear waves**

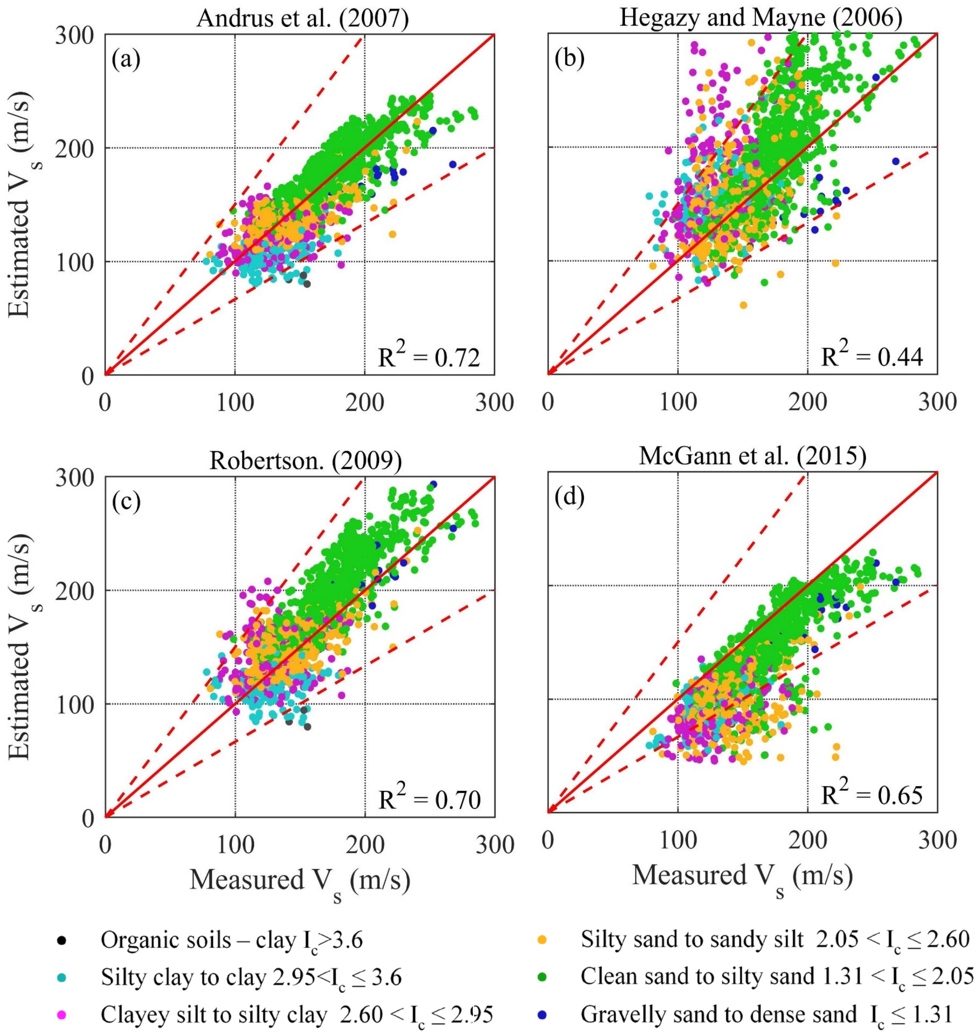
Base DPCH database

- ❑ **1485 CPT-Vs data pairs**



Histograms of measured V_s and CPT parameters for the base DPCH database: (a) measured V_s; (b) q_c; (c) f_s; (d) midpoint depth, z and (e) I_c.

