Financial Failure—The High Cost of Not Knowing

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ABSTRACT: Geotechnical engineers predict the outcome of their design. The uncertainty with design occurs from the accuracy of the test and method and the variability of the soil properties. When the engineer chooses tests that are poor predictors, then he/she will believe that the site is highly variable, and his/her design tends to be too safe, overly conservative, and costly to the owner. When the tests do not measure the soil properties needed for accurate design and rely on correlations that have high uncertainty and high standard deviations, financial failure occurs. The owner pays for foundation systems that are not needed. Beta probability distribution curves illustrate financial failure.

Keywords: beta probability distribution, dilatometer, cone penetrometer, pressuremeter, borehole shear, k_0 step blade

1. Introduction

The engineer should always choose the in-situ test that best predicts the outcome of the geotechnical design. That outcome could be the amount of settlement that the structure will have, the stability of the slope or retaining wall, the lateral movement of a structure (electrical tower or wind turbine from wind loads, bridge from a barge impact), or the vertical capacity of a deep foundation system.

The most accurate prediction provides the lowest cost foundation solution. Prediction uncertainty comes from 1) the test and design method and 2) subsurface variability. Choosing the most accurate test and design method minimizes its uncertainty, while performing enough tests throughout the site and designing each foundation system individually minimizes its uncertainty. The engineer adjusts the applied bearing pressure for each footing so that the predicted settlement is the same or adjusts the pile tip depth and number of piles so that the allowable pile capacity matches the load. Where tests show soil that is either stiffer or stronger, the foundation support system will be smaller or shorter. Where tests show the soil is compressible or weaker, the foundation system will be larger or longer.

Contrarily, choosing one bearing pressure or pile tip depth for an entire site maximizes the uncertainty from the variability of the subsurface conditions. This simpler "one size fits all" design approach is a poor choice, but has historically been used because the engineer has not used high quality test data to make accurate predictions.

Correlating from a less accurate test to the parameters of a more accurate test only results in an additional layer of unnecessary uncertainty and inaccuracy (for example using computer programs to get DMT parameters from CPT parameters or using N-values to get deformation moduli). Simply perform the test that gives the most accurate design predictions.

2. *Choosing the best in-situ test for design*

Historically, the inventor engineer developed the in-situ test to solve a particular geotechnical engineering problem. For example, P. Barentsen (1932) invented the cone penetrometer test to model the vertical capacity of a pile foundation. As one pushes the CPT probe into the soil, it fails the soil just like pile fails the soil as it is driven into the soil. Professor Silvano Marchetti (1975) invented the dilatometer test to model the lateral capacity of a pile. After inserting the dilatometer blade against the soil, the membrane pushes outward into the soil just like a pile moves outward against the soil when lateral forces act on it. Professor Louis Menard (1954) invented the pressuremeter test to predict the deformation and strength properties of soil. Because of his confidence in the prediction accuracy from the pressuremeter test, Menard even guaranteed his foundation solutions backed by a \$10,000,000 professional liability insurance policy from Lloyds of London (Hartmann, 2008). Laboratoire Central des Ponts et Chaussees (LCPC), the French Department of Public Works, has performed a vast number of load tests and adjacent pressuremeter tests to improve and verify foundation design based on pressuremeter tests. Professor Dick Handy (1967) invented the borehole shear test to replicate the laboratory direct shear test but used the borehole sidewalls in the field instead of an undisturbed soil sample in the laboratory. Dr. Handy (1982) also invented the k_o step blade to measure the lateral earth pressure at rest. By measuring the lateral pressure needed to lift-off the membrane at different blade thicknesses, the engineer can extrapolate the pressure at a zero-blade thickness or the lateral stress at rest pressure.

Often, design methods use correlation coefficients based on load tests performed globally. The engineer should choose the most accurate in-situ test/design method based on the predicted/measured outcome ratio that has its average near 1.0 and the lowest coefficient of variation. The standard deviation equals the coefficient of variation times the average value. Where the predicted/measured ratios are not available in literature, the engineer can evaluate the logic that the inventor engineer used to develop the test and determine its prediction validity. Figure 1 shows how well data from the dilatometer test (Failmezger, Bullock, 2004) predicts settlement. Table 1 summaries the design need and recommended in-situ test.

