Evaluating CAPWAP Analysis as a Method of Predicting Skin Friction Resistance in Tension for Driven Piles in Clays

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ABSTRACT

Dynamic monitoring with Case Pile Wave Analysis Program (CAPWAP) analysis is an economical alternative to uplift static load testing to estimate the ultimate skin friction resistance of driven piles to tensile forces (i.e. frost adhesion, wind, hydrodynamic/hydrostatic, etc.). CAPWAP analysis estimates the ultimate axial geotechnical resistance of driven piles and the relative contribution of skin friction and end bearing resistances. The skin friction portion may be used in design for estimating uplift resistance of a pile. While CAPWAP analysis is less expensive than uplift static load testing, the results are non-unique and may vary depending on many factors including the data point (i.e. the "blow") selected, the experience and level of effort of the CAPWAP user, etc. A sensitivity analysis was performed on the previously reported CAPWAP results of 20 dynamically monitored piles to observe the effects of intentionally varying skin friction resistances of a clay layer within the CAPWAP model on the accuracy of the model, quantified by the Match Quality (MQ) calculated in the CAPWAP software. The author also performed independent CAPWAP analyses on the dynamic monitoring data to observe the differences/similarities in skin friction resistance estimates from the "best estimate" CAPWAP results. The results demonstrated that while it is possible to show largely varying skin friction estimates (-60% to +60% in many cases) for the same dynamic monitoring data and still have satisfactory CAPWAP results, it is likely that multiple independent CAPWAP users would get similar skin friction estimates when following the standard CAPWAP procedure and averaging the results from multiple dynamically monitored piles from the same project site.

RÉSUMÉ

Le suivi d'essai dynamique utilisant l'analyse CAPWAP (Programme d'analyse d'équation d'onde par la méthode de CASE) est une alternative économique aux essais de charge statique de soulèvement permettant d'estimer la résistance ultime du frottement des pieux battus contre les forces de tension (i.e. l'adhérence au gel, le vent, forces hydrodynamiques/ hydrostatiques, etc.). L'analyse CAPWAP effectue l'estimé de la résistance axiale ultime des pieux battus, et évalue les contributions relatives de la résistance du frottement et de la résistance de pointe. La portion du frottement peut être utilisée en conception afin d'estimer la résistance au soulèvement d'un pieu. Alors que l'analyse CAPWAP est moins coûteuse que les essais de charge statique de soulèvement, ses résultats sont non-uniques et varient en fonction de nombreux facteurs. Ces facteurs incluent le point de données (impact provoqué) sélectionné, l'expérience et les efforts déployés par l'utilisateur CAPWAP, etc. Une analyse de sensibilité a été effectuée sur des résultats CAPWAP provenant d'un programme de suivi dynamique effectué sur 20 pieux. Cette analyse avait pour objectif d'observer les effets de la variation de la résistance du frottement au sein d'une couche d'argile dans le modèle CAPWAP sur la précision du modèle, quantifiée par la qualité de correspondance (Match Quality) calculée dans le logiciel CAPWAP. L'auteur a également effectué des analyses CAPWAP indépendantes, utilisant des données de suivi dynamique, afin d'observer les différences et similitudes des estimés de la résistance au frottement à partir des résultats CAPWAP correspondant aux meilleures évaluations. Les résultats ont démontré qu'alors qu'il est possible de démontrer des estimations de frottement grandement variables (souvent de -60% à +60%) pour les mêmes données de suivi dynamique, et de toujours obtenir des résultats CAPWAP acceptables, il est probable que différents utilisateurs CAPWAP indépendants obtiennent des estimés de frottement semblables lorsqu'ils utilisent la méthode CAPWAP standard et en faisant la moyenne des résultats des différents pieux suivis au cours d'un même projet.

