Value of pile tests to inform detailed design in Canada

Andrew Sorrie, Andrew Cushing
Arup Canada Inc., Toronto, Ontario, Canada

Michael Lewis
Bechtel Infrastructure, Evans, Georgia, USA

ABSTRACT
It is generally apparent to geotechnical designers that having access to pile load test data prior to the detailed design stage reduces the quantity and magnitude of design unknowns and allows for somewhat less conservative design assumptions, resulting in a more efficient pile design. Unfortunately, for many projects, particularly lump sum public private partnerships (P3), pile load test data is not available to inform the design, acting only to validate conservative assumptions at a later stage.

The barriers are typically commercial, however this misses a valuable opportunity for more efficient design, reduced construction cost and additional “soft” benefits by virtue of increased risk awareness, reduction, and mitigation. The combined benefits gained when pile test data is available early will typically outweigh the initial financial outlay for the test. This study will consider a number of case studies to highlight the benefits and risks of undertaking pile tests in the tender stage and/or early in the project execution phase to better inform commercial decisions.

RESUME
Il est acquis pour les concepteurs géotechniques que l'accès aux données d'essai de charge de pieux avant la phase de conception détaillée réduit la quantité et l'ampleur des inconnues de conception et permet d’adopter des hypothèses de conception moins conservatrices, ce qui produit une conception plus efficiente. Malheureusement, pour de nombreux projets, en particulier les partenariats public-privé à prix forfaitaire (P3), les données d'essai de charge de pieux ne sont pas disponibles pour informer la conception, servant simplement à valider les hypothèses conservatrices après le fait.

Les obstacles à l’implémentation d’un programme d’essais sont généralement commerciaux, mais cela laisse passer une opportunité précieuse pour une conception plus efficiente, une réduction des coûts de construction et des avantages «immatériels» supplémentaires en raison de la prise de conscience, de la réduction et de mitigation des risques. Les avantages combinés obtenus lorsque les données d’essais de charge sont disponibles tôt l’emportent généralement sur l’investissement initial de l’essai. Cette étude examinera un certain nombre d'études de cas pour mettre en évidence les avantages et les risques liés à la réalisation d’essais de charge de pieux lors de la phase d'appel d'offres et / ou au début de la phase d'exécution du projet.

1 INTRODUCTION

Drilled shafts (also referred to as caissons or bored piles, or generally as piles) are common foundation solutions for large transportation and infrastructure projects, particularly under heavy loading conditions and space limitations or where competent strata are found at a significant depth. In these conditions, the size of piles is often governed by axial compressive capacity.

In Canada, it is typical to undertake drilled shaft designs based on empirical relationships or local and/or regional historical correlations. These relationships are often generic, and not based on the same geology as the proposed project. Material parameters to determine unit skin friction and end bearing values can require conservatism to account for potential uncertainty or limited ground information. This is a particular issue for P3 projects where the geotechnical risk is placed solely on the contractor, typically with no differing site condition clause in the contract, and limited geotechnical data are provided at the tender stage which can also be caveated as data “not to be relied upon”. Thus, the dilemma of how much monetary contingency to include in the tender while remaining competitive.

Canadian design codes recognize the benefits of pile testing, allowing a significant reduction on overdesign by using a less-conservative geotechnical resistance factor if the pile test verifies the ultimate resistance of the pile.

Where early pile tests are undertaken on projects, it is typically based on a direct commercial comparison between the cost of the pile test and the drilled shaft length savings associated with the higher, less conservative geotechnical resistance factor. Pile tests are often undertaken at the start of the construction phase, a decision typically driven by the project schedule. This results in the test acting merely as a verification exercise, whereby either the test verifies a minimum of the design assumption allowing construction of production piles to progress, or the result identifies an issue in the design or construction of the piles requiring some form of design modification.

This process misses a significant opportunity and value that pile testing can offer, which is to optimize the design for the specific geology, pile size and construction methods for the project. To do so, however, requires agreement from all key stakeholders early in the process to undertake pile tests sufficiently in advance of construction (e.g., immediately or shortly after project award) to allow the results of such testing to more optimally inform the detailed design. An alternative to this, which would benefit the project immensely, is to have Owner-provided pile load test data for all proponents to use at the tender stage. This puts all the proponents on equal playing field, reduces the uncertainty, thereby reducing risk, and results in a more certain outcome. Additionally, it would most likely result in lower foundation costs since a good deal of the uncertainty would be alleviated, particularly with significant reduction in contingency allowances for risk of ground conditions.

