Evaluation of Determination Methods for Ultimate Axial Capacity of Micropiles in Ontario soils

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ABSTRACT
This paper evaluates different methods to determine the failure load of micropiles in Ontario soils. Micropiles are small-diameter, grouted piles installed with a high amount of steel reinforcement. Since a higher level of uncertainty exists in geotechnical load capacity of micropiles than of conventional piles, designers commonly rely on the confirmation of geotechnical capacity based on the maximum test load achieved during pre-production testing on sacrificial piles in representative soils. This research analyzed 47 full-scale micropile load tests, conducted by Keller Foundations Ltd, to determine the most suitable method for the evaluation of the ultimate geotechnical capacity in Ontario soils. Since most tests terminated before reaching the ultimate capacity, the load-displacement curves were first extrapolated to provide sufficient data for the analysis by various criteria from literature. Results were compared in terms of closeness to the average failure load, variation, and goodness of fit to normality. Based on the study, Fuller and Hoy (1970) and Butler and Hoy (as cited in Fellenius, 1980) provided the best estimation of ultimate load capacity of micropile in Ontario soils.

RÉSUMÉ

Cet article évalue différentes méthodes pour déterminer la charge de rupture des micropieux dans les sols de l'Ontario. Les micropieux sont des pieux cimentés de petit diamètre installés avec une grande quantité de ferraillage. Comme la capacité de charge géotechnique des micropieux est plus incertaine que celle des pieux conventionnels, les concepteurs s'appuient généralement sur la confirmation de la capacité géotechnique basée sur la charge d'essai maximale atteinte lors des essais de pré-production sur des pieux sacrificiels dans des sols représentatifs. Cette recherche a analysé 47 essais de chargement de micropieux à grande échelle, menés par Keller Foundations Ltd, afin de déterminer la méthode la plus appropriée pour l'évaluation de la capacité géotechnique ultime dans les sols de l'Ontario. Comme la plupart des essais se sont terminés avant d'atteindre la capacité ultime, les courbes charge-déplacement ont d'abord été extrapolées pour fournir des données suffisantes pour l'analyse selon différents critères de la littérature. Les résultats ont été comparés en termes de proximité avec la charge de rupture moyenne, la variation et la qualité de l'ajustement à la normalité. Selon l'étude, Fuller et Hoy (1970) et Butler et Hoy (cités dans Fellenius, 1980) ont fourni la meilleure estimation de la capacité de charge ultime des micropieux dans les sols de l'Ontario.

1 INTRODUCTION

A micropile is a small-diameter pile (usually less than 300 mm) which is constructed by drilling a borehole, placing a central reinforcement, grouting the drilled hole with or without pressure- or post-grouting, depending on the micropile type. A micropile is a deep foundation element and, as such, it can resist static and seismic loading conditions. Additionally, it can be used as reinforcement for slope and excavation stability via direct or indirect loading (Federal Highway Administration (FHWA), 2000).

Micropiles can be beneficial for many engineering applications due to its low energy installation process, utilization of small drilling equipment for restricted access work, ease of installation in rock and stiff soil, high-load capacity, and high geotechnical capacity (i.e. grout-to-ground adhesion).

The geotechnical capacity of a micropile is generated by the grout-to-ground adhesion within the bond zone. A higher level of uncertainty exists for the geotechnical load capacity of micropiles than for conventional piles, especially if subsurface conditions, testing and local experience are not taken into account. Pre-production static compression and static tension pile load tests are typically performed on sacrificial piles to establish and/or verify the pile geotechnical axial capacity.

Static pile load tests are widely recognized as the most representative method to establish the geotechnical capacity of micropiles on a project by project basis. The failure load, if not actually achieved during testing, can be determined by many empirical methods. Some of the available methods provide the plunging failure and others define failure as a state which is gradually reached (i.e. gradual failure methods). Designers usually trust more in one method based on their personal experience. Due to this approach, analysis is a subjective task in current geotechnical engineering practice.

Failure load is often difficult to achieve during testing of sacrificial micropiles due to the high grout-to-ground adhesion, structural capacity of bond zone, testing apparatus and safety considerations. Consequently, common design practices frequently rely on achieving the anticipated failure load or the maximum test load.

When the geotechnical failure is not achieved during testing, a useful approach is to extrapolate the loading portion of the load-displacement curve (Q-s curve). Extrapolation is possible through the application of available methods. In addition, these methods can provide the plunging failure load. According to Fellenius (1980), relying on the plunging failure load by considering these methods is a risky decision.