Assessment results

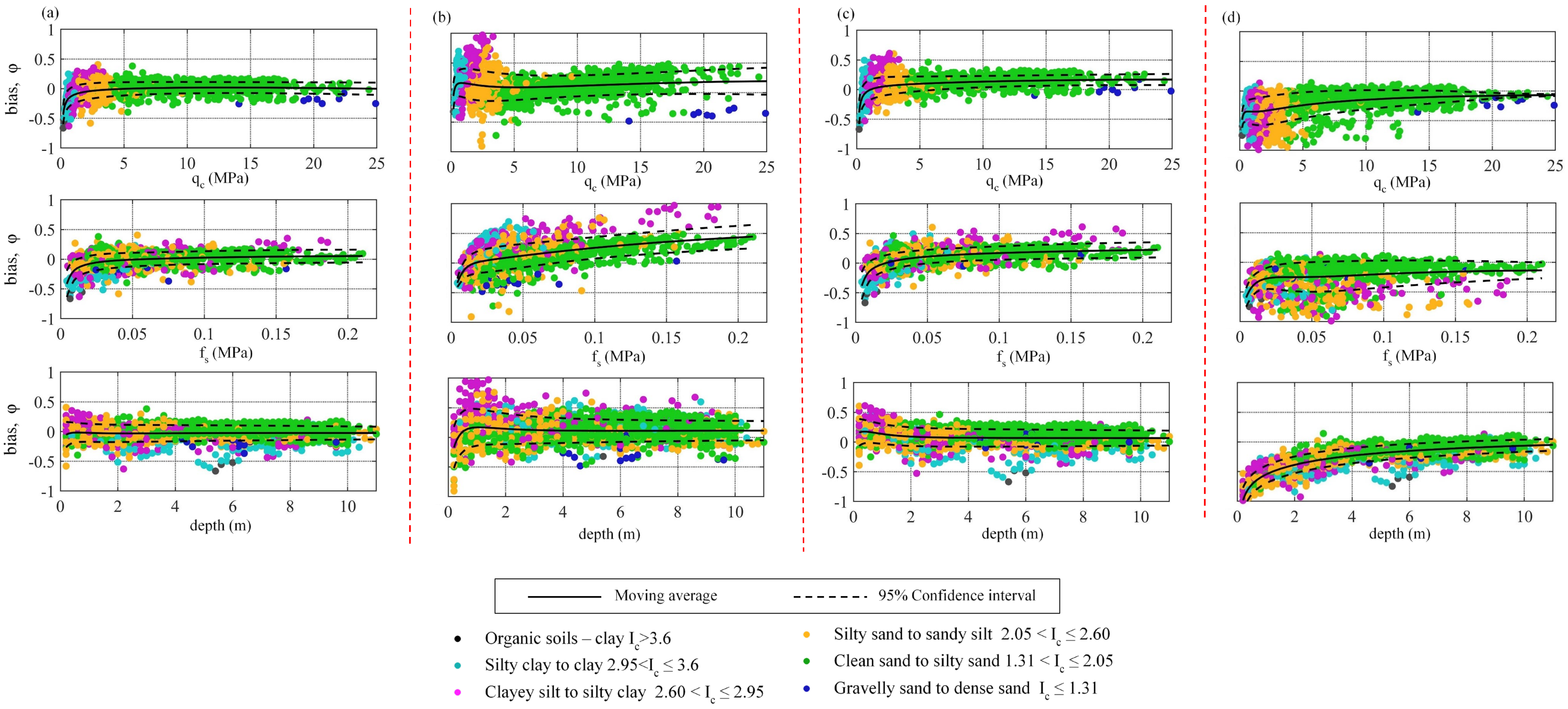


Comparison of selected existing CPT-Vs correlations for the base database. The solid lines represent a 1:1 relationship, while the dashed lines represent 1.5:1 and 0.67:1 (±50% of the 1:1 relationship).

- High measured V_s values dominated by coarse-grained soils ($I_c \leq 2.05$)
- The Andrus et al. correlation shows the best balance between over- and under-prediction
- The Hegazy and Mayne and Robertson correlations have trend to overestimate V_s
- The McGann et al. correlation underestimates V_s with great underestimates dominated by fine-grained soils($I_c > 2.05$)

Bias - CPT-based parameters

- Bias, $\varphi = ln(V_{sE}) - \ln(N_{sM})$



Variation in bias with respect to q_c, f_s, and z for the correlations of (a) Andrus et al. (2007), (b) Hegazy and Mayne (2006), (c) Robertson (2009), and (d) McGann et al (2015b).