In comparing available case history data, this study will consider key barriers preventing pile testing to inform design, and summarize some key conclusions to act as a tool to inform future decisions on when pile testing should be undertaken in similar circumstances.

2 APPROACH TO PILE TESTING IN CANADA

Pile load tests are generally performed as either “proof tests”, which are intended to verify the production shaft performs satisfactorily under the required working load in strength or serviceability performance, or as “pre-production” load tests which load the pile beyond that of the working load and ideally to the point of geotechnical failure to determine information of the proportion of load transferred in side (or shaft) resistance and end (or tip) resistance in the founding strata.

This paper shall focus on the added value that can be achieved by carrying out pile testing early in the process, and in particular when axial load governs the pile design.

2.1 Limitations of Pile Testing Benefits

While there can be considerable benefits of undertaking pile testing, which shall be discussed further, it must be acknowledged that there are certain limitations which affect the value of undertaking load testing.

Firstly, pile testing involves costs which need to be factored into the project budget, and this is an oft-cited reason for testing not being undertaken. Secondly, Owners and Clients can be unwilling to spend their money (or tax-payer money) to provide pile test data during the tender phase. This reasoning is often short sighted, as the upfront cost of the pile test is often small in comparison to the potential benefits which will be outlined in this paper, and does not account for potential reduced uncertainty, risk and added contingency money.

In some circumstances however, such as a site with significantly variable ground conditions or with very few drilled shafts, the number and cost of pile tests can outweigh the direct benefits.

Additionally, there may be instances where the required pile dimensions may not be governed by the geotechnical axial capacity. This can include scenarios where embedment is governed by lateral performance, or where a nominal embedment in a very strong material achieves capacity even with a very conservative approach.

2.2 Motivation to undertake load testing

The motivation behind performing load testing varies depending on one’s perspective.

The designer is typically motivated to provide as efficient a design as practical, reducing uncertainties and ensuring a sufficiently robust solution is developed. However, the designer can be limited by uncertainties in ground conditions, whether they be derived from variability in ground conditions, lack of ground related information, or reliance on non-site-specific empirical correlations which can result in undue conservatism. The Owner or contractor is often motivated by cost and schedule, but can be limited by phases of release of funding and limited upfront funds and a lack of consideration of whole-life costs.

Other benefits and motivations are also gained from pile tests, but these are often considered secondary. Undertaking pile tests to inform design can aid in reducing environmental impact. This can be achieved through less conservative parameters resulting in smaller foundation sizes, and consequently reduced volumes of high embodied energy materials such as concrete and steel. Further, a pre-production test pile can be used to verify levels of noise and vibration prior to the program of production piles, which is particularly useful at sites close to residential areas or sensitive historic buildings.

Additional benefits include reduced risk of deferred identification of issues during the construction period with negative impacts on schedule, and verification of construction means and methods or identification of unexpected ground conditions prior to construction. Further, the benefit of potentially shorter shaft lengths accumulates an added benefit of simpler construction methods and a shorter construction period associated with drilling piles to a shallower depth and reduced risk of encountering challenging construction conditions.

2.3 Design Codes

Design codes in Canada promote the use of pile testing and as such provide a direct mechanism to achieve certain design efficiencies.

The National Building Code of Canada (NRCC, 2010) and the Canadian Highway Bridge Design Code (CSA, 2014) do so by providing increased values of geotechnical resistance factor if ULS geotechnical resistance is determined from in-situ load testing in representative ground conditions. These factors allow for reduced conservatism to account for the reduced potential for variability in geotechnical performance.

As well as the analysis method or model, the Canadian Highway Bridge Design Code also accounts for the degree of understanding (DoU) of the ground conditions based on the available ground investigation information, as well as consequence factor for the type of structure.

2.4 Barriers to full benefits

The most significant driver affecting whether a pile test is undertaken either early in the execution phase or by the Owner during the tender phase is typically cost, and the reduced geotechnical resistance factor is the only guarantee the designer can offer.

While through these improved factors certain economic benefits can immediately be achieved, the full benefit is often not unlocked.

The added benefits are often limited by the second most significant driver, which is schedule, and often there is insufficient time allowed during the execution phase to maximize the added value pile tests offer. However, carrying out testing during the tender phase obviates the project schedule concern.