In order to account for the actual geotechnical ultimate load and provide a more reliable failure load, a database of micropile load tests was analyzed by the combination of extrapolation methods with gradual failure methods. The aim of this study was to compare these methods and provide the most accurate prediction method for micropiles in Ontario soils. This was done by evaluating both closeness to the average failure load determined from all the methods and goodness of fit to the normal distribution

The database consisted of 47 micropile load tests provided by Keller Foundations Ltd, operating at the time of load testing as Geo-Foundation Contractors. Tremie grouted and continuous grout-flushed micropiles formed the major part of the dataset, but a few micropiles with pressurized grout were also evaluated. Figure 1 shows the location of these tests. As illustrated, the majority of the available data was obtained from Southern Ontario and a few tests were located in Northern Ontario. Details on the micropile geometry, soil type, and loading methods are shown in Table 1.

2 KEY MICROPILE FEATURES

Micropile is a type of deep foundation element, but it differs in several aspects when compared with conventional driven piles or large diameter drilled shafts. In regard to axial load resistance, the most important difference is related to the bearing strata and load transfer mechanism. Micropiles are usually composed of a bond length and typically an upper-cased length, which connects the pile to the footings/structure. The contribution of the cased length to the load resistance is minimal and typically neglected (Ramirez, 2006). This can be explained by the different structural stiffness present in the two sections of the pile. The cased length is frequently stiffer than the bond length due to the necessity of resisting buckling, providing grout confinement and structural connection. Structural deformations might primarily occur along the bond length.

Furthermore, because of the reliance on high values of the grout-to-ground bond stress, the skin frictional resistance is the major component of the design considerations. The contribution from tip resistance due to end bearing is generally ignored (FHWA, 2000).

All micropiles are tremie grouted, but some micropiles are, in addition, pressure grouted (Type B grouting as per FHWA, 2000). Type B grouting involves the placement of additional grout during the extraction of the temporary drill casing or after its complete extraction. The additional grout is introduced at the top of the casing by securing a cap with a pressure gauge. Post grouting is conducted along the bond zone for Type C micropiles, or it is repetitively applied locally or globally 8-12 hours after the initial grouting phase is completed for Type D micropiles

3 PILE FAILURE METHODS

3.1 Extrapolation Methods

Generally, extrapolation methods are based on a pattern associated with the Q-s behavior of piles. Three methods were considered for this study: Chin (1970), Décourt (1997), and Van Der Veen (1953).

The first considers the Q-s curve to be a hyperbolic one. As such, after some initial scattered points at the beginning of the load application, a hyperbolic behavior is seen – which is shown in Equation 1. Equation 2 provides the plunging failure according to Chin's method.

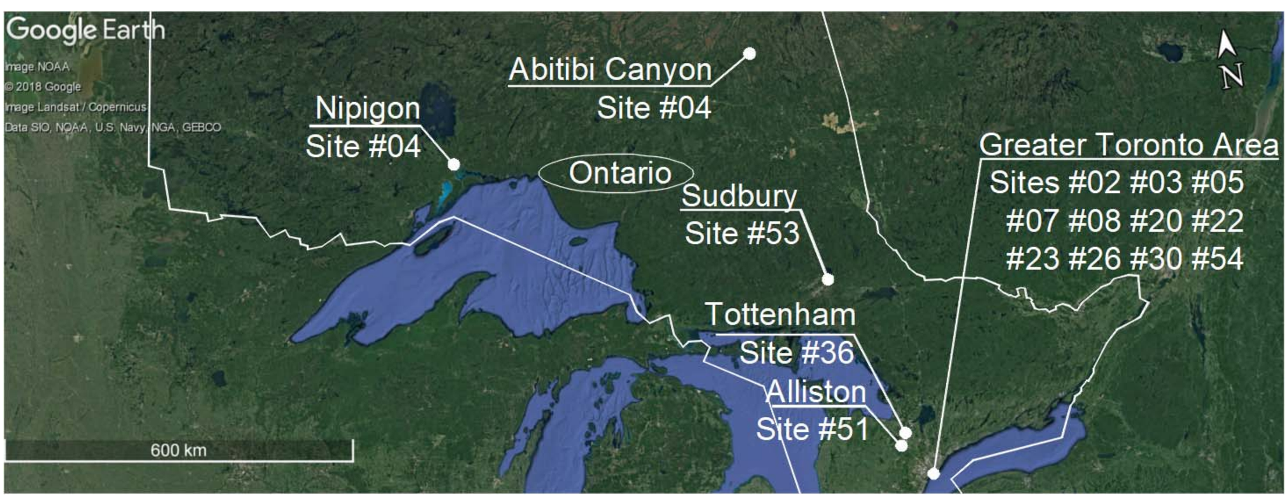

Figure 1. Site locations of the micropile load tests (Google Earth, 2018)