1 INTRODUCTION

A key part of designing deep foundation elements is to assess the uplift resistance to forces such as frost adhesion, wind, hydrodynamic/hydrostatic, and seismic loading. The total resistance of a pile to tensile forces is typically taken as the sum of the buoyant weight of the pile, the permanent axial vertical load, and the factored skin friction resistance in tension (i.e. ultimate skin friction resistance in tension multiplied by the appropriate geotechnical resistance factor). The two primary methods for measuring skin friction resistance of piles in tension to confirm design values (based on analytical methods) are: (1) uplift static load tests; and (2) dynamic monitoring of piles (i.e. Pile Driver Analyzer® (PDA) testing) with Case Pile Wave Analysis Program (CAPWAP) analysis. Uplift static load tests are considered the "gold standard" and a direct measurement of the skin friction resistance of a pile but come with a high cost to the project. Dynamic monitoring with CAPWAP analysis is considered a suitable alternative that can be performed at a much lower cost than an uplift static load test. Because dynamic monitoring is fundamentally a test in compression, it measures both the skin friction and end bearing resistance as one combined value and the relative contribution of each must be estimated following dynamic monitoring using CAPWAP analysis. It is important to note that CAPWAP analysis requires subjectivity and interpretation by the user and therefore, the results are not unique. Varying results in terms of overall resistance and the relative contribution of skin friction and end bearing resistance can be expected when CAPWAP analysis is performed by different users using the same data, while still maintaining an acceptable level of accuracy. Many factors can account for the differences in CAPWAP analysis results such as expertise/experience of the user, individual judgements, and the level of effort on each analysis. The accuracy of the CAPWAP model is represented by the Match Quality (MQ) and the "suggestions" provided by the CAPWAP software. The MQ is a measure of "*the difference between the actual soil behaviour and the assumed set of soil parameters*" (Pile Dynamics Inc., 2014). The relevant "suggestions" are summarized in Table 1.

A sensitivity analysis of the previously reported CAPWAP results was performed by the author to observe the effects of varying skin friction resistances within the CAPWAP model in relation to the accuracy of the model (i.e. Match Quality and "suggestions" provided by the CAPWAP software). The scope of the sensitivity analysis was limited to concrete and steel piles driven through a lacustrine clay layer in and around Winnipeg, Manitoba, to practical refusal within an underlying hard bearing surface (dense silt till or limestone bedrock) while maintaining a total estimated pile resistance within 5% of the original CAPWAP analysis results. The sensitivity analysis included consideration of a total of 20 piles from various sites that were previously dynamically monitored with CAPWAP analysis. The sensitivity of the skin friction resistances in the clay layer on the MQ was plotted for each pile evaluated. An independent CAPWAP analysis was also performed by the author on each data set to assess whether a large variability in skin friction resistance is likely when following the general procedure for performing CAPWAP analysis, as presented in the CAPWAP Background Report (Pile Dynamics Inc., 2014).

2 BACKGROUND

2.1 CAPWAP Analysis

CAPWAP analysis is fundamentally a signal matching exercise using one-dimensional wave theory to match the computed soil response to the measured soil response and is considered "*an essential part of the PDA practice*" (Pile Dynamics, Inc., 2017). It is used to provide the best estimate of ultimate axial geotechnical resistance using dynamic monitoring data and to provide a reasonable estimate of the relative contribution of skin friction and end bearing resistances to the total resistance of a pile.

There are four sets of unknowns required for dynamic analysis of piles which include: internal pile forces, pile motions, soil resistance forces, and soil motions (Pile Dynamics Inc., 2014). During dynamic monitoring of piles, the PDA system measures force and velocity near the pile head but there are still multiple unknowns including static and dynamic soil resistance, external pile forces and motions, and soil motions. These unknowns cannot be calculated directly but can be evaluated by assuming a soil model which includes the following:

- Dividing the soil into short soil segments and assigning soil resistance parameters along each soil segment (i.e. ultimate resistance, quake values, and damping values); and
- Dividing the pile length into short pile segments and distributing available soil resistance along each pile segment.

The pile and soil system can then be analyzed by assigning one of the measured quantities near the pile head (force or velocity) or force in the wave down (equal to the average of the force and velocity measured near the pile head) and calculating the complementary quantity (velocity, force, or force in wave up). The quantities can then be compared by summing the differences over time to calculate the MQ. This process then continues iteratively by changing soil resistance parameters to improve the MQ. The MQ of the last iteration performed by the user is considered the "best estimate" of the ultimate soil resistance and breakdown of skin friction and end bearing resistances.