3 TIMING OF PILE TESTING DURING PROJECT EXECUTION

There are two primary phases when pile testing is typically undertaken during project execution; during the design phase or at the start of foundation construction. A less frequently exercised option is undertaking testing in the tender phase.

Assuming equivalent tests, both timing options should satisfy the requirements of the design codes to achieve the benefits of increased geotechnical resistance factors which will achieve a base level of economic benefits.

However, the two phases differ in their additional benefits and limitations for a project.

3.1 Testing at the Design Phase

In general, the benefits for foundation design, cost and constructability can be maximized when pile testing is undertaken prior to the final design, either before or within the detailed design phase or at the tender phase. However, testing at this stage requires additional effort to procure a load testing program separate from the construction-phase procurement.

The primary benefit that can be achieved is the certainty of the foundation performance, and the opportunity to optimize the foundation design for the actual ground conditions and construction techniques. This also allows the opportunity to consider alternative foundation options should the results be significantly higher or lower than expected. This does however require a significant amount of time to be allowed for during the design period to undertake the pile testing, which may be difficult in a relatively short design-build schedule environment.

The contractor can also benefit from a “trial run” of construction means and methods, to work out any constructability problems without affecting construction schedule. This also allows for more certainty in the time and techniques during construction, and can allow for reduced contingency allowances, as well as shorter construction period as pre-production pile testing has already been completed. However, some sites may have onerous conditions which mean mobilization and preparation of the test pile are prohibitively costly and multiple mobilization costs may not justify the benefits.

3.2 Testing at the Start of Foundation Construction

Only if sufficient time is allowed for in advance of the production piles can test results be utilized to reduce pile lengths without impact on construction schedule, and so the full value of testing is typically not utilized. Similarly, if the test dramatically outperforms its expectations, there is limited schedule to implement significant changes or test the revised options.

Conversely, if testing underperforms its design expectations, then redesign is required and can result in the construction delays. Due to this risk, the designer must account for potential variation in their design and is likely to result in a more conservative design at this stage to account for this risk. Similarly, the contractor would typically need to include contingency in their price for the most onerous anticipated conditions.

On the other hand, undertaking test piles at the start of the construction period benefits from the ability to commence production piling immediately after successful completion of the test pile and avoiding additional mobilization costs, assuming that the test is successful. However, if the test is not successful, while the results are being assessed and the production pile are systematically redesigned, there could be significant standing time costs accrued for the piling rig or additional demobilization and remobilization costs.

3.3 Testing at the Tender Phase

All the benefits described in Section 3.1 regarding *Testing at the Design Phase,* and more, can be realized when the Owner carries out load testing for the tender phase and provides that data as “relied upon” for all proponents to use.

This can be done in the form of a Geotechnical Baseline Report (GBR). Although not normally seen on P3 projects in Canada, the GBR can be used as the geotechnical baseline for tender and would serve as the basis for changes during the execution phase. The GBR would benefit the project and Owner greatly.

Additional benefits at this stage include; certainty in design parameters for all tendering proponents, certainty in feasibility of proposed construction methods and verification of scheme foundation solutions. As well as the potential cost benefits the increased certainty in these aspects would provide, they would also provide a more dependable construction schedule.

Further, this option would allow for more appropriate and consistent levels of risk contingency sums for tender foundation costs. This could also allow Owners to move away from the current by-product of limited geotechnical data, which is the inadvertent promotion of proponents to submit higher-risk tenders to increase likelihood of a successful outcome. Having all proponents on equal playing field with less risk associated with foundations would result in significantly reduced contingency, lower tender estimate and less risky project delivery.

In the same way, the negative impacts can be reduced by providing load testing data to all proponents during the tender phase.

4 CASE STUDIES

While the general benefits as summarized previously are generally understood by geotechnical designers, it is often difficult to explain the benefits to Owners, project managers or decision makers and persuade them to undertake pile testing at the most opportune time.

This section shall consider five sites, designed and constructed between 2008 and 2017, for infrastructure projects where drilled shafts have been deployed as the foundation method. Each site adopted empirical design methods to determine drilled shaft end bearing and shaft resistance capacities. These sites adopted well accepted empirical methods (CGS, 2006; AASHTO, 2006, FHWA, 2010) and utilized pile tests at the construction phase to verify the performance met the design assumptions and allow use of increased resistance factors.

