

Testing and Remediation Observational Method for the Design and Construction of Non-Redundant Pile Foundations

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ABSTRACT This paper demonstrates that reducing uncertainties in pile design and construction has the potential to greatly reduce foundation money and time costs for non-redundant driven and drilled pile foundations. It describes the statistics-guided Testing and Remediation Observational Method (TROM). This method permits reducing the factor of safety (FOS) in deterministic design, or increasing the Φ resistance factor in load resistance factor design (LRFD), while maintaining a target reliability for all piles by remediating as needed. Three example case histories demonstrate the method and the advantages of testing every pile.

1. INTRODUCTION

The observational method in geotechnical engineering provides a powerful tool for dealing with uncertainty (Peck 1969). This paper provides a summary of the statistics-guided Testing and Remediation Observational Method (TROM) for building pile foundations to a target reliability and at least cost in money and/or time. As explained, and perhaps surprisingly, for non-redundant piles the maximum savings comes from testing every foundation pile. This paper concerns non-redundant piles. Redundant piles in groups greater than one have different statistics.

2. MINIMIZING UNCERTAINTY

Engineers counter uncertainties in pile support by increasing the design factor of safety (FOS) in deterministic design, or by decreasing the resistance-factor (Φ) in LRFD design. Doing either increases costs. If one wishes to minimize costs but retain reliability, then one must minimize uncertainties.

Denoting uncertainty by “U”, we have U_Q for pile support, U_S for the site, U_C for construction methods, U_D for the design model and U_t for any test uncertainties. Using an informal equation, U_Q equals ($U_S + U_C + U_D + U_t$). Engineers usually quantify uncertainty by using the coefficient of variation, V . A pile’s probability of

failure decreases with design FOS, and increases with V_Q . Failure probability increases with V_Q because, at any chosen FOS, unfavorable circumstances have a higher probability.

The engineer can therefore achieve a target reliability level either by increasing design FOS, or by reducing uncertainty about pile resistance. One can reach any desired level of reliability at a lower design FOS, for example, under a plan that reduces uncertainty via testing and possible remediation of all piles. In this paper we demonstrate that such a testing plan can lead to substantially lower money and time costs. Table 1 summarizes the above reasoning.

Table 1 Reducing Uncertainty by Testing Produces Cost Savings

$V = \left[\frac{\text{Std.Deviation}}{\text{Mean}} \right]$	
A convenient measure of Uncertainty "U"	
If no piles tested ($n = 0$): $U_Q = [U_{\text{Site}} + U_{\text{Construction}} + U_{\text{Design}}]$	If all piles tested ($n = N$): $U_S + U_C + U_D \approx 0$ $U_Q \approx U_{\text{test}}$
U_Q Large <hr style="border-top: 1px dashed black;"/> V_Q Large High Costs	U_Q Small <hr style="border-top: 1px dashed black;"/> V_Q Small Low Costs
Potential savings High	

3. TROM

To realize the potential of TROM one must design (FOS or resistance-factor) with the intent of testing all the piles. One must also prepare to remediate those that fail according to your definition of failure and then retest them, etc., until they pass the required remediated FOS_r or resistance-factor. Statistical analysis determines the amount of remediation needed to achieve the target reliability for each non-redundant pile in a group of N similar piles.

The following summarizes TROM:

- For N non-redundant piles, choose a single design FOS. (= load-factor Ψ /resistance-factor Φ) that will apply to all N piles.
- Test the capacity of all the piles after construction.
- Remediate any tested pile to ensure that its tested capacity equals or exceeds FOS_r, a statistically-calculated minimum-cost FOS that ensures the reliability p of the group of non-redundant piles.

Note that the engineer can separate pile testing into two types with different purposes. Type 1 – testing for design before construction, and Type 2 – testing the product after construction. Using TROM involves Type 2 testing and assumes the prior completion of any Type 1 testing needed to establish and/or refine the design.

4. STATISTICS

We assumed log-normal frequency distributions, with coefficient of variation V_P for uncertainty in pile loading, V_Q for uncertainty in soil resistance resulting from geology, construction and design, and V_t for uncertainty due to testing errors and any differences between the test versus actual load application. This paper does not include the details of the statistical model, which involve primarily the interaction of the extremes or ‘tails’ of the log-normal distributions.