Table 1. Details of studied micropiles

#[1]	Micro pile	Free Length L (m)	Free Length Dia (mm)	Bond Length L (m)	Bond Length Dia (mm)	Bond Length Soil Type	Design Load[2]
2	TP2	3.0	220	4.5	220	Silty Clay	154
	TP3	3.0	220	4.5	220	Sand/Clay	154
	TA	4.6	220	4.5	220	Silty Clay	-154
3	TP1	15.5	218	4.5	218	Clayey Silt / Sand	-370
	TR1	3.0	114	7.5	114	Silty Sand / Clay	-120
	MP6	9.5	193	7.8	193	Sandy Silt	520
	MP7	9.5	193	8.3	193	Sandy Silt	510
	MP8	8.3	193	6.3	193	Sandy Silt	290
4	LT1	6.0	273	10.0	273	Sand	-710
5	LT1	15.0	400	5.0	279	Silt Till/Sand	2200
7	TP9	2.8	219	5.0	90	Sandy Silt	-230
8	LTS	2.7	324	8.6	175	Sand	-1000
	LTN	4.0	324	10.0	175	Sand	-1000
20	2T	9.6	125	5.0	125	Silt/Sand	-350
	3T	9.0	150	6.5	150	Silt/Sand	-203
	6T	9.6	125	5.0	125	Silt/Sand	-350
	15T	9.6	125	5.0	125	Silt/Sand	-350
22	LT3	0.0	115	6.1	115	Sand / Sand Till	360
	LT4	0.0	115	6.1	115	Sand / Sand Till	360
23	LT1	10.3	245	9.9	203	Silt Till	1000
26	LT1	0.0	229	13.9	175	Silty Clay / Sand Till	1000
30	LT1	3.6	273	5.4	203	Clay Till	133
32	CE1	9.9	273	14.6	273	Silt	1222
	RE1	0.0	273	11.4	273	Silt	-611
	CE2	11.9	273	15.2	273	Silt	1219
	LRE	7.0	273	20.5	273	Silt	-1196
	RE2	7.0	273	18.4	273	Silt	-1196
	CW1	6.9	273	9.4	273	Sand	1201
	LRW	7.0	273	9.1	273	Sand	-1201
	RW	0.0	273	16.4	273	Sand	-1201
	P131	7.3	273	13.2	273	Silt	1200
	P134	7.3	273	13.2	273	Silt	1200
	P22	7.9	273	12.8	273	Sand/Silt	1200
	P27	7.9	273	12.8	273	Sand/Silt	1200
	P28	9.5	273	11.5	273	Sand/Silt	1200
	P211	7.9	273	12.8	273	Sand/Silt	1200
	P33	9.3	273	9.1	273	Sand	1200
	P310	9.1	273	9.3	273	Sand	1200
	P318	9.3	273	9.1	273	Sand	1200
	P324	9.3	273	9.7	273	Sand	1200
36	LT1	2.7	130	9.0	130	Silt / Clayey Silt	500
53	TP1	10.7	194	14.0	194	Sand	874
	TP2	9.8	194	4.9	194	Silty Sand	-477
	TP3	5.2	194	4.9	194	Sand	-477
	C1	12.0	194	6.0	194	Sand	-630
	C2	12.0	194	6.0	194	Sand	-630
54	TP1	1.2	115	4.6	115	Silt Till	225

[1]Site number designation
[2]Negative loads are tensile loads, and positive loads are compressive loads

$$\frac{s}{Q} = a\,s + b \qquad [1]$$

$$Q_{ult} = \frac{1}{a} \qquad [2]$$

Where s is the measured displacement for each load, Q is the applied load, a is the slope of the straight line formed on the plot of s/Q versus s, and b is the y-intercept of the same line (Chin, 1970).

Décourt's method is similar to Chin's, but instead of a hyperbolic curve definition, it extrapolates the Q-s curve by the stiffness concept as shown in Equation 3.

$$\frac{Q}{s} = c\,Q + d \qquad [3]$$

Where c is the slope of Décourt's straight line and d is its y-intercept. It is worth noting that this line is formed during the final loading stages, defined as the upper bound for the tip resistance line (Décourt, 2008). The failure is achieved when the pile stiffness trends towards zero (Décourt 1997). This is shown in Equation 4.

$$Q_{ult} = -\frac{d}{c} \qquad [4]$$

Moreover, a rough estimation of the skin frictional resistance is viable through Décourt's method. This is done when the lower bound for the skin resistance line is formed (Décourt, 2008).

The last extrapolation method was described by Van Der Veen (1953) as shown in the equation below.

$$-\ln\left(1 - \frac{Q}{Q_{ult}}\right) = m\,s + n \qquad [5]$$

Where m is the slope of Van Der Veen's straight line and n is its y-intercept. Q_{ult} is achieved when the equation 5 forms a line of best fit with load-displacement results.