Each site undertook testing at the start of the construction phase, and therefore only if a failure occurred (not verifying required capacity) would the design be re-addressed. The sites shall be summarized to show the benefits that hindsight provides had testing been available to inform the design phase.

4.1 Site 1 – Rail Viaduct, Province of Alberta

The first case study is a large elevated viaduct structure over 1km in length, supported by twenty-nine (29) piers founded on bored piles of either 1.8 m and 2.5 m diameter, with lengths typically between 30-50 m.

The ground conditions at the site generally consist of a sequence of fill, glacio-lacustrine clay, glacial till, and extremely weak clay shale. Two distinct regions were identified, the first with shale present between 10-15 m below ground level and only around 5 m of till, and the second with shale at around 35 m below ground level and around 30 m thickness of till. The tender design assumed pre-production pile tests would be undertaken.

The detailed design was based on the Canadian Highway Bridge Design Code (CSA, 2014) and had a high degree of understanding due to the ground investigation completed. The structure was deemed a high consequence structure. The design therefore adopted a resistance factor of 0.63 accounting for the geotechnical resistance factor of 0.7 multiplied by the consequence factor of 0.9.

Pile tests were undertaken at the construction stage using Osterberg load cells (O-Cells) towards the base of the test shaft. Two pile tests were undertaken, one for each set of differing ground condition. Both pile tests verified the design pile capacities.

The designer's review of the test results indicated that one pile test was close to mobilizing the full pile capacity (80-100% of ultimate load), while the other test mobilized around 60% of the projected ultimate load capacity.

Table 1 summarizes the cumulative pile length for the site, showing that the use of pile tests alone saved approximately 1033 m of pile length (35%) when using empirical design methods. Following the results of the pile tests, it is shown that based on the minimum mobilized test results a further 293 m of pile length could have been saved, equating to a total saving of 1335 m (46%). However, it was further noted by the designer that if the parameters were based solely on the fully mobilized test, then this could have been greater, up to approximately 60% savings.

4.2 Site 2 – Maintenance Building, Province of Alberta

The second site is a large maintenance facility for rolling stock in Alberta. This structure was supported on two-hundred-and-twenty (220) individual drilled shafts ranging from 0.6 m up to 1.0 m diameter, with lengths generally between 10-25 m.

Table 1. Summary of Cumulative Pile Lengths for Site 1

Cumulative Pile Length	Site 1
Empirical Design - with Pile Test	1859 m
Empirical Design - without Pile Test Resistance Factor	2891 m
Length Saving with Pile Test	1033 m (35%)
Estimated length based on Pile Test parameters	1556 m
Length saving with Pile Test & Verified Parameters	1335 m (46%)[1]

[1] Based on minimum mobilized resistance values of two tests.

The ground conditions at the site generally consist of a sequence of fill, glacio-lacustrine clay, glacial till, and weak clay shale. The depth of clay shale varied across the site, with two ground models adopted, one with shale at a depth of 5 m below ground level, and the other at 11 m below ground level.

The detailed design was based on the National Building Code of Canada (NRCC, 2010), and adopted a geotechnical resistance factor of 0.6 associated with adopting pile tests, one in each set of ground conditions.

Two pre-production pile tests were undertaken at the construction stage, using conventional static load test methods with reaction piles, instrumented to allow determination of unit end bearing and side resistance values. Both piles established the failure load, with one test verifying the design capacity, while the other failed lower than was expected through the design.

The result of the test pile not achieving the expected capacity required the designer to reassess the proposed drilled shaft lengths. As the test was undertaken at the start of the construction phase, this led to a negative impact on the construction schedule. The exact delay period was not reported for the site. The designer identified that the test results indicated the clay shale at shallower elevations performed less favorably in shaft resistance than it did at deeper elevations.

Table 2 summarizes the cumulative pile length for Site 2 based on the empirical design approaches adopted. It is shown that while 375 m of length savings (11%) were anticipated based on the empirical design approach, following the pile tests the actual length reduction achieved was 225 m (approximately 7%).

Table 2. Summary of Cumulative Pile Lengths for Site 2

Cumulative Pile Length		Site 2
Empirical Design - with Pile Test		2926 m
Empirical Design - without Pile Test Resistance Factor		3300 m
	Length Saving with Pile Test	374 m (11%)
Estimated length based on Pile Test parameters		3075 m
	Length saving with Pile Test & Verified Parameters	225 m (7%)

4.3 Site 3 – Rail Viaduct, Province of Alberta

The third site is a rail viaduct spanning over a number of highways, for approximately 0.5 km over five spans. The spans were supported on piers and founded upon drilled shafts of 1.8 m and 2.5 m diameter, typically to a depth of 15-22 m.