One must choose a design target reliability p , typically 0.90 to 0.999, that each of the non-redundant piles in a group will have a resistance that meets or exceeds its loading. The higher p , the higher the design FOS or the lower the design resistance-factor required and the higher the cost of a pile. As shown subsequently, using a statistics-guided observational method (TROM) increases the potential percent savings as p increases when compared to the no-testing alternative.

While convenient for mathematical modeling, any assumed frequency distribution may only roughly approximate reality at any one site and pile foundation. Statistics provide a guide to ground truth, but tests come much closer. In addition to cost savings, testing every pile ($n=N$) under the TROM method has the extra advantage of minimizing potential errors caused by using an inexact statistical model. The ability to remediate as needed maintains the reliability.

5. COSTS

The writers have included estimated money costs in their calculations for the purpose of optimizing to least cost and maximum savings. We first established a reference base cost per pile.

5.1 Base Cost

It seems reasonable to expect that the cost per pile, C_p , would increase with increasing the design FOS or decreasing the resistance factor (piles longer, larger diameter, etc.). For convenience the writers have expressed relative costs by $(FOS)^X$. If the exponent $X = 1$ we have costs proportional to the FOS. If one doubles the design FOS and $X = 0.25$, then cost increases by a factor of 1.19. If $X = 2$ the factor equals 4. Subsequently, the writers will show other examples of varying X from 0.25 to 2 in Equation (1).

$$C_p = FOS^X = \left(\frac{\text{load factor } \Psi}{\text{resistance factor } \Phi} \right)^X \dots\dots\dots(1)$$

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5.2 Costs

Assuming equation (1) and a base cost per-pile $C_p = 1$ when the FOS = 1, then one can include estimates of the various additional cost multipliers for construction ($1+C_c$), testing ($1+C_t$) and remediation (C_r). This does not include costs such as those related to time and insurance because their importance varies greatly from project to project. But in principle, one can include and compare any costs if estimated on a per pile basis. Sometimes time can dominate the economics of a situation as shown in the subsequent 7.1 case history.

6. PARAMETRIC EXAMPLES

The following *Figures 1 to 7* show results from various combinations of the 11 parameters listed in *Table 2* and used to obtain the statistical and cost calculation results presented in these figures. As also listed in *Table 2*, we chose two reference site and project specific combinations of high V_P and V_Q coefficients of variation, 'H', and average coefficients, 'A', based on judgment and experience. We then checked within H or A for sensitivity to some of the other parameters. The comments below show the progression of our major findings from figure to figure.

Table 2 – List of parameters in high (H) and average (A) variability examples

Parameter (also see Notation)		Example		Other Sensitivity Checks
		H = high V	A = average V	
No. of N		N = 10	N = 10	1 to 1000
No. of n		0 to N	0 to N	
Statistics	V_p	0.3	0.1	0 to 0.75 0.90, 0.95, 0.999
	Ψ	1.75	1.25	
	V_Q	0.9	0.5	
	V_t	0.1	0.1	
	p	0.99	0.99	
Costs	C_c	0.1	0.1	0.5 to 0.01
	C_t	0.2	0.2	
	C_r	1.2	1.2	0.25 to 2
	X	1	1	

Figure 1 shows how the relative cost of $N = 10$ similar, non-redundant piles in the H example decreases with the number of n piles randomly tested, and remediated if needed, for the group of non-redundant piles to have the target reliability of $p = 0.90$. Almost no cost reduction occurs until $n = 6$ of 10, and the maximum increment of cost reduction occurs when testing the final $n = N =$ pile 10. This occurs because the final test removes the most uncertainty. TROM includes testing all piles. *Figure 1* also shows how the lowest cost foundation results when using an assumed maximum allowable resistance factor ($\Phi = 1$) when using TROM.

Figure 2 generalizes the Figure 1 results by normalizing with the percent cost savings compared to the cost with no Type-2 testing ($n = 0$) versus the percent of piles tested, for both the H and A examples. It shows again how dramatically the final $n = N$ test

produces the largest increment of savings, and that the percent savings do not depend significantly on N over the range of 5 through at least 100.