In theory, CAPWAP analysis for one data set (i.e. one blow of a pile driving hammer) could produce a unique solution that would be represented by one pile model and one defined set of soil model parameters that represents the lowest possible MQ. In reality, it is not practical for one CAPWAP user to search a nearly infinite array of possible combinations to find a unique solution and to be able to confirm that it is, in fact, the lowest possible MQ. For this reason, CAPWAP analysis solutions are considered non-unique and are open to the interpretation and judgement of the CAPWAP user. The "best estimate" is not necessarily the CAPWAP analysis with the lowest possible MQ (i.e. highest accuracy), rather the CAPWAP analysis that was deemed acceptable by the CAPWAP user.

2.2 Evaluation of Ultimate Skin Friction Resistance in Tension using CAPWAP

The ultimate skin friction resistance of a pile may be estimated with caution using the “best estimate” CAPWAP analysis results which includes a breakdown of skin friction resistance along the pile segments. One of the limitations of CAPWAP analysis is that it is difficult to discern end bearing resistance from skin friction resistance along the bottom one or two of the user-defined pile segments in conditions with high end bearing resistance due to limitations of the CAPWAP model; the skin friction resistance along these pile segments is sometimes ignored in practice (Robinson, 2021). Ignoring skin friction resistance in the upper seasonal frost zone (i.e. active soil zone) is also typical practice as these soils cannot be relied on to provide frictional resistance due to the seasonal changes in moisture and temperature. In the Winnipeg region, this active soil zone is typically the upper 1.5 m to 2 m.

The dynamic monitoring data used in CAPWAP analysis is recorded during pile driving and is therefore fundamentally a measurement of geotechnical resistance in compression. For this reason, a correlation to skin friction resistance in tension to skin friction resistance in compression must be assumed. Although it has been observed to be similar in some research, it is typical to assume a 20% to 30% reduction of the skin friction resistance in compression when estimating the skin friction in tension (O'Neill, 2001), (Teferra, et al., 2008).

2.3 Project Data

The pile installation and CAPWAP data used for this evaluation was taken from five different project sites in and around Winnipeg, MB (i.e. within 10 km of city limits). The locations and details of the individual project sites have intentionally been kept anonymous; however, the data used is considered to be typical for Winnipeg and the surrounding area.

Of the piles selected for CAPWAP re-evaluation, 10 were steel H-piles and 10 were precast prestressed concrete hexagonal (PPCH) piles. The steel H-piles were all HP310x110 sections and the PPCH piles consisted of varying sizes including 305 mm, 356 mm, and 406 mm diameters. All piles were driven through a layer of high plastic lacustrine clay to refusal in a dense silt till or limestone bedrock, with the majority of the resistance derived from end bearing. The thickness of the lacustrine clay layer varied by project site but ranged from approximately 10 to 20 m thick for the piles evaluated.

The dynamic monitoring data used for this evaluation consisted of Beginning of Restrike (BOR) data only which was recorded a minimum of 24 hours after the initial pile installation in all cases. This data is considered more representative of the long-term condition than the End of Initial Drive (EOID) data as it has allowed for some degree of time-related effects (i.e. increase/decrease in geotechnical resistance with time). The Canadian Foundation Engineering Manual (4th Edition) recommends waiting a minimum of two weeks prior to BOR testing to allow for pile soil setup; however, typical local practice in the Winnipeg region is for BOR testing to be completed between 24 and 72 hours after initial pile installation. The sets (i.e. penetration per blow) of the data used in the CAPWAP analyses were generally lower than the minimum 3 mm recommended to fully mobilize pile resistance (Pile Dynamics, Inc., 2017). For these reasons, skin friction resistances estimated using CAPWAP analysis from these project sites are likely underestimated.

