A Formula for Savings

Full scale testing of deep foundations pays for itself and more

by

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The problem is not that engineers like uncertainty and risk, but sometimes we have difficulty communicating justification for reducing it. That is, until now. Reducing uncertainty and risk is free, and can often generate positive returns for the owner. There is a simple, one-step formula that even purchasing agents can understand: execute a static load testing program.

The Best Design

There is hardly an owner out there, who upon leaving the conference table after meeting with his foundation engineer, has not been convinced that his foundation design is the best that money can buy. For the most part, engineers are providing a quality product given the constraints under which we work. But is it the *best* design? I maintain that a better, safer and less expensive design exists in almost every case and the proof is hidden in the resistance factor used in design.

Load and Resistance Factored Design (LRFD) or Limit State Design (LSD) as it is known in Canada, factor both applied loads and expected resistances to ensure a target reliability of the design. Using a lower resistance factor means a pile must be longer or larger (in diameter) to provide the same factored resistance than a pile designed with a higher factor. All things being equal, this inverse relationship means that the change in pile length (or diameter) is proportional to the ratio of the resistance factors used (ϕ_0 / ϕ_1).

The Role of Load Testing

Both U.S. and Canadian design guidelines allow for an increase in the resistance factor to 0.60 for foundation designs where a static load test is carried out to ultimate capacity. The beauty of this provision is that it is very simple to calculate the *minimum* economic benefit of performing a load test. As an example, consider a pile foundation designed solely in friction, in a uniform soil stratum. As noted above, the increase in resistance factor as a result of testing can be considered as shortening the pile by a length equal to that required to provide the additional resistance gained. The shortened length is simply expressed as a ratio of the original to the improved resistance factor, times the original pile length. Considering an original resistance factor of 0.4, the new pile length is 67% (0.4/0.6) of the original length, or reduced by 33%. For a tip bearing pile, the area would be reduced by this same amount, resulting in a potential diameter reduction of over 18%. This is the equivalent of going from a 1,500-mm diameter to a 1,220-mm diameter or from a 1,220-mm diameter to a 1,000-mm diameter. The *minimum* potential savings can then be estimated using the prevailing construction rates. Table 1 illustrates the potential cost reduction for a small, 50-pile foundation project simply due to increasing the resistance factor by incorporating static load tests during design.

Table 1

Assumptions	Diameter (mm)	1,000	1,220	1,500
	Original Length (m)	15	25	30
	Estimated cost per meter	$1,000	$1,500	$2,000

	Impact of Increasing Resistance Factor from 0.4 to 0.6			
Friction Only Pile	Revised Length (m)	10	16.7	20
	Length Reduction (m)	5	8.3	10
	$ Reduction per pile	$5,000	$12,500	$20,000
	Cost Reduction (50 Pile project)	**$250,000**	**$625,000**	**$1,000,000**

End Bearing Only Pile	Estimated original pile cost	$15,000	$37,500	$60,000
	Reduced diameter pile cost [1,2]	$12,000	$25,000	$45,000
	$ Reduction per pile	$3,000	$12,500	$15,000
	Cost Reduction (50 Pile project)	**$150,000**	**$625,000**	**$750,000**

[1] Reduced pile diameter cost assumes changing from 1500-mm to 1220-mm, 1220-mm to 1000-mm and 1000-mm to 914-mm. [2] Cost of 914-mm diameter pile assumed $800 per meter

While the cost reductions in the table monetize the uncertainty, they also reveal a hidden load testing budget already built into the design. Even if the cost of a static load testing program were equal to the cost reductions presented above, removing the uncertainty from the design will have been free. However, experience tells us that the net cost of the test program often leaves a healthy return on the investment in testing.

Why is it the minimum savings?

We refer to the *minimum* potential savings throughout the description above because the resistance factor is only part of the equation. The savings highlighted above assume that the estimated nominal resistance—and nothing more—is confirmed by the load test, so the ratio of the resistance factors (R_0/R_1) is 1.0. In the absence of full scale load testing, nominal resistances are based on code values, guessed, or at best, calculated from empirical correlations to site investigation data. In our experience, accurate predictions are practically nonexistent. Consider that even a 20% under-estimation of the nominal resistance—whether intentional or not—means the foundation is far more expensive than necessary. Recall from the table above, the cost reductions for the friction piles were generated based on a new pile at 67% of the original length. Confirming a 20% higher nominal resistance means the new pile length would be only 56% (0.4/0.6 x 1.0/1.2) of the original. In the case of the tip bearing pile, this translates into an overall 25% reduction in diameter. The original 1,220-mm pile could go to 914-mm and the 1,000-mm pile could be reduced to 760-mm. The 1,500-mm pile could not be reduced enough to make a 1,067-mm diameter feasible, but in addition to reducing to 1,220-mm, the number of piles could be reduced for additional savings. In general, the reduced length (or area for tip bearing piles) can be calculated by multiplying the original dimension by the ratio of the resistance factors and then by the ratio of the nominal resistances (ϕ_0/ϕ_1 x R_0/R_1). Table 2 illustrates the original example, assuming the increase in resistance factor *and* proving a 20% higher nominal resistance.