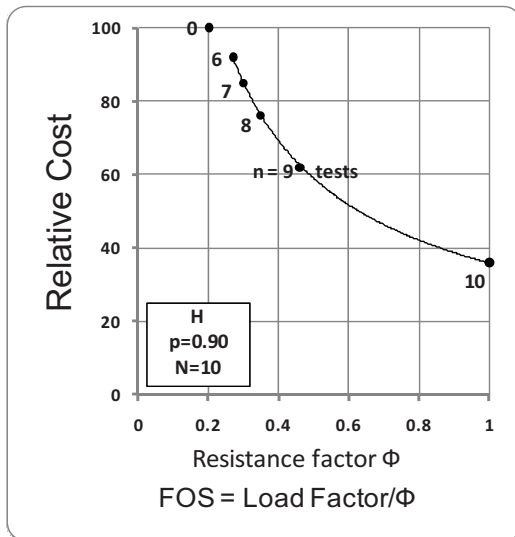


Fig. 1 Cost and required FOS decreases as the number of piles tested increases

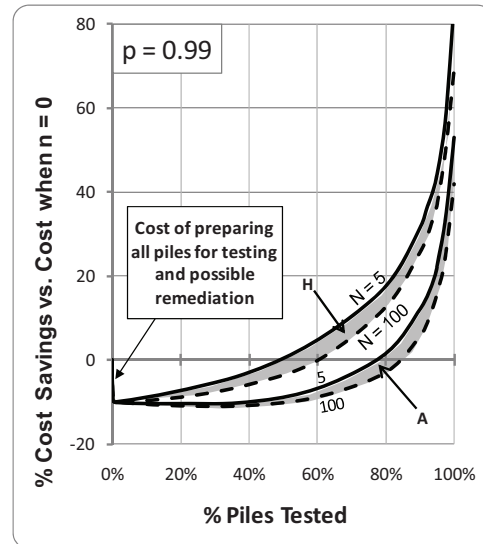


Fig. 2 Cost savings vs. percent of piles tested and remediated as needed

Both the H and A examples predict large percentage savings when the percent of piles tested equals 100%. For example, when N = 10 the savings equals 78% for H and 57% for A. This shows how the TROM effectively reduces uncertainty despite large initial site differences in V_p and V_Q . Note that Figures 1 and 2 do not match exactly because the target p changed from 0.90 to 0.99.

Figure 3 shows how the percent savings increases with the target reliability and the number of similar piles considered, for both H (upper shading) and A (lower shading) example sets of parameters. The more variable the site parameters, the greater potential percent savings versus costs without testing and remediation.

Figure 4 deals with the relative cost of a pile foundation when the target reliability p increases. It shows the cost increase factor F_c compared to the cost of providing p = 0.90 for the example H combination of parameters. It also shows a perhaps unexpected advantage of using TROM. The set of four (n = 0) curves give F_c as it varies with N from 1 to 1000 as p increases from 0.90 to 0.999 (log 0.10 to 0.001), all for a design without planned testing and remediation. For example, when N = 10 it costs 3.2 times as much to increase p from 0.90 to 0.999 than it costs to design with p = 0.90. In dramatic contrast, a design using TROM with all piles tested produces a much lower F_c value of 1.3 in the Figure 4 example. Using TROM allows increasing p with almost no cost sensitivity to N. This occurs despite the additional costs of testing and remediation when using TROM in the H example. Designing with TROM not only reduces cost at a given reliability, but it makes it much more affordable to increase reliability in non-redundant foundation piles.