Figure 1. Dilatometer Predicted Settlements after Schmertmann (1986) and Hayes (1986)

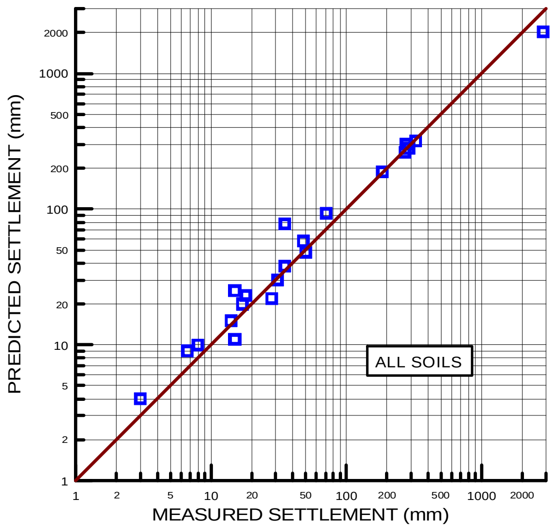

Table 1. Suggested in-situ test for geotechnical design

Design Need	Recommended Test	Predicted/Measured Ratio: Average/ Coefficient of Variation	Source
Vertical Deep Foundation Capacity	CPT	Schmertmann & Nottingham Method: 0.94/0.25	Robertson, Campanella, Davies, Sy--Driven Steel Pipe Piles
		de Ruiter & Beringen Method: 1.09/0.14	
		LCPC Method:1.00/0.15	
	PMT	Not known	LCPC
Lateral Deep Foundation Capacity	DMT	Not known	Marchetti, Totani, Calabrese, Monaco (1991)
		Not known	Robertson, Davies, Campanella (1989)
	PMT	Not known	LCPC
Setttlement	DMT	Schmertmann Method: Excluding quick clays: 1.06/0.18	Schmertmann (1986) Hayes (1986)
	PMT	Not known	LCPC
	Plate load/screw plate test		
	Conical Test Load		Schmertmann (1993)
Modulus of Rock	Rock PMT	Not known	Failmezger (2006)
Shear Strength of Rock	Rock BST	Not known	Failmezger, Handy, White (2008)
Shear Strength of Soil	Soil BST	Not known	Handy
	VST-Undrained shear strength for cohesive soil	Not known	
	DMT-Undrained shear strength for cohesive soil—average of other methods	Not known	Marchetti (1980)
	DMT with thrust measurements-Angle of Internal Friction based on elastic half space theory	Not known	Schmertmann (1982)
Ko	Ko step blade	Not known	Handy
	Self-boring pressuremeter	Not known	

3. Scale Effects/Construction Techniques

Because each test is a smaller version of the foundation system and the foundation installation method can influence capacity, the design engineer must use correlation coefficients to make his/her prediction to correct for scale effects and construction methods. However, better correlation coefficients can be developed based on load tests performed at the site. Tweaking the global correlation coefficients to site-specific correlations, lets the engineer hone-in on his/her outcome prediction.

4. How often should tests be performed?

The engineer must have confidence that the structure will perform as intended. Design should always be safe but not overly-conservative and expensive. Each test location should serve as an outcome prediction. The number of tests needed depends on how variable the subsurface conditons are. For perfectly homogeneous conditions, only one test is needed!

If the foundation system is non-redundant, then every support location should be tested. Schmertmann (2012) shows that testing every location results in the lowest cost in his "Test and Remediation Observation Method" (TROM).

For redundant foundation systems, the engineer must assess how variable the subsurface conditions are. Understanding the local geology aids the engineer in planning the subsurface investigation. For hetergeneous or large sites the engineer should develop contour maps that use numerical modelling of the predicted outcomes, such as settlement, pile tip depth, or lateral movement of deep foundations. Each test location becomes an outcome prediction data point to develop the contour map. Holes or hills on contour maps represent areas that need additional testing to understand those discrepancies and need to be redesigned. The engineer's final design adjusts the footing size or tip depth so that each foundation provides the same support to each foundation load. A flat contour map for the site illustrates the same amount of support everywhere and no differential movement will occur. The contour map and design for each foundation individually minimizes the uncertainty from the variability in the subsurface conditions.

As another approach for foundation locations where there is no test sounding, a weighed average may be used to determine the footing size or pile tip depth based on surrounding soundings. The soundings closer to the foundation location should have more importance or weight. Weighing factors can be calculated as 1/distance to the foundation from each sounding. Each weighed percentage is computed as its weighing factor divided by the sum of all weighing factors. For settlement prediction, the engineer first calculates settlement at the surrounding soundings using that footing's column load. The total predicted settlement is computed the sum of the weighed percentage times the predicted settlement for each nearby sounding. A similar approach could be used predicting pile tip depths.