Influence of CPT-based parameters

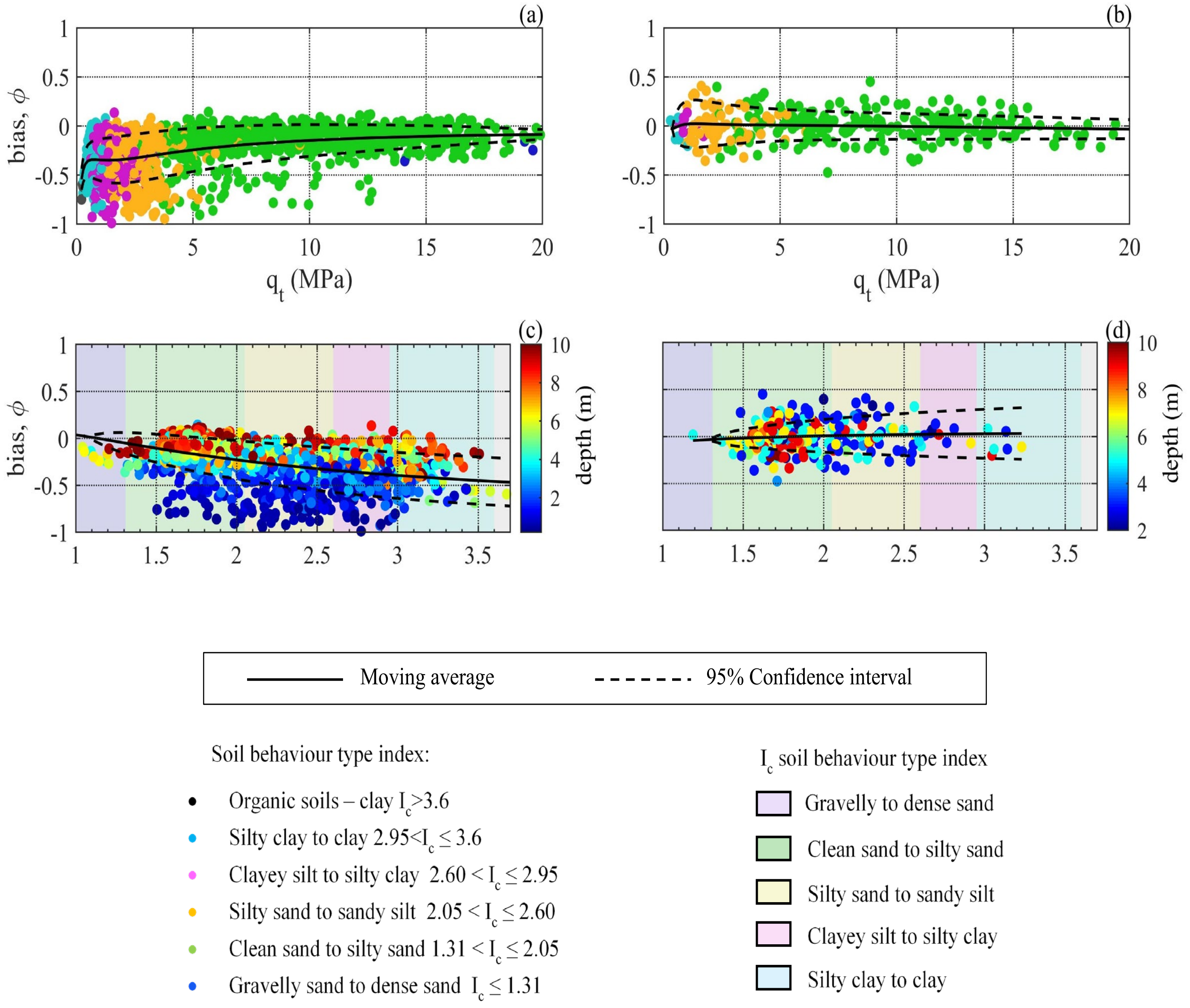
- The Andrus et al. correlation has the least variation in bias with respect to the parameters considered and the narrowest 95% confidence interval bandwidth.