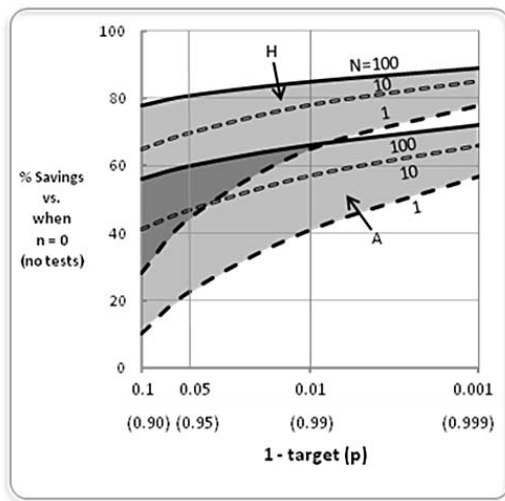


Fig. 3 – Savings vs. Reliability and Number of Piles

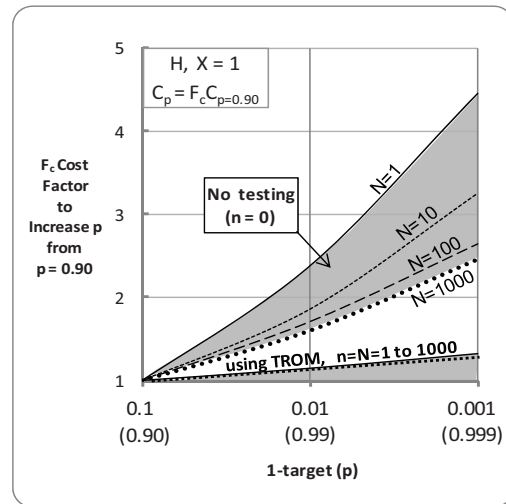


Fig. 4 – The Cost of Increasing p Decreases when using TROM

A separate parametric study explored the importance of the cost parameters used when determining F_c with TROM. Only the cost exponent “X” seems important, with F_c approximately proportional to X at all N. Note that Figure 4 uses X = 1.

Figure 5 shows the effect of the exponent X = 0.25 to 2.0 in equation (1) on the savings potential at different p and N values. The percent savings increase as X, p and N increase.

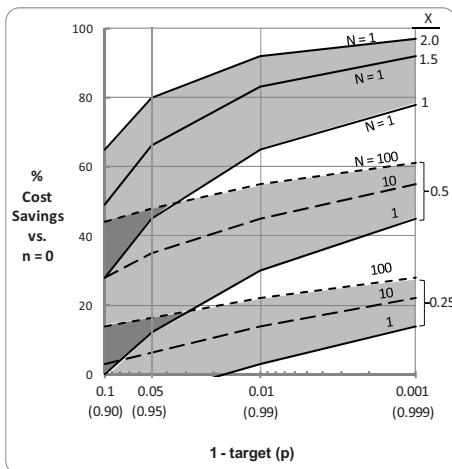


Fig. 5 - Effect of p, X, and N in H example

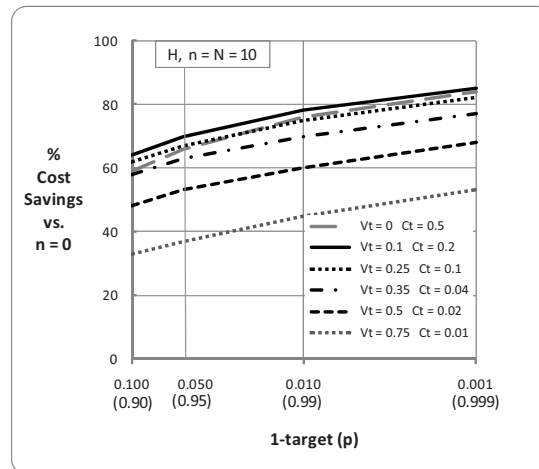


Fig. 6 – Example of Effect of V_t and C_t Combinations on Savings

Figure 6 shows the effect on cost savings for the H example when using different combinations of test uncertainty and test costs. In general, the less the V_t coefficient of variation of a type of test the greater its cost C_t . The writers used the following six combinations of V_t and C_t that seemed reasonable for illustrating their effect on costs:

- 0 and 0.5 for an imaginary perfect test
- 0 and 0.2 for static tests
- 0.25 and 0.1 for quasi-static tests
- 0.35 and 0.04 for dynamic tests with wave signal matching
- 0.5 and 0.02 for dynamic tests without signal matching
- 0.75 and 0.01 for Hiley-type impact formula tests.

The reader should use his/her own judgment about variability and cost for a particular foundation design and test method. *Figure 6* again shows an increasing percent savings when p increases. *Figure 6* also shows similar savings when $V_t \leq 0.35$, and significantly less savings with greater V_t despite a lower cost per test.