3.2 Gradual Failure Methods

In contrast to the extrapolation methods, the gradual failure methods can only analyze the Q-s curve and define the failure load by reaching a gradual failure state. The following methods were considered in this study: Davisson (1972), Fuller and Hoy (1970), Butler and Hoy (as cited in Fellenius, 1980), DeBeer (as cited in Fellenius, 2001), Hansen (as cited in Fellenius, 1980), and Mandolini (as cited in Bellato and D'Agostini, 2013).

Davisson's method gives the failure load as the intersection of the offset elastic line (offset criterion) and the Q-s curve. The expression for Davisson's offset criterion is described in Equation 6.

$$s = \frac{PL}{EA} + \frac{D}{120} + 4 \qquad [6]$$

Where P is the applied load, E is the equivalent Young's modulus (due to two different sections – cased and bond length), A is the cross-sectional area of the micropile, L is the micropile length, and D is the micropile diameter. L, D, and s are given in mm.

Fuller and Hoy's method determines the failure load by the point on the Q-s curve that corresponds to a slope of 0.13 mm/kN. This study considered this value to be equal to 0.15 mm/kN recommended by FHWA (2000).

Butler and Hoy's method establishes the failure load when Fuller and Hoy's line – the tangent with a 0.15 mm/kN slope – and the extension of the Q-s curve initial straight portion intercepts each other.

DeBeer's method proposes a plot between ln Q and ln s. The failure load is the one that corresponds to the greatest change in slope (or maximum curvature) on the plot.

Similarly, Hansen's method suggests the plot of $\sqrt{s}/Q$ versus s. After some initial scattered points, a line is formed and the failure load is given by Equation 7.

$$Q_{ult} = \frac{1}{\sqrt{C_1 C_2}} \qquad [7]$$

Where C_1 is the slope of the straight line formed in Hansen's plot and C_2 is the y-intercept.

Hansen's method can also provide extrapolation to the Q-s curve, but it requires greater load applications - which were not reached in the dataset. Therefore, it was considered to give the failure load only in this study.

Mandolini's method is a simple reduction of Chin's plunging failure by 90%.

Figure 2 depicts an example of the proposed approach of analysis. It shows the raw test data with loading and unloading phases (Test Data); the Q-s curve; extrapolated data by Chin's, Décourt's (Déc.'s), and Van Der Veen's (VDV's) methods; and failure loads by Davisson's Offset Limit (Dav.'s Offset Line), Fuller and Hoy's method (FH), and Butler and Hoy's method (Initial Line interception with either FH by Chin's, Décourt's or Van Der Veen's). 3 regions of failure are exemplified: a) and b) Davisson's failure load; c) and d) Butler and Hoy's; and e) and f) Fuller and Hoy's. The combination of extrapolated data and failure load determined by a gradual failure method was done with all other methods. In contrast to the general behavior, Davisson's failure load provided the highest load from the gradual failure methods in Figure 2.

Figure 3 illustrates the plunging failure provided by various extrapolation methods. Failure can be obtained from the last points of the extrapolated curve. Since failure typically requires a much greater displacement, the given ultimate load is greater than the gradual failure loads.