- The Hegazy and Mayne and the Robertson correlations exhibit similar variation trend of bias: bias increase as q_c and f_s increase with underestimates dominated by fine-grained soils (I_c >2.05) at low q_c and f_s values, less variation in bias with respect to measurement depth.

- The McGann et al. correlation consistently underestimates V_s across the parameter ranges considered, with great underestimates at depths less than 4 m with low q_c and f_s values.

- The application of the sCPT-based McGann et al. correlation may not be suitable at depths less than 4 meters due to the travel path assumption between DPCH and sCPT V_s measurements.

Influence of Vs technique



Bias for the McGann et al. correlation for the DPCH Subset 1 database of 1470 CPT-V_s data pairs as a function of (a) q_t; and (c)I_c; and 306 CPT-V_s data pairs using sCPT method as a function of (b) q_t and (d) I_c.

- most of the data points in Subset 1 DPCH database
- the average bias with respect to the CPT-based parameters for the refined sCPT database is stable around zero
- the large underestimation in Subset 1 database as a result of: S-wave travel path assumption used for in sCPT data processing; over-extrapolation of the correlation beyond the range of data used development; variable nature of the soil deposits in the region where data was sourced.

Summary – Existing Correlations

- Care needed when applying empirical correlations for specific region/zone
- Used to provide initial insight into site conditions
- Further in-situ testing is recommended
- New correlations could be developed based on NZ databases

Development of CPT-Vs correlations

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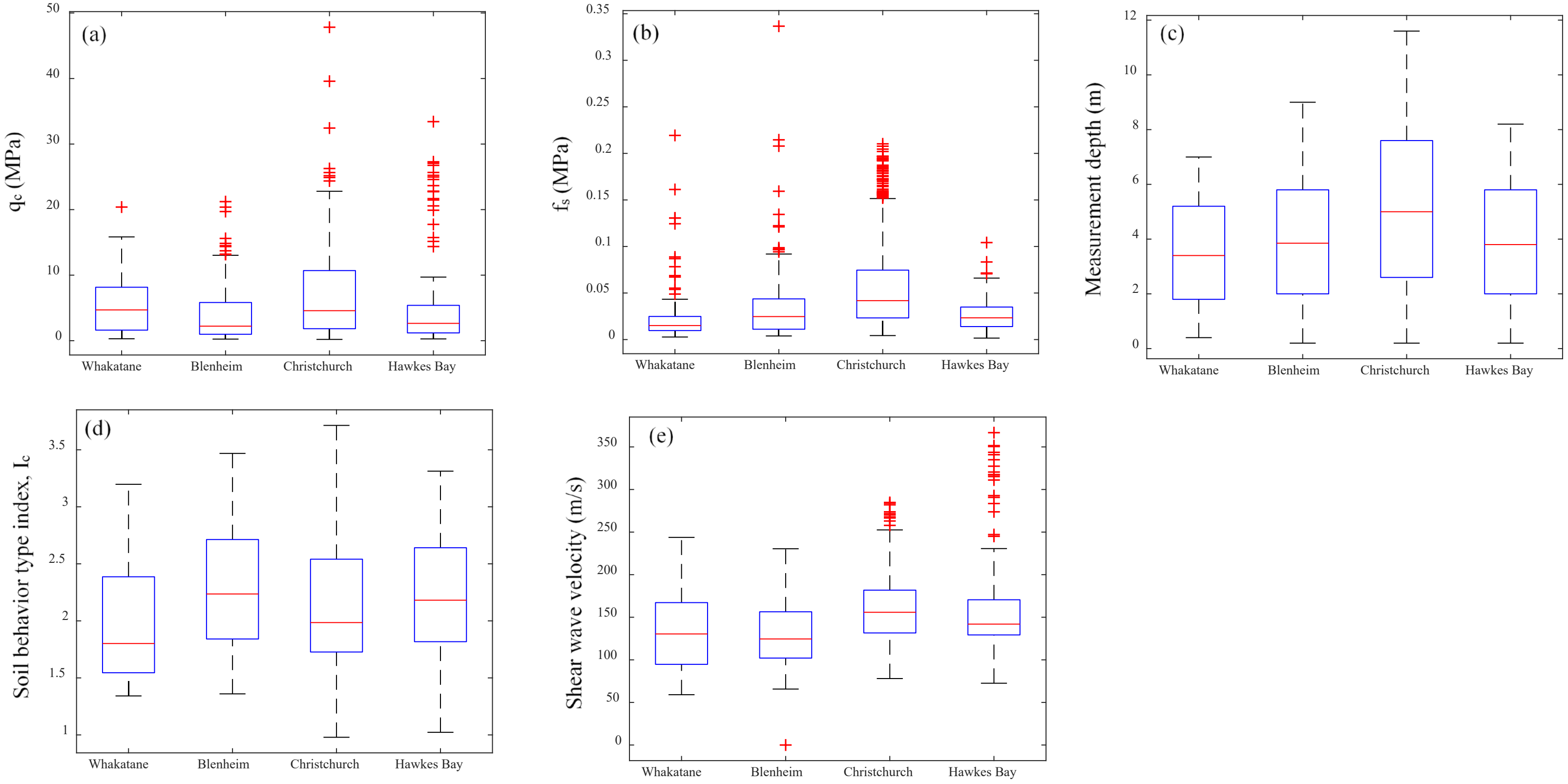
Region DPCH databases