Even for a site whose subsurface conditions are perfectly homogenous, if the column loads differ, then the footings must be sized for different bearing pressures for equal settlement. Figure 2 shows the settlement for different column loads that would occur for a site, whose soil had a constant constrained deformation modulus of 100 bars and the applied bearing pressure was a constant 143.6 kPa (3000 psf). Because higher loads have larger stress bulbs, the applied bearing pressure will need to be reduced or more ground improvement will be needed to get equal settlement. For the lighter loads, higher bearing pressures should be used, but not too high to cause bearing strength capacity failure, or little to no ground improvement should be used.

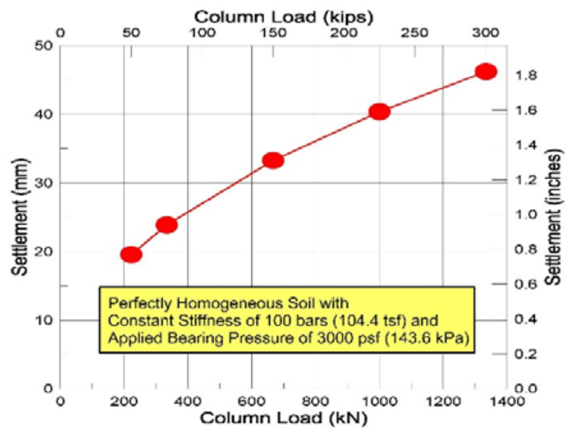

Figure 2. The importance of stress bulb for settlement computations

5. Probability of Success

The engineer should choose a probability of success that balances the risk of performance failure with the risk of financial failure. Mathematicians have made probability distribution functions seem much more complicated than they actually are. With civil engineering applications, the probability distribution curve is "bell-shaped" with the answer tending to be closer to the center. The axiom that must be satisfied is that the area under the probability distribution curve must equal 1.00. The outcome must always occur—it has 100% certainty or 1.00.

Researchers have often used either the normal probability distribution function or log-normal probability distribution function to represent risk for civil engineering design. However, the end limits for both distributions are not representative: the normal curve ranges from negative infinity to positive infinity and the log-normal curve ranges from slightly more than zero to positive infinity. But with the beta probability distribution function, the engineer chooses realistic minimum and maximum end limits that represent the lowest possible and highest possible values. With spreadsheets, the equation for the beta distribution function is easily solved using the gamma function. Furthermore, the solution is checked by computing the area under its curve, which must equal 1.00, using numerical methods, such as the trapezoidal method.

To determine the probability of success, the engineer first defines the beta probability distribution curve using the following four input parameters: the average value, its standard deviation, minimum possible end limit and maximum possible end limit. Curves that are steep and narrow represent accurate predictions (the answer is narrowly defined), while flat and wide curves represent predictions that have high uncertainty.

For a factor of safety design, the success zone is that portion of the curve that is more than 1.0, and for a settlement design, the success zone is that portion of the curve that is less than the maximum tolerable settlement. For a pile capacity design, two beta distribution curves may be used: one that represents the pile load and one that represents the pile capacity. The area under the pile capacity curve that exceeds the pile load curve is the probability of success. The engineer then calculates the probability of success as the area in the success zone. Alternatively, the engineer can calculate the probability of success by subtracting the area in the failure zone from 1.00.

Figures 3 to 5 show the probability distribution functions for the factor of safety, settlement, and pile capacity analyses. For each curve the minimum limit was 3 standard deviations less than the average and the maximum limit was 3 standard deviations more than the average value. Each curve has a probability of success equal to 95% or a probability of failure equal to 5%. As the standard deviation decreases, the curve becomes steeper and narrower and closer to a factor of safety equal to 1, the threshold settlement or the pile load curve.

Failmezger et. al. (2004) found when plotting the average factor of saftey versus its standard deviation, the probability of success of 95% had a linear relationship. Linear relationships were also found for probability of successes of 90%, 99%, 99.9% and 99.99%. Linear relationships for probability of success were also found for the settlement and pile capacity analyses. Figures 6 to 8 show these linear relationships. By plotting the average value and its standard deviation and assuming the minimum and maximum limits are 3 standard deviations away from the average value, the engineer can simply see what the probability of success is for his/her design.