3 METHODOLOGY

The methodology developed to re-evaluate previously reported CAPWAP analyses to assess the sensitivity of the skin friction resistance on the accuracy of the CAPWAP model is as follows:

1. Select five project sites situated in and around Winnipeg, MB with available dynamic monitoring and CAPWAP data. The project sites were selected based on having an upper lacustrine clay layer of significant thickness (10+ m) and at least five PDA test piles per site to choose from.
2. Select a total of 20 piles (10 steel H-piles and 10 PPCH piles) over the five project sites to evaluate the sensitivity of skin friction on the MQ of the “best estimate” CAPWAP analysis. Piles were selected to be typical of the site (i.e. no anomalies were used) based on the author’s judgement.
3. Re-analyze the “best estimate” CAPWAP analysis of each of the selected piles after re-distributing the skin friction and end bearing resistance proportions while maintaining approximately the same total pile resistance (within 5%). The CAPWAP input parameters (not including resistance inputs) were then adjusted to improve the MQ. Each pile selected was re-evaluated using -60%, -40%, -20%, +20%, +40%, and +60% of the total skin friction resistance from the “best estimate” CAPWAP analysis; the end bearing resistance was then adjusted inversely to maintain approximately the same overall geotechnical resistance. The changes in skin friction were applied proportionally over all pile segments, with the exception of the bottom two pile segments which were left unchanged as it is difficult to differentiate between skin friction and end bearing resistance in this region using CAPWAP analysis.
4. Evaluate the results of each new CAPWAP analysis and address any “suggestions” from the CAPWAP software to be consistent with standard practice. The various “suggestions” and how they were addressed are summarized in Table 1.
5. Observe the results of the sensitivity of the skin friction resistance on the MQ of the CAPWAP model. Any results with a MQ>5.0, an unresolved “Blow Count Match” suggestion, or where the Ru/Quake reduction required was >5% were considered unsatisfactory.

An independent CAPWAP analysis was also completed by the author for each set of dynamic monitoring data presented herein to compare the skin friction resistances with those of the “best estimate”, as presented in the original dynamic monitoring reports. This comparison was completed to assess whether a large variability in skin friction resistance is likely when following the general procedure for performing CAPWAP analysis, as presented in the CAPWAP Background Report (Pile Dynamics Inc., 2014).

Table 1. CAPWAP Analysis Suggestions Summary

Suggestion	Description
"Blow Count Suggestion 2"	Record was based on a small set per blow (<3 mm per blow) and therefore may be conservative. This is typical for driven piles in the region and was not addressed.
"Blow Count Match"	The measured set and computed set varied by more than 1 mm. The author made an attempt to adjust the quake and damping parameters of the soil to clear the suggestion. If the Blow Count Match suggestion could not be cleared, the results were considered unsatisfactory.
"Ru not fully activated"	The total resistance (Ru) is not fully activated in the model. CAPWAP suggests reducing Ru and Quake proportionally, which was performed by the author. If the Ru reduction required was greater than 5%, the results were considered unsatisfactory.

4 RESULTS AND DISCUSSION

4.1 "Best Estimate" Results

The re-evaluation of skin friction resistances was performed using the "best estimate" CAPWAP models as a starting point. The "best estimate" CAPWAP models were taken as the models used to estimate the total geotechnical resistances that were presented in the final dynamic monitoring reports for each of the five sites.

The "best estimate" results for the steel piles and concrete piles are summarized in Table 2 and Table 3, respectively.

Table 2. Best Estimate CAPWAP Results – Steel Piles

Pile Number	Mobilized Static Resistance			MQ
	Skin Friction (kN)	End Bearing (kN)	Total (kN)	
S1	1,125	3,020	4,145	3.03
S2	560	2,515	3,075	2.25
S3	1,316	2,965	4,281	2.58
S4	1,144	2,414	3,558	2.57
S5	1,061	1,759	2,820	3.73
S6	241	4,708	4,949	2.97
S7	709	3,009	3,718	3.38
S8	696	2,845	3,541	2.74
S9	382	906	1,288	1.56
S10	333	1,294	1,627	1.24

Table 3. Best Estimate CAPWAP Results – Concrete Piles

Pile Number	Mobilized Static Resistance			MQ
	Skin Friction (kN)	End Bearing (kN)	Total (kN)	
C1	237	720	957	3.43
C2	927	1,091	2,018	2.89
C3	864	683	1,547	4.11
C4	570	1,087	1,657	3.16
C5	575	1,250	1,825	3.05
C6	426	1,239	1,665	3.74
C7	439	640	1,079	3.83
C8	771	1,310	2,081	3.31
C9	595	1,525	2,120	3.11
C10	1,457	1,068	2,525	2.26

4.2 Sensitivity Analysis Results

The sensitivity analysis results of skin friction resistance on the CAPWAP model accuracy for the steel piles and concrete piles are provided in Figure 1 and Figure 2, respectively.