- 150 CPT-Vs data pairs in Whakatane DPCH database
- 189 CPT-Vs data pairs in Blenheim DPCH database
- 1485 CPT-Vs data pairs in Christchurch full DPCH database
- 188 CPT-Vs data pairs in Hawkes Bay DPCH database



Comparison of (a) q_c; (b) f_s; (c) midpoint depth, z; (d) I_c; and (e) V_s distribution for DPCH database obtained from Whakatane, Blenheim, Christchurch full, and Hawkes Bay regions.

CPT-Vs functional form

- the Andrus et al. functional form

$$V_s = a q_t^b I_c^d z^e$$

- the McGann et al. functional form

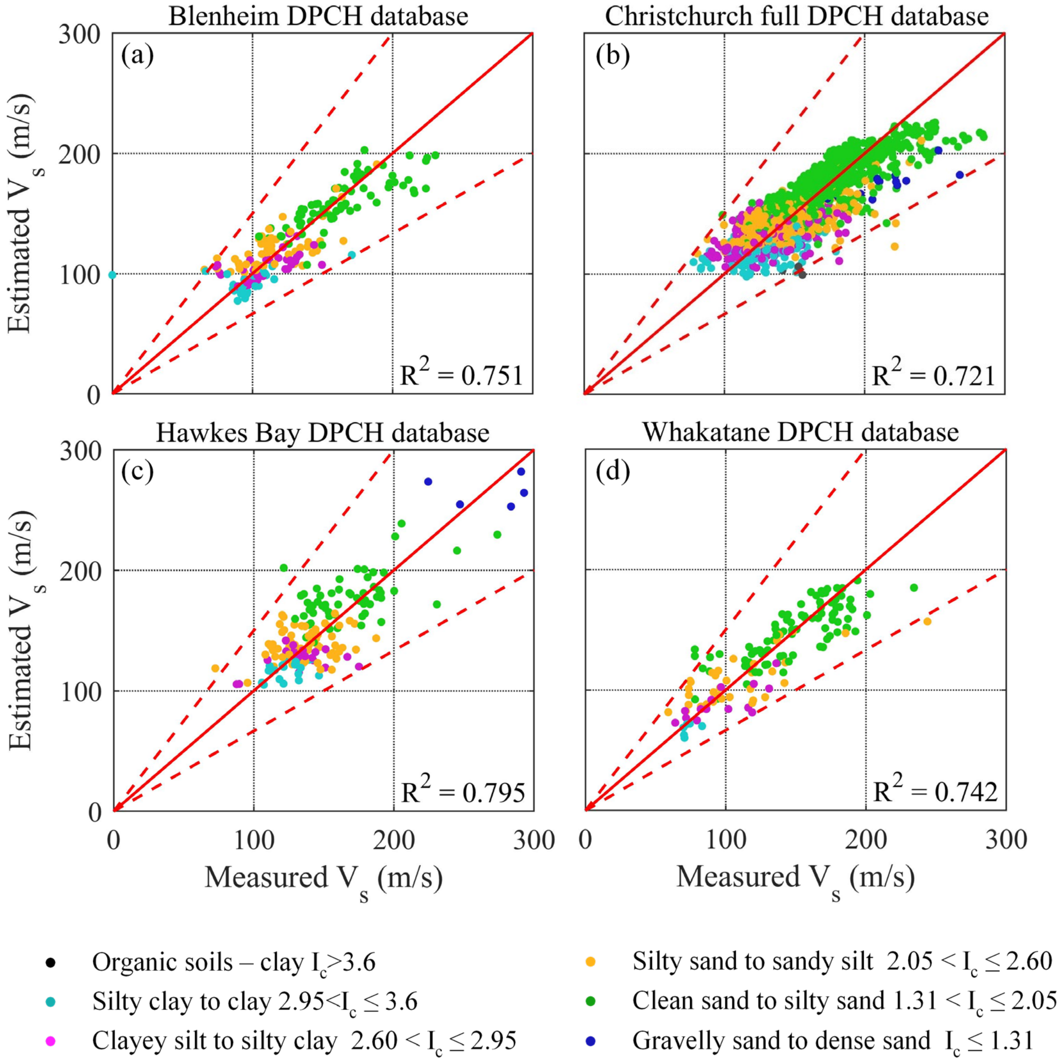
$$V_s = a {q_t}^b {f_s}^d z^e$$

Region CPT-Vs correlations

CPT-V_s functional forms based on regional DPCH databases.

Region	No. of pairs	Relationship	a	b	d	e	R^2
Blenheim	189	The Andrus et al.	44.463	0.332	0.809	0.098	0.751
		The McGann et al.	157.761	0.096	0.116	0.11	0.76
Christchurch	1485	The Andrus et al.	56.494	0.295	0.707	0.054	0.721
		The McGann et al.	165.555	0.098	0.09	0.073	0.718
Hawkes Bay	188	The Andrus et al.	320.627	-0.058	-1.029	0.085	0.795
		The McGann et al.	88.92	0.218	-0.06	0.1	0.746
Whakatane	150	The Andrus et al.	38.726	0.405	0.766	0.139	0.742
		The McGann et al.	106.17	0.201	0.061	0.145	0.721

Assessment results



Comparison of new region-specific CPT-V_s correlation for the (a) Blenheim; (b) Christchurch full; (c) Hawkes Bay; and (d) Whakatane DPCH base database. The solid lines represent a 1:1 relationship, while the dashed lines represent 1.5:1 and 0.67:1 (±50% of the 1:1 relationship).

- Good performance of region-specific correlation as indicated by high R^2 value.
- Data points outside the ±50% limits are still existing.
- The applicability of these new CPT-Vs correlations based on DPCH should be used according to the characteristics of soils of interest.
- Development of nation-specific CPT-Vs correlation based on the total DPCH database for wider use.

Future Work

- The applicability including the uncertainty of new region/nation-specific CPT-Vs correlations for other regions need to be further confirmed.

- The representation of existing empirical CPT-DMT correlations for NZ soils.

- New CPT-DMT correlations could be developed based on NZ databases.

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