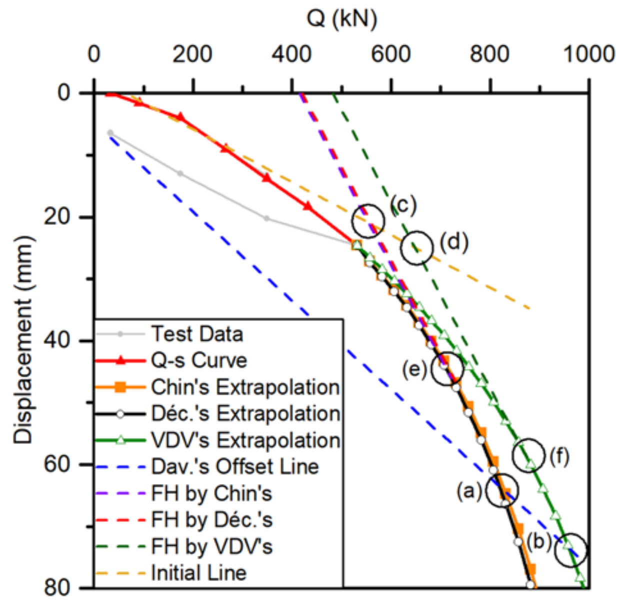

Figure 2. Example of extrapolation and gradual failure methods combination

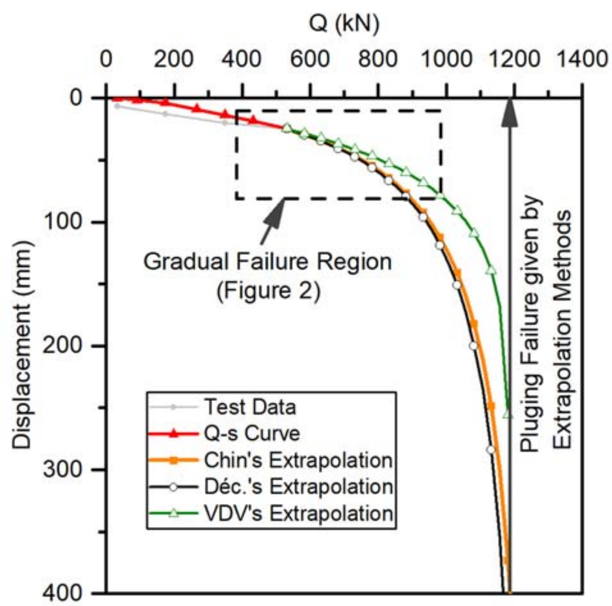

Figure 3. Example of plunging failure given by extrapolation methods

4 RESEARCH METHODOLOGY AND RESULTS

4.1 Analysis Procedure

In order to compare these methods, it is required to fully analyze the data. The first step comprised of extrapolating the Q-s curves. Secondly, the plunging failure load was determined according to the extrapolation methods. Thirdly, the gradual failure load was calculated for each case. Lastly, a statistical analysis was performed. Data evaluation consisted of assessing the load variation, closeness to the average of all possible failure loads and the normality goodness of fit for each method. This was deemed as the most suitable approach for micropile load test analysis.

4.2 Micropile Specification and Soil Conditions

The Standard Penetration Test (SPT) was used primarily for the geotechnical investigations of the sites within the dataset. Other soil profile characterization tests were rarely found due to current micropile design practices being performed mainly with SPT results. Most of the micropile bond zones were embedded in silty and sandy soils.

Micropile design specification and soil conditions are key parameters for load test preparation. They influence the amount of applied load, type of test, and other pertinent aspects. Nonetheless, the only factor which influences the failure load determination based on the Q-s curve is the load type – whether tension, compression with tip mobilization, or compression without tip mobilization. Table 1 provides information regarding the site location, load type, cased and bond lengths, drill bit diameter, and embedded soil type of the analyzed micropiles.

4.3 Extrapolation and Failure Methods Combination

The proposed analysis was performed in two sequential steps: 1) analysis of data extrapolation; and 2) load determination by the gradual failure methods. This approach generated a substantial amount of analyzed scenarios for each micropile. Table 2 summarizes all possible combinations.

4.4 Load Variation and Closeness to Mean Failure Load

A reliable method would have a low range of variation which means that data is concentrated as much as possible near its average. Yet, it should also be near the average of all predicted loads. This provides not only a stable method in terms of variation, but neither a non-conservative nor conservative approach.

The ultimate geotechnical load ($Q_{ult,i}$) from a method i for all piles was normalized through Equation 8. The number of gradual failure methods (n) is equal to 15. In this manner, normalization of the failure loads was based on the mean load of all gradual failure methods. Thus, a N_Q value closer to 1.0 would be ideal.

Table 2. Summary of combined methods

Methods Combination	Chin (Ch)	Décourt (Dec)	Van Der Veen (VDV)
Plunging	Ch	Dec	VDV
Davisson (Dav)	Dav & Ch	Dav & Dec	Dav & VDV
Butler and Hoy (BH)	BH & Ch	BH & Dec	BH & VDV
Fuller and Hoy (FH)	FH & Ch	FH & Dec	FH & VDV
DeBeer (DB)	DB & Ch	DB & Dec	DB & Dec
Hansen (Han)	Han & Ch	Han & Dec	Han & Dec
Mandolini (Man)	Man	-	-

$$N_Q = \frac{Q_{ult,i}}{\frac{\sum_{i=1}^{n} Q_{ult,i}}{n}} \qquad [8]$$

Figures 4 and 5 show the boxplot of the variation of normalized load. The former provides the assumption of all studied micropiles being considered part of the same sample space and the latter the case of compressed micropiles with mobilized tip being solely analyzed. When the mean normalized load of a method is closer to 1.0, it means that this method is near to the average of all gradual failure loads. Furthermore, if the whiskers, 25th, and 75th percentiles are closer to each other, it means that it has a low variation. This box compactness is achieved better in Butler and Hoy's and Fuller and Hoy's methods.

In Figure 5, the friction resistance was predicted according to Décourt's method. Its average was approximately 0.80. Neglecting the tip resistance in compressed micropiles might not be the most reasonable consideration. Tip mobilization was seen in 30% of the compressed micropiles (8 out of 26 cases of compressive tests).

Fuller and Hoy's method, combined with either one of the extrapolation methods, provided better results in terms of proximity to the gradual failure average. Butler and Hoy's method experienced a similar behavior with slightly lower average than Fuller and Hoy's method.