Table 2

Assumptions	Diameter (mm)	1,000	1,220	1,500
	Original Length (m)	15	25	30
	Estimated cost per meter	$1,000	$1,500	$2,000

Friction Only Pile	**Impact of Increasing Resistance Factor from 0.4 to 0.6 *and* confirming 20% higher nominal resistance**			
	Revised Length (m)	8.3	13.9	16.7
	Length Reduction (m)	6.7	11.1	13.4
	$ Reduction per pile	$6,675	$16,688	$26,700
	Cost Reduction (50 Pile project)	**$333,750**	**$834,375**	**$1,335,000**

End Bearing Only Pile	Estimated original pile cost	$15,000	$37,500	$60,000
	Reduced diameter pile cost [1,2]	$10,500	$20,000	$45,000
	$ Reduction per pile	$4,500	$17,500	$15,000
	Cost Reduction (50 Pile project)	**$225,000**	**$875,000**	**$1,020,000[3]**

[1] Reduced pile diameter cost assumes changing from 1500-mm to 1220-mm, 1220-mm to 914-mm and 1000-mm to 760-mm. [2] Cost of 914-mm and 760-mm diameter piles assumed $800 and $700 per meter, respectively. [3] Project savings for 1,500 mm case assumes additional reduction in number of piles by 6 (reducing the total pile area by ~45%)

It should be pointed out that the tables above illustrate potential reductions based only on material costs. Although additional savings in the form of time and risk reduction are beyond the scope of this article, they can increase the potential savings dramatically.

A recent example of applying this methodology is discussed in a case study of the Anthony Henday Drive Southeast Ring Road by Skinner et. al., presented at Geo-Edmonton 2008. The author stated that given the increased resistance factor and an increased nominal resistance, “the load test results allowed the design axial resistance of a single pile to increase by 50%.” Even more remarkable was the fact that although the three tests were carried out well into the construction process, the results were applied to seven structures and it was estimated that “the pile load testing saved approximately 15% (net) on the foundation cost for each associated structure.” Consider that this is the equivalent of constructing six and getting one for free! The author continues to state that “had the testing program been undertaken at an earlier stage . . . there would have been potential for additional savings.”

Case histories such as this underscore the inefficiencies buried in many of our “best” designs and highlight the value proposition of load testing. Many engineers are tempted to skip testing, or increase pile lengths in lieu of testing, thinking that this may somehow save time or is at least a *conservative alternative*. The flawed assumption is that they have guessed, extrapolated or calculated their nominal capacity correctly. To illustrate this, we need look only as far as south Florida in 1999 for a case wherein a perceived “safe” design was shown to be anything but safe. Even though the engineers on the subject high-rise hotel were confident that their design was conservative, they carried out a load test. The initial results indicated their actual nominal resistance was only 30% of what was assumed in design. After two additional tests confirmed the results, the foundation design had to be modified, increasing the cost by 60%. In this case, the savings that resulted from the load test are measured in the untold millions of dollars worth of remediation, construction delays and litigation, if not loss of property and life.

Just the beginning

The modest increases that result from testing noted above are only the beginning. A number of design codes offer additional incentives to remove uncertainty in design. The American Association of State Highway and Transportation Officials (AASHTO) 2008 Bridge Design Specifications includes a provision for the use of resistance factors for compressive loading of 0.70 when a static load testing program is incorporated in design. A supplement to the Canadian Highway Bridge Design Code (CHBDC) S6-06 similarly allows for a factor of 0.70 to be used for design, providing that a static load test that can separate resistance from the toe and the shaft (such as the Osterberg Cell load test) is performed. Comprehensive risk mitigation studies have further shown that performing proof testing on every pile—such as was done at the L.A. Coliseum—can help reduce uncertainty enough to use resistance factors in excess of 0.90, resulting in a less expensive and safer foundation.

Conclusion

Every foundation design balances risk and uncertainty with economics. In today's economic environment, engineers are under increasing pressure to provide big value on a small budget. Fortunately, we have a formula for savings that every design engineer can use to begin reducing uncertainty and risk, add value to the project and in many cases, put money back in the owner's pocket.