Figure 7 shows the individual and cumulative effect of construction plus testing plus remediation costs for the same six combinations of V_t and C_t as in *Figure 6*, in order of increasing V_t and decreasing C_t . This example of cost versus test uncertainty comes from the H-case with $n = N = 10$ and $p = 0.99$. A similar example using the A-case produced similar trends.

The trends seem clear. The total cost has a broad minimum value over $V_t = 0$ to 0.25 . This occurs in part because the writers conservatively used a maximum $\Phi = 1$ over this V_t interval. The cost of testing seems minor. The remedial costs increase as V_t increases, as do the construction costs. The latter occurs because as V_t increases the design FOS to maintain reliability also increases dramatically from 1.75 ($\Phi = 1$) to 5.54 ($\Phi = 0.32$).

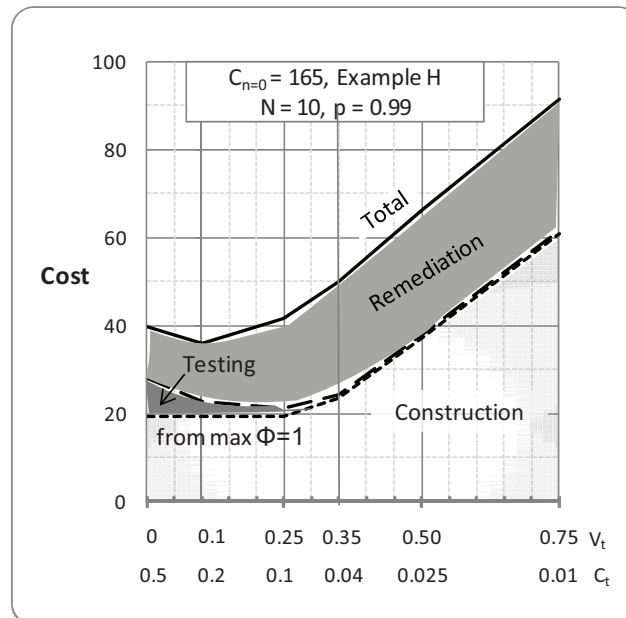


Figure 7 Cost Breakdown vs. Combinations of V_t and C_t

The percent savings varies from only 70 to 78% between $V_t = 0$ and 0.35 in the H example. It varies from only 50 to 57% between $V_t = 0$ and 0.2 in a similar study of the A example. The optimum savings for both occurred at approximately $(V_t/V_Q) = 0.2$. For the maximum $V_t = 0.75$ the savings equaled 45% and 1%, respectively. The writers computed the savings relative to the no-test costs of 165 and 50, respectively, for a group of $n = N = 10$ piles with $p = 0.99$.

7. CASE HISTORY EXAMPLES

Example 7.1 - In January 1994 an earthquake damaged an old professional football stadium in Los Angeles. Engineers then determined that some of the existing foundations required repair and the owners decided to add skybox capacity in conjunction with the repairs. The eventual design-build contract, with appropriate bonus and penalties, required the completion of the foundation and construction work prior to the beginning of the next football season in September 1995. The design-build team had only six months. The foundation work required the installation of twenty-eight bored piles with a service load of 8.9 MN (2,000 kips) and with difficult working conditions. The contractor experienced serious delays constructing and testing the first two piles. The geotechnical engineers changed their design to allow them to speed construction and still meet the looming football deadline.

By using an early version of TROM described herein, the engineers recommended the O-cell testing of all the remaining piles. This theoretically allowed reducing their FOS from 2.5 to 1.36 for a reliability of $p = 0.99$ for all the piles in the non-redundant foundation design. As described in Meyer and Schade (1995), this approach proved successful and resulted in a \$1 million bonus for on-time completion. Table 3 summarizes the situation and the solution.

Figure 8 shows a load test under the low overhead stands. Table 4 briefly lists the results from the testing of the 26 bored piles. As shown in Figure 9 by comparing O-cell load versus movement curves from the downward first loading A and the second loading B, the piles had their end bearing greatly improved by the first expansion preloading. The engineers then grouted the O-cells in place. Two piles required more remediation with smaller diameter and shorter straddle piles.