DeBeer's method combined with Van Der Veen's method provided good agreement with the average, but encountered a higher variability compared to either Butler and Hoy's or Fuller and Hoy's methods.

Davisson's method generally provided an underestimation for the failure load - especially in compressed micropiles with tip mobilization. Nevertheless, Hansen's method generated a load similar to the plunging failure. If this method is used, it is recommended to reduce its value by a coefficient of approximately 1.2 to 1.3 (obtained from the mean of Hansen's method in both boxplots) to provide a value closer to the average failure load.

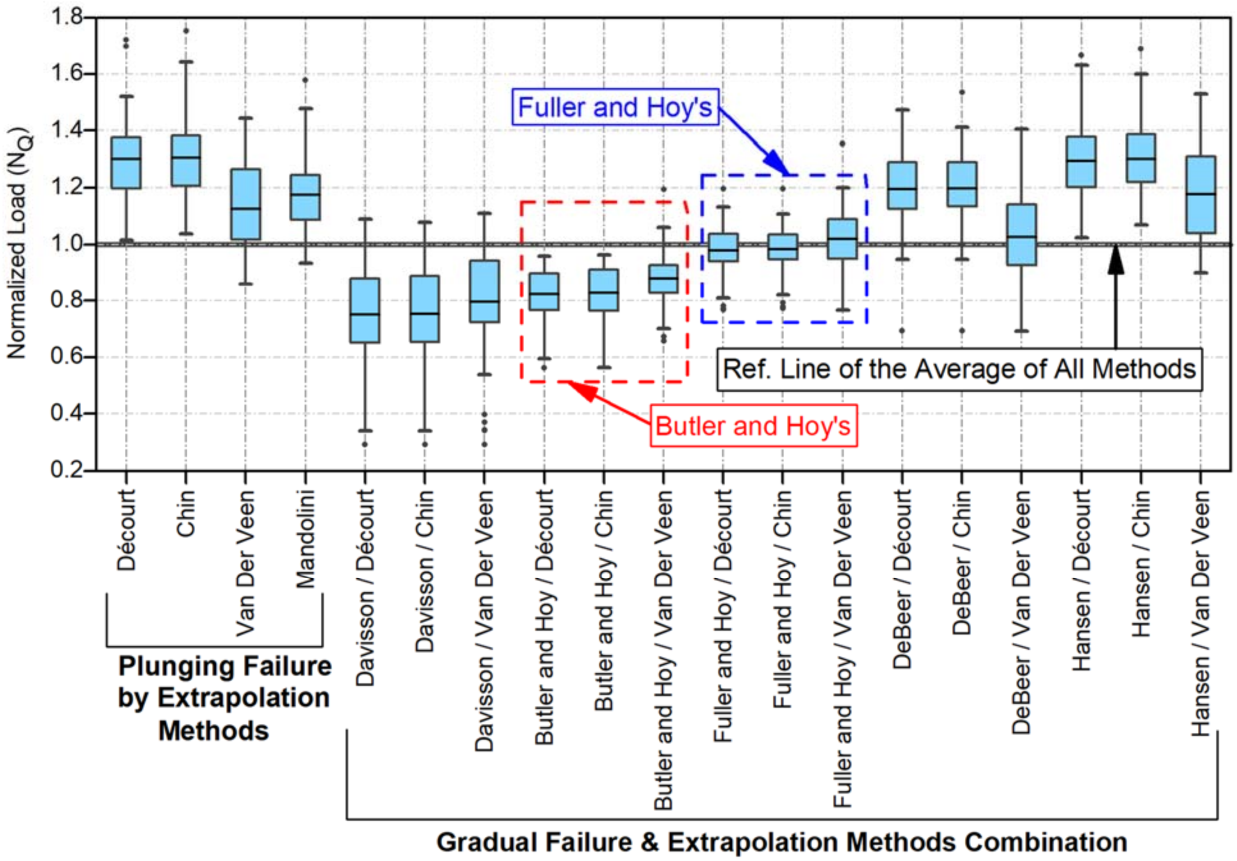

Figure 4. Boxplot of load variability for all studied micropiles

4.5 Goodness of Fit to Normality

Normal distribution is a usual assumption made in many statistical analyses, such as linear regression and correlation (in some cases). A method where its distribution is closer to a Gaussian distribution would be suitable to consider for further statistical and reliability analyses.

Goodness of fit to normality was evaluated through visual methods and the Shapiro-Wilk normality test. This normality test is generally the most powerful one, especially for sample sizes lower than 50 observations (Razali and Wah, 2011).

Visual methods were investigated for each case through histograms, Q-Q plots, and boxplots. When the distribution is approximately equal to a Gaussian distribution in these methods, it is classified as a normal distribution.