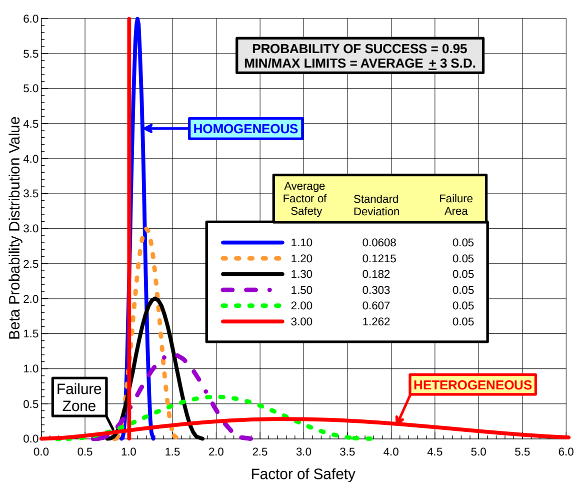

Figure 3. Probability Distribution Functions for Factor of Safety

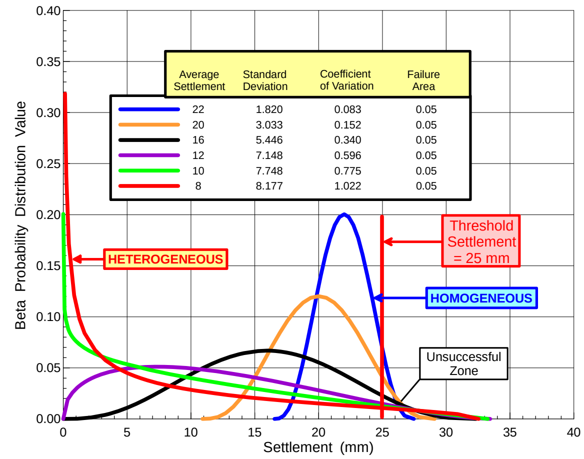

Figure 4. Probability Distribution Function for Settlement

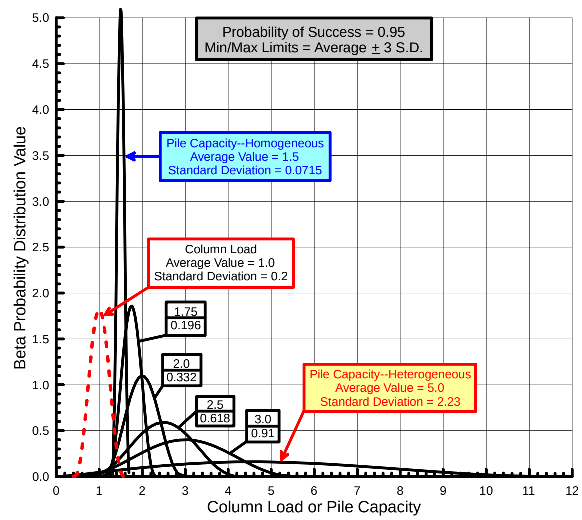

Figure 5. Probability Distribution Functions - Pile Capacity Analyses

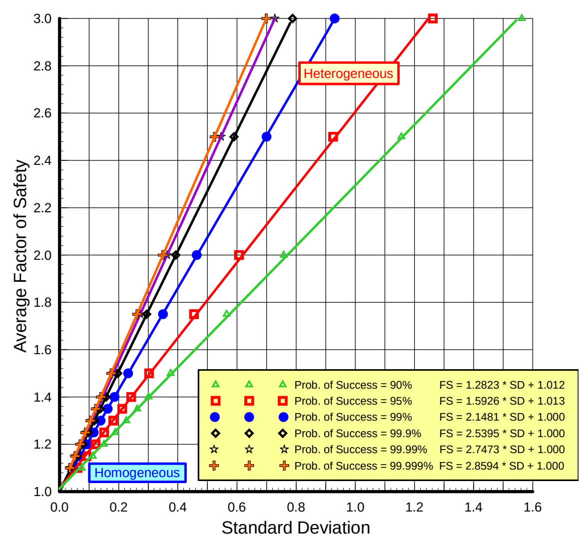

Figure 6. Probability of success for factor of safety analyses

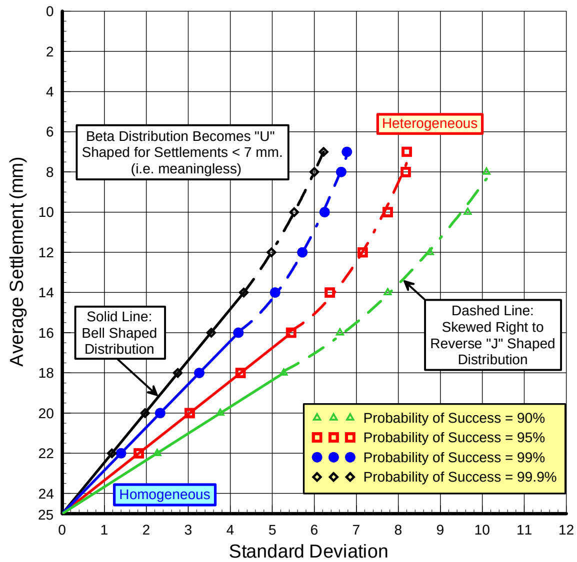

Figure 7. Probability of success for settlement analyses