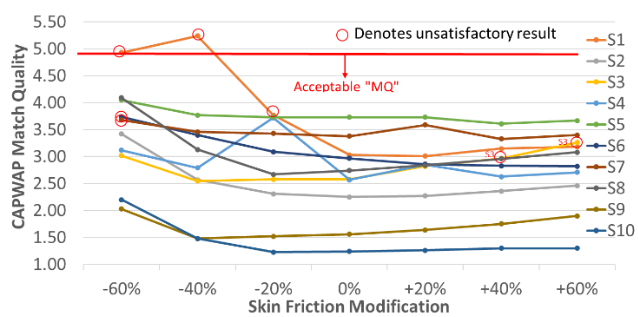

Figure 1. Skin friction sensitivity on CAPWAP accuracy for steel piles

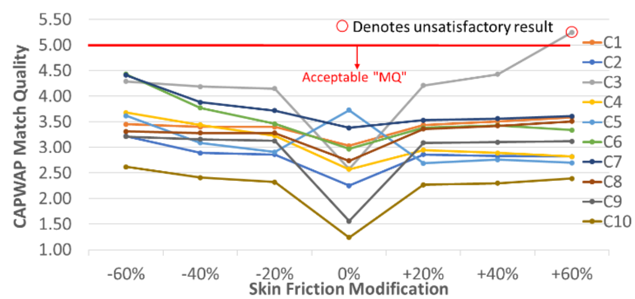

Figure 2. Skin friction sensitivity on CAPWAP accuracy for concrete piles

The results of the sensitivity analysis demonstrate that it is possible to have widely ranging skin friction resistances in the CAPWAP model, while still being considered as satisfactory which has been defined as a MQ less than 5.0 and no "suggestions" from the CAPWAP software (see Table 1). For the steel piles evaluated, 7 of the 10 piles had skin friction modifications from -60% to +60% while still producing satisfactory results. For the concrete piles evaluated, 9 of the 10 piles had skin friction modifications from -60% to +60% while still producing satisfactory results.

It is important to distinguish that the sensitivity analysis was performed to intentionally skew the skin friction resistances to observe whether the CAPWAP analysis results could still be considered satisfactory based on MQ and other "suggestions" in the CAPWAP analysis software. However, the methodology used to evaluate the various skin friction resistances was not typical and would not be considered standard practice. The following section discusses an independent check completed by the author to gain an understanding of whether the large ranges in skin friction resistance estimates would be likely when multiple CAPWAP users are following the general CAPWAP procedure, as presented in the CAPWAP Background Report (Pile Dynamics Inc., 2014).

4.3 Independent CAPWAP Results

An independent CAPWAP analysis was completed by the author for each set of dynamic monitoring data presented herein to compare the skin friction resistances with those of the "best estimate", as presented in the original dynamic monitoring reports. This comparison was completed to assess whether a large variability in skin friction resistance is likely when following the general procedure for performing CAPWAP analysis, as presented in the CAPWAP Background Report (Pile Dynamics Inc., 2014). It is important to understand the CAPWAP analysis results achieved by the author are only one set of non-unique solutions that have not been independently reviewed. The intent is not to improve on the "best estimates" but to assess whether it is likely for skin friction resistances to differ greatly when following best practices for performing a CAPWAP analysis. The comparison of the "best estimate" and the independent CAPWAP skin friction resistances for the steel and concrete piles are presented in Tables 4 and 5, respectively.