The ground conditions at the site generally consisted of a layer of variable fill, underlain by a sequence of sand, then gravel, then clay shale present between 5-10 m below finished ground level.

The detailed design was based on the Canadian Highway Bridge Design Code (CSA, 2014) and had a high degree of understanding due to the ground investigation completed. The structure was deemed a high consequence structure. The design therefore adopted a resistance factor of 0.63 accounting for the geotechnical resistance factor of 0.7 multiplied by the consequence factor of 0.9.

The pile test was undertaken at the construction stage using an O-Cell test, located towards the base of the test shaft. While the pile test verified the test pile capacity and unit parameters, it was identified that competent rock was deeper than assumed by design which negated the benefits of the improved parameters.

Table 3 summarizes the cumulative pile length for the site, showing that the use of pile tests alone saved approximately 70 m of pile length (26%) when using empirical design methods. Following the results of the pile tests, it is shown that based on the minimum mobilized test results theoretically a further 70 m of pile length could have been saved, equating to a total saving of 140 m (52%).

Table 3. Summary of Cumulative Pile Lengths for Site 3

Cumulative Pile Length		Site 3
Empirical Design - with Pile Test		200 m
Empirical Design - without Pile Test Resistance Factor		270 m
	Length Saving with Pile Test	70 m (26%)
Estimated length based on Pile Test parameters		200 m
	Length saving with Pile Test & Verified Parameters	140m (52%)

4.4 Site 4 – Station Building Structure, Province of Alberta

The fourth site is that of a rail station building in Alberta, which at platform level is connected to a rail track entering above ground level, as well as a mezzanine connecting to the ground floor level. The raised structure at platform level is supported on eight (8) piers founded on bored piles 1.8 m diameter with lengths generally between 25-30 m.

The ground conditions at the site consist of over 5 m of variable fill, over glacial till over extremely weak clay shale at around 20 m below ground level. A consistent ground model existed for the structure.

The detailed design was based on the Canadian Highway Bridge Design Code (CSA, 2014) and had a high degree of understanding due to the ground investigation completed. The structure was deemed a high consequence structure. The design therefore adopted a resistance factor of 0.63 accounting for the geotechnical resistance factor of 0.7 multiplied by the consequence factor of 0.9.

The pile test was undertaken at the construction stage using an O-Cells test, located towards the base of the test shaft. The pile test verified the design capacity.

Table 4 summarizes the cumulative pile length for the site, showing that the use of pile tests alone saved approximately 181 m of pile length (35%) when using empirical design methods. Following the results of the pile tests, it is shown that based on the minimum mobilized test results a further 43 m of pile length could have been saved, equating to a total saving of 224 m (44%). However, it was noted by the designer that this test was not taken to failure and the savings could have been in excess of this value had the full resistance values been mobilized.

Table 4. Summary of Cumulative Pile Lengths for Site 4

Cumulative Pile Length		Site 4
Empirical Design - with Pile Test		325 m
Empirical Design - without Pile Test Resistance Factor		506 m
	Length Saving with Pile Test	181 m (35%)
Estimated length based on Pile Test parameters		282 m
	Length saving with Pile Test & Verified Parameters	224m (44%)[1]

[1] Full resistance not mobilized

4.5 Site 5 – Bridge - Province of Quebec

The final case history involves a large bridge structure over water to be supported by 2 m diameter bored piles with 1.85 m diameter rock sockets which were typically 4 m long.

The ground conditions at the site encountered superficial deposits typically of fill, overlying Champlain clay deposits underlain by glacial till. The surficial deposits were underlain by a strong to very strong sandstone.

The tender and design phases of the project had included the execution of two pre-production sacrificial pile load tests

The detailed design was based on the Canadian Foundation Engineering Manual (CGS, 2006) and Canadian Highway Bridge Design Code (CSA, 2006), where a geotechnical axial compression resistance factor of 0.6 was employed based on load testing (compared to 0.4 without such testing.)

At construction phase, two O-cell tests were undertaken as a means of axial capacity verification. Test piles were scaled down to reduce the cost of the test piles, to a socket diameter of approximately 1.2 m but maintaining the equivalent rock socket length:diameter ratio as that of the production shafts.