Figure 6 compares the significance level for each method in tension tests. A significance level equal to or lower than 5% indicates that the distribution is not normal. If it is higher than 5%, it cannot reject the hypothesis of the distribution not being normal, which favors the assumption of being normal. Extrapolation data generated from Van Der Veen's method performed reasonably well on rejecting the normality hypothesis. Only in DeBeer's and Hansen's method a higher than 5% significance level was generated. Décourt's and Chin's methods generated significance levels in favor of normality when compared with all gradual failure methods.

Figure 7 shows a similar case compared to Figure 6, but for compressed micropiles. Contrary to tension tests, Van Der Veen's extrapolation method tend to generate normal distributions with compression tests. Only for Davisson's method, its significance level was lower than 5%; and then it rejected the normality hypothesis. Meanwhile Chin's and Décourt's methods have reasonably generated good significance values again.

Regardless of the load type, Fuller and Hoy's method generated good agreement for normality by the Shapiro-Wilk test when extrapolated by Chin's or Décourt's method. Visual methods, nonetheless, indicated a weaker normal distribution. Butler and Hoy's method generated high values of significance level when extrapolated by Décourt's or Chin's methods with both tension and compression micropiles; and it also provided good agreement to normality using visual methods. DeBeer's method is not consistent when compression and tension micropiles are compared among themselves. Hansen's method, however, is very consistent in the two considered scenarios.

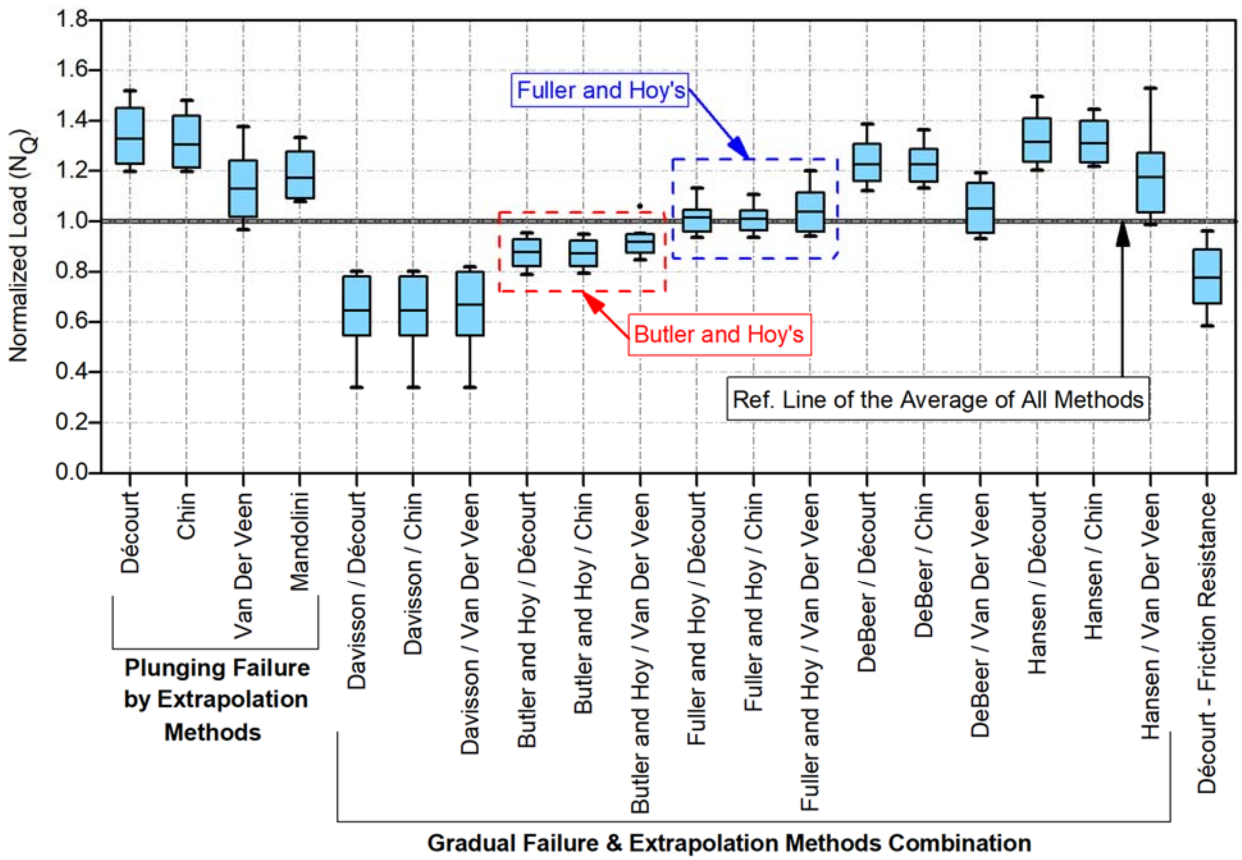

Figure 5. Boxplot of load variability for compressed micropiles with mobilized tip

Davisson's method gives strong indication to be a normal distribution when using Décourt's or Chin's methods, but this does not occur when Van Der Veen's extrapolation method was used. Analyzing it by visual methods, this was not established very well. However, DeBeer's seems to agree the most with Van Der Veen's.