Table 4. Comparison of Total Skin Friction Resistance from "Best Estimate" to Independent CAPWAP Performed by Author – Steel Piles

Pile Number	Skin Friction Resistance (kN)			MQ	
	"Best Estimate"	Independent CAPWAP	Change	"Best Estimate"	Independent CAPWAP
S1	1,125	813	-27.7%	3.03	3.18
S2	560	693	23.7%	2.25	2.65
S3	1,316	1,495	13.6%	2.58	2.68
S4	1,144	873	-23.7%	2.57	2.60
S5	1,061	824	-22.3%	3.73	4.22
S6	241	237	-1.9%	2.97	3.03
S7	709	568	-19.9%	3.38	2.53
S8	696	519	-25.4%	2.74	3.30
S9	382	443	16.1%	1.56	1.74
S10	333	299	-10.2%	1.24	1.22
		Average	-7.8%	2.61	2.72

Table 5. Comparison of Total Skin Friction Resistance from "Best Estimate" to Independent CAPWAP Performed by Author – Concrete Piles

Pile Number	Skin Friction Resistance (kN)			MQ	
	"Best Estimate"	Independent CAPWAP	Change	"Best Estimate"	Independent CAPWAP
C1	237	280	17.9%	3.43	3.22
C2	927	1,023	10.4%	2.89	3.17
C3	864	874	1.1%	4.11	4.18
C4	570	731	28.3%	3.16	2.25
C5	575	897	55.9%	3.05	3.31
C6	426	718	68.6%	3.74	3.29
C7	439	317	-27.7%	3.83	3.54
C8	771	293	-62.0%	3.31	3.11
C9	595	608	2.1%	3.11	3.06
C10	1,457	1,049	-28.0%	2.26	3.08
		Average	6.7%	3.29	3.22

Based on the results of the independent CAPWAP analyses, it can be shown that although there were significant changes in the estimated total skin friction resistances from the "best estimate" for some individual piles (as high as a 68.6% change), when averaging the changes over 10 steel H-piles and 10 PPCH piles, the overall discrepancies were relatively small. For the steel piles evaluated, the change in total skin friction resistance was less than 30% in all 10 piles with an average change of -7.8%. For the concrete piles evaluated, the change in total skin friction resistance for 7 of 10 piles evaluated was less than 30% with an average change of 6.7%.

It is shown that a large range in skin friction resistances may produce acceptable CAPWAP results; however, it is the author's opinion that independent CAPWAP users evaluating the same data using the standard CAPWAP analysis procedure would expect to observe some variation in skin friction resistances but not to the extent evaluated in the sensitivity analysis (-60% to +60%) when averaging over multiple piles. This generally agrees with the results of a study conducted by Dr. Bengt Fellenius where he had 18 participants perform CAPWAP analysis on the same four sets of data (i.e. one hammer blow on four different piles) to evaluate the variability of the estimated pile capacities (Fellenius, 1988). The study shows that the standard deviations for the estimated total pile capacities on the four data sets were 5%, 6%, 13%, and 15%, with the two higher standard deviations associated with the data sets that were considered more difficult to analyze with CAPWAP. The breakdowns of the skin friction and end bearing components were not presented in numerical form in Dr. Fellenius' paper; however, the graphs show relatively tight correlations of resistance as a function of depth below the PDA gauges. Figure 3 shows the results of one data set analyzed by all study participants as an example.

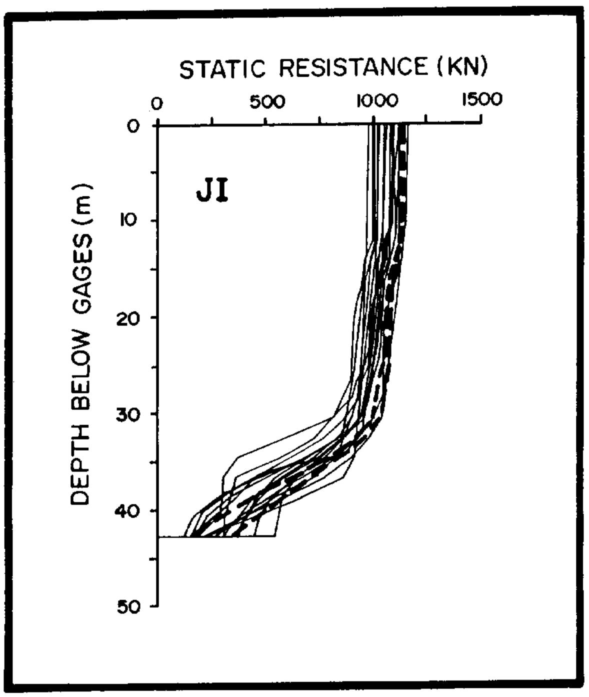

Figure 3. Results of CAPWAP analyses performed on one hammer blow by 18 study participants; reproduced with permission from Dr. Fellenius (Fellenius, 1988)