One of the two test piles achieved the desired axial capacity, while the other did not. The pile which did not reach the desired capacity failed prematurely in a cone breakout mechanism within the rock mass itself, as opposed to rock-shaft side shear. This was a function of the O-Cell test, as it uses an upward load to simulate a compressive load, resulting in potential for cone failure which would not occur in production piles loaded primarily in axial compression. Furthermore, the failed test shaft had a larger proportion of its total length installed through a weathered rock, which was not fully-representative of the deeper, less-weathered rock mass that production piles would be constructed through.

Table 5 provides a summary of the cumulative pile lengths for Site 5. This shows the envisioned lengths based on the empirical design methods, including the expected savings of 120 m (17%) when resistance factors associated with pile testing were adopted. Additionally, following recognition of the test results and the rock mass shear strength reduction and accompanied by socket lengthening, Table 5 shows the revised pile length and final cumulative length which was still a reduction of 60 m (9%) compared to the originally expected 700 m cumulative length had no testing been undertaken.

Table 5. Summary of Cumulative Rock Socket Lengths for Site 5

Cumulative Rock Socket Length	Site 5
Empirical Design - with Pile Test	580 m
Empirical Design - without Pile Test Resistance Factor	700 m+
Length Saving with Pile Test	120 m (17%)
Estimated length based on Pile Test parameters	640 m
Length saving with Pile Test & Verified Parameters	60 m (9%)

5 DISCUSSION

Tables 1 to 5 above summarize the cumulative pile lengths for each site. The tables show the lengths determined at detailed design based on empirical design methods, showing the difference in length with and without the benefit of a pile test resistance factor. Further, they show the length required had the pile test results been available to inform the design and estimate of the total length that theoretically could have been saved in this scenario. From the available case studies, a number of points can be concluded.

Sites 1, 3, and 4 show that as well as savings associated with the geotechnical resistance factor in the range of 26-35%, if the design could have relied upon the parameters identified in the test additional savings could have been achieved, totaling 44-52%. It is also highlighted that in the cases of Site 1 and 4, the test piles did not induce failure, and had the full resistance been mobilized and verified, further savings would have been likely.

Sites 2 and 5 highlight the risk that can be encountered should unexpected results be identified in the pile test. While the test results did not verify the assumed design parameters, the benefit of improved geotechnical resistance factor still provided a positive benefit in terms of a reduced pile length when compared to if no pile testing was undertaken. While these sites show limited length savings, the actual benefit of these tests is highlighting the variability in ground conditions for the site and the limitations of empirical methods to accurately assess the capacity. Further, Site 2 highlights the risk associated with undertaking pile testing at the start of the construction period, as the failed test resulted in a delay to the construction schedule.

Further, Site 5 provides an example and lesson learned that scaling down the size of the pile in apparent up-front economy benefits, can induce failure mechanisms which may not actually be encountered in the full scale pile, resulting in reduction in savings.

The Sites 1, 3 and 4 had an approximate average cost of pre-production test piles of 10% of the total piling cost, while Site 2 was approximately 6%, while the relative proportion of pile testing cost to total foundation cost for Site 5 is not available.

5.1 Additional benefits

A number of benefits discussed earlier in this paper would also have been achieved if pile tests were undertaking at the design stage or earlier, but it is not possible to quantify with the data available.

This includes the benefits of verifying construction techniques, allowing for additional certainty, reduced claims potential and reduced contingency allowance within the construction costs. This is particularly true if the project documents provided by the Owner include pile testing data for tender and contain a GBR.

An aspect that is not evident from the available information for the case studies is the impact that these lower test results had on the construction schedule. However, as each test was undertaken within the construction phase, the tests which did not validate the original design assumptions likely had a negative impact on the construction schedule. Had the tests been undertaken at the design phase, or earlier, the results would have been accommodated during the design and would not have had an impact on the construction phase schedule.

A further benefit that comes hand-in-hand with the economic benefit is the environmental benefit that can be achieved. Nonetheless, the case studies presented, show that a significant percentage of piling length can be reduced by undertaking pile testing, and can be fully optimized by doing so during the design phase. A similar percentage in reduced concrete and steel volumes is a strong benefit in reduced environmental impact.

5.2 Scheduling options

The above case studies provide examples of the benefits of undertaking a pile test at construction phase, but also the missed added value that can be achieved if they were undertaken to inform the detailed design phase or earlier.