Table 4 shows an actual reliability of $24/26 = 0.92$ vs. the 0.99 target. The remediation of the remaining 2 piles discovered by the testing raised the actual reliability of each pile to at least the target 0.99.

Table 3 – Summary of Case History

CASE EXAMPLE – LOS ANGELES FOOTBALL STADIUM (ASCE CIVIL ENGINEERING, FEB 95, P.57)	
<ul style="list-style-type: none"> • Built 1923 and 1931, damaged by Jan 94 earthquake • Must repair before next football season in Sept 94 • Design-build contract ○ 6 months ○ Big on-time bonus, even bigger penalty 	
<ul style="list-style-type: none"> ➤ 9m fill (sand and silt) ➤ 21+ m (sand with gravel) ➤ 20 m depth to GWT 	<ul style="list-style-type: none"> ➤ 8.9 MN service load ➤ 5.5 m working headroom ➤ 26 non-redundant bored piles
<ul style="list-style-type: none"> • Serious construction delays ○ 1.2m piles to 29m ○ 3 weeks to install 2 piles to 29m ○ Collapsing holes ○ Panic • O-testing all piles, allows reducing FOS from 2.5 to 1.36 • Shortened to 18-20m, test enhanced end bearing • Very successful, review some results in Table 4 	



Figure 8 O-cell test under stadium seats

L.A. Stadium Test-All FOS Results
(after O-cell testing and end bearing enhancement)
$\text{FOS} = \frac{Q_{\Delta=.25\text{mm}}}{8.9\text{MN}}, \text{ target} = 1.36$
26 – 1.32m piles, $\text{FOS}_t = 1.1 \text{ to } 2.6$
Avg = 1.94
$V_{\text{FOS}} = 0.16$
2 piles ($\text{FOS}_t = 1.11, 1.34$) < 1.36
Remediated to $\text{FOS}_r \leq 2$ (OK)

Table 4 FOS Results from Testing and Remediation

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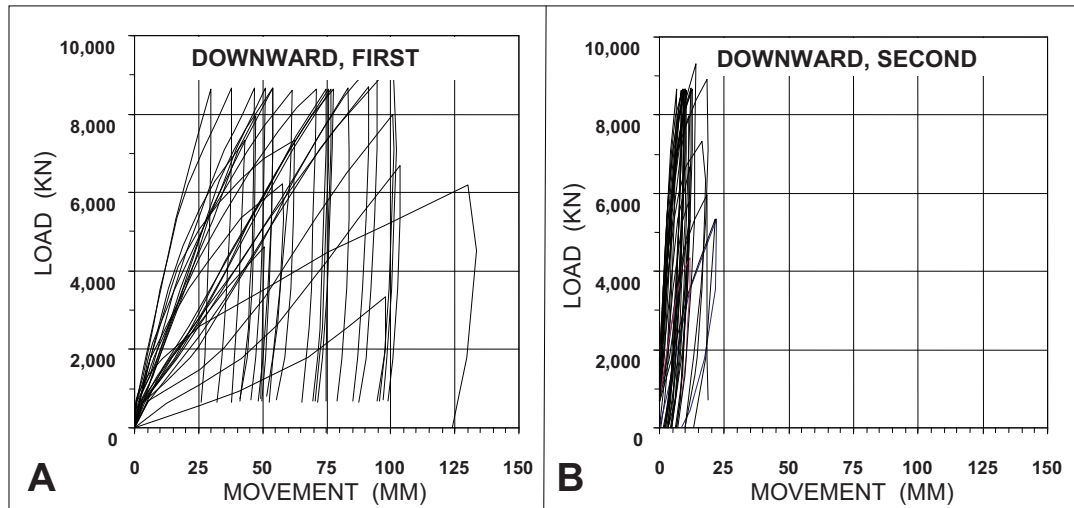


Figure 9 First O-cell Loading Improves End Bearing for Second Loading

Example 7.2 – Within the last 10 years an elevated motorway under construction experienced a serious, and ultimately a very expensive, problem during construction. The more than 200 pier-foundations each consisted of a single bored pile, all clearly non-redundant. After constructing almost all the piles, and construction-loading 80 of the piers, pier number 80 failed dramatically under the advancing overhead roadway and caused it to collapse. Figure 10 shows the collapse after the pier settled over 3m.