5 SUMMARY AND RECOMMENDATIONS

Dynamic monitoring of piles with CAPWAP analysis is an economic and effective alternative to uplift static load testing for evaluating skin friction resistance of piles in tension. While the results of dynamic monitoring with CAPWAP analysis correlate well with static load testing (in compression) for total pile capacity in compression (Likins & Rausche, 2017), there is additional uncertainty when using CAPWAP analysis to evaluate skin friction resistance. This uncertainty is a result of the inherent uncertainties in the CAPWAP model and the judgement required by the CAPWAP user. A sensitivity analysis was performed to observe the effects of varying skin friction resistances of a clay layer within the CAPWAP model on the accuracy of the model (i.e. MQ and "suggestions" as defined in Table 1). The sensitivity analysis was conducted on Winnipeg, MB lacustrine clays using pre-existing dynamic monitoring data from 20 piles installed at five different project sites in and around Winnipeg.

The results of the sensitivity analysis demonstrated that it is possible to show largely variable skin friction resistance estimates (-60% to +60% in most cases) for the same dynamic monitoring data while still having satisfactory CAPWAP results, defined as a MQ less than 5.0 and adequately addressing "suggestions" from the CAPWAP software (see Table 1). However, the average skin friction resistance values estimated by independent CAPWAP analyses performed by the author when following the general CAPWAP procedure matched relatively well with the average skin friction values from the "best estimate" CAPWAP analyses. The steel piles were within 8% of the "best estimate" average and the concrete piles were within 7% of the "best estimate" average. A previous study completed by Dr. Fellenius where 18 CAPWAP users performed CAPWAP analysis on the same four data sets also showed that skin friction values estimated had a relatively low variability (see Figure 3).

Based on a review of the sensitivity analysis results, the independent CAPWAP analyses results, and Dr. Fellenius' 1988 study (Fellenius, 1988), it is the author's opinion that dynamic monitoring with CAPWAP analyses is an acceptable method for estimating/confirming skin friction resistance in tension, however the CAPWAP user/review engineers should account for the uncertainties that are inherent to this method. The following are recommended to reduce the uncertainty associated with estimating skin friction in tension using dynamic monitoring data and CAPWAP analysis:

- CAPWAP analysis be performed by experienced users following the general procedure as presented in the CAPWAP Background Report (Pile Dynamics Inc., 2014) and reviewed in detail by a senior engineer also experienced in CAPWAP.
- Additional CAPWAP analyses be performed by an independent CAPWAP user on a portion (e.g. 25% as a "spot check" for a start) of the same dynamic monitoring data. Significant differences should be investigated.
- Estimate skin friction based on an average of all available data across the project site (or area of similar stratigraphy if variable conditions exist across the project site). Using one single CAPWAP analysis to estimate skin friction in tension for design purposes would not be defensible in the author's opinion.
- Uplift static load testing be performed to complement CAPWAP estimates in instances where a large variability in skin friction estimates is being observed or the consequences of failure in uplift are high.

In addition to the above, it is also recommended that standard industry practice be followed when using CAPWAP results to estimate skin friction in tension which includes the following:

- Ignore skin friction in the upper active soil zone (e.g.

upper 1.5 m to 2 m in Winnipeg region).

- Investigate skin friction in the lower two pile segments (typically 2 m of pile length) in high end bearing conditions to ensure it aligns with expectations. If the skin friction resistance values in the lower two pile segments are greater than anticipated based on the soil stratigraphy as shown on the borehole logs, the skin friction along these segments should be reduced to an appropriate level; this requires judgement from the geotechnical engineer.
- Apply a 20% to 30% reduction of the skin friction resistance in compression (from CAPWAP analysis) to estimate the skin friction resistance in tension to be used for design purposes.

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