5 CONCLUSIONS

A total of 47 static load tests on micropiles were statistically analyzed in this study to determine the most suitable method to evaluate the geotechnical load capacity of micropiles in Ontario soils.

Determining the failure load by the plunging failure using the extrapolation methods seems to be a risky approach. This study, however, suggested an alternative option to use the extrapolation methods to only extrapolate the curve; followed by an analysis of the failure using the gradual failure methods. The proposed approach could generate more realistic failure loads, while considering both the capacity of the pile and a safer and practical failure.

Regarding the most accurate method, Butler and Hoy's method generated good agreement with the proposed methods of evaluation in terms of closeness to the average data and goodness of fit to a normal distribution. It was followed by Fuller and Hoy's method, which provided a better closeness to the average. Also, their variation using each one of the extrapolated methods was not as high as the other methods.

Hansen's method might also be used with caution by reducing its failure load by a factor of 1.3 for Chin's and Décourt's methods and 1.2 for Van Der Veen's method. Davisson and DeBeer's might not be as reliable for compression micropiles.

The main limitation of this research is related to the use of extrapolated data to determine the failure load instead of data from the field test. Also, the achieved loading level during testing may have influenced the extrapolated portion of the curve. Other potential limitations include procedures of the load tests, such as human error during data acquisition, which is invariably present in all types of test.

The next steps of this research will correlate the results from the geotechnical investigation to the capacity. A reliability analysis will also be conducted. In this manner, it is expected to better understand micropile failure behavior and create an improved design approach for micropiles in Ontario soils.

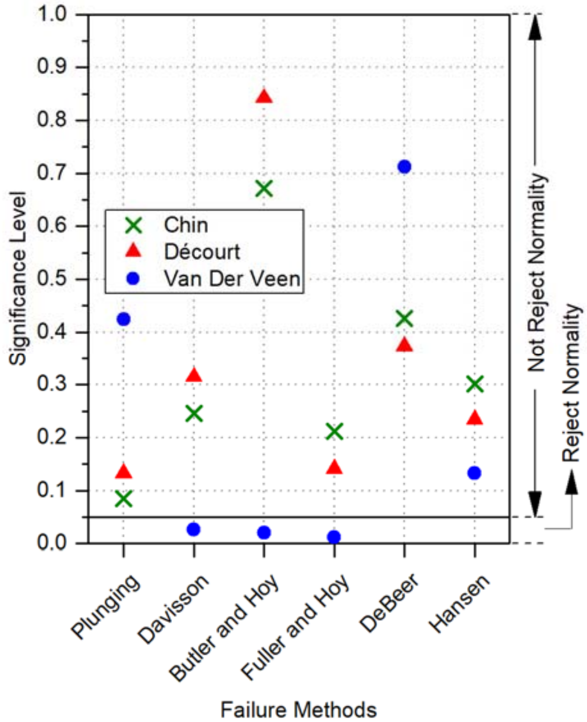

Figure 6. Significance level for each method according to Shapiro-Wilk test – tension tests

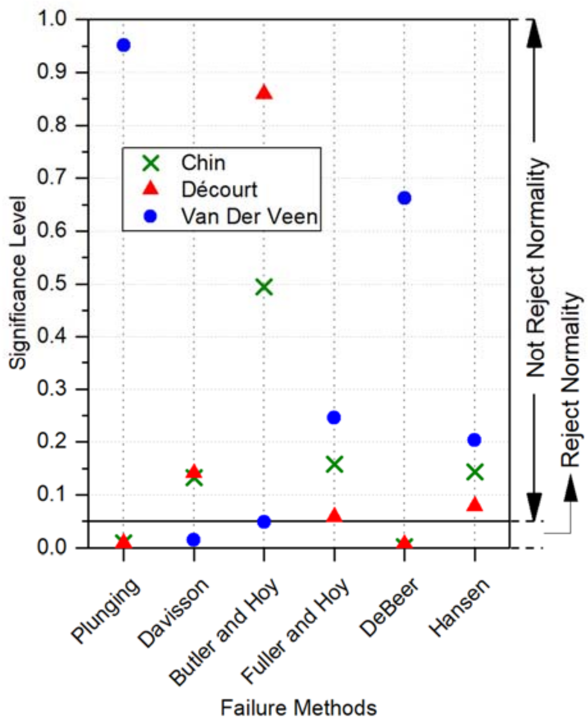

Figure 7. Significance level for each method according to Shapiro-Wilk test – compression test

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