A subsequent investigation showed that very likely only the pile at the failure location would have failed. The engineers did not predict this failure location in advance despite a comparatively extensive site investigation. This included performing an unusually high number of 8 preliminary (Type 1), full scale, static pile load tests, but not at the location of the pile that failed.

The eventual total remedial costs, not including over a year of time lost and some tarnished reputations, exceeded by a factor of roughly 10 the probable cost of testing all the piles in advance and remediating the failed pile. This case provides a dramatic example of the need to test every non-redundant pile.

Example 7.3 – For some wall and slope anchoring systems, such as soil nailing, engineers already use TROM for design. They design using a low FOS, typically 1.25 to 1.50, knowing they will test every anchor and remediate (i.e., lengthen and/or grout) those with an FOS_t less than a previously determined FOS_r .



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Fig. 10 – Motorway Collapse during Construction

8. SUMMARY AND CONCLUSIONS

This paper describes the statistics-guided, Testing and Remediation Observational Method (TROM) for the design of non-redundant piles. Using TROM, testing every pile, produces the following.

1. Reduces uncertainty and its costs.
2. The maximum cost and/or time savings comes from testing all the piles in a group of any number of similar piles, including a single pile.
3. The percent cost savings when designing using TROM vs. no testing, for the same reliability p , increases with p , the number of piles N , and the cost exponent X in equation (1).
4. The cost of increasing reliability reduces dramatically when using TROM.

5. Using tests with greater variability (uncertainty), V_t , but which have a lower C_t cost per test, can sometimes significantly increase total pile costs by increasing construction and remediation costs.

The first case history demonstrates TROM and that its cost benefits can also come from reducing the construction time. A second case history dramatizes the need to test every pile. A third case history reminds the reader that engineers already use TROM for the design of wall and slope anchors.

TROM gives the engineer a powerful and general tool for designing and building efficiently and reliably. The writers have herein applied it to non-redundant pile foundations.

9. COMMENT AND ACKNOWLEDGEMENT

It took an engineer father's and an economist-demographer son's combined part-time efforts over many years to produce this paper. In hindsight, we finally mutually understood the problem of solving for least cost and controlled risk when we introduced costs and remediation into our TROM method. Loadtest, Inc. and then Fugro-Loadtest Inc., patiently and generously supported our efforts. We consider this paper an important first step to even more general and practical solutions based on the TROM concept.

NOTATION

C_p = base cost of single pile at design FOS (see Equation 1)

C_c = additional construction cost to prepare piles for possible remediation

C_r = additional remedial incremental cost factor when increasing FOS_t to FOS_r

C_t = additional cost of a test

FOS = minimum design factor of safety = Ψ / Φ

FOS_r = minimum factor of safety needed for each tested pile, determined by statistical analysis for each combination of parameters. Remediate to FOS_r if $> FOS_t$

FOS_t = factor of safety determined from a test. (user can use any load or service definition of FOS)

LRFD = Load and Resistance Factor Design

n = number of pile load tests

N = number of similar non-redundant piles

p = target reliability for all N piles, failure rate = $(1-p)$

TROM = the Testing and Remediation Observational Method

U = symbol denoting uncertainty

- V = coefficient of variation = (standard deviation/mean)
 V_p = coefficient of variation for pile loading
 V_Q = coefficient of variation for pile resistance
 V_t = coefficient of variation for test method
 X = exponent in equation (1) relating cost to FOS or Φ
 Δ = settlement of top of pile
 Ψ = load factor in LRFD (assumed a given constant)
 Φ = resistance factor in LRFD

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- Peck, R. B. (1969), "Advantages and limitations of the observational method in applied soil mechanics", Ninth Rankine Lecture, *Geotechnique*, 19(1) 171-187. Reprinted by Dunncliff J. and Deere, D. in *Judgment in Geotechnical Engineering* (1984), Wiley and Sons, Inc. pp. 122-127.