If tests are undertaken to inform the design, they are typically undertaken at the detailed design phase, and the above sections outline the typical benefits of this approach, as well as a review of a number of sites that in hindsight would have benefitted from this approach. Additionally, taking pile tests to geotechnical failure provides the most valuable information and would provide the designer the ability to fully optimize the design without compromising schedule.

The earlier pile test data is made available to the designer, the greater the opportunity to more fully optimize the design. An interesting consideration would be to undertake pile tests to as part of the tender design phase. This would allow the benefits of actual in-situ test results to be available early, and would reduce a number of the issues at the detailed design phase. However, this would have a number of limitations, and would likely only be appropriate when it is certain that deep foundations are the most appropriate solution. Additionally, on certain procurement routes this may result in potential conflicts of interest with the testing party having inside information on the test offering an advantage come to bidding for detailed design and could result in limited attraction of high quality contractors who may wish to bid on the full construction contract. However, the benefits, particularly for lump-sum P3 projects, would, in the opinion of the authors, greatly outweigh the negative impacts. Uncertainty and risk would be reduced, and subsequent foundation costs would likely reduce and construction schedule would be more certain.

A more commonly observed scenario to optimize the results would be to undertake the test(s) at the beginning of the detailed design phase. Caution would need to be taken to ensure that the test(s) captured potential variations of sizes and scaling (as encountered in the case studies), captured the construction techniques and tested all strata that could potentially need to be relied upon by the final design.

A potential middle-ground option would be to undertake the test later in the detailed design phase, when the design is more certain, but allow sufficient time prior to construction so the design can be readdressed and optimization considered without impacting the construction schedule. This would be a careful balance however, and would be unlikely to allow time for major changes to be incorporated.

6 LIMITATIONS AND FURTHER WORK

There are a number of variables which are external to the direct benefits of pile length which could not be captured in these examples. These include items such as contractor and designer experience with the ground conditions, selected procurement methods, governing codes, project specific requirements, and degree of quality assurance testing.

Additionally, errors or oversights are an aspect that cannot be ruled out during pile testing. This could include designers underestimating resistances and failing to mobilize the full capacity, contractors not constructing the piles adequately – with potential negative impacts to test results, or even failure of testing equipment or instrumentation which could render the results unclear or contentious.

The test results cited in this study also have the benefit of hindsight after the design has been completed. It is not certain that the same decisions would have been made during the design process as other factors such as time pressures could influence the final designs.

While this study has considered a number of recent sites to highlight the benefits of undertaking pile tests early in a project life cycle (e.g., during the design phase), it is acknowledged that this is a small sample group. The conclusions would be reinforced by considering data from a larger number of sites.

7 CONCLUSIONS

This study has considered a number of recent case studies in Alberta and Quebec which have adopted pile testing during the construction phase.

The study summarizes the benefits that were achieved for these sites in terms of reduced pile length associated with use of improved geotechnical resistance factors in accordance with the applicable design code.

Further, the paper summarizes the potential added benefits that could have been achieved had the pile test results been available to inform the design process, whether that be in the tender process or immediately after project award. The benefits not only include the ability to optimize pile designs to account for potential conservatism or lack of accuracy in empirical methods, but also explains the secondary benefits such as reduced environmental impact, potential construction schedule benefits, constructability and reduced construction phase risk.

It was highlighted that although there are added benefits at this stage, there are certain limitations and drawbacks with this option which mean it is not necessarily preferable in all scenarios.

It is the intention of this study to demonstrate through case study examples, with the aid of hindsight, how benefits to pile designs could have been achieved with pile load testing be made available earlier in the overall project schedule. It is hoped that this information can be used to better explain the benefits of undertaking pile tests to inform design in similar circumstances.

8 REFERENCES

NRCC, 2010. National Building Code of Canada (NBCC), Volumes 1 and 2, National Research Council of Canada (NRCC).

CSA, 2006; 2014. Canadian Highway Bridge Design Code (and Commentary) (CHBDC), CAN/CSA-S6-06;

CAN/CSA-S-14, Canadian Standards Association (CSA).
AASHTO, 2006. LRFD Bridge Design Manual. American Association of State Highway and Transportation Officials (AASHTO).
CGS, 2006. Canadian Foundation Engineering Manual 4th Edition, Canadian Geotechnical Society (CGS).
FHWA, 2010. Drilled Shafts: Construction Procedures and LRFD Design Methods, FHWA-NHI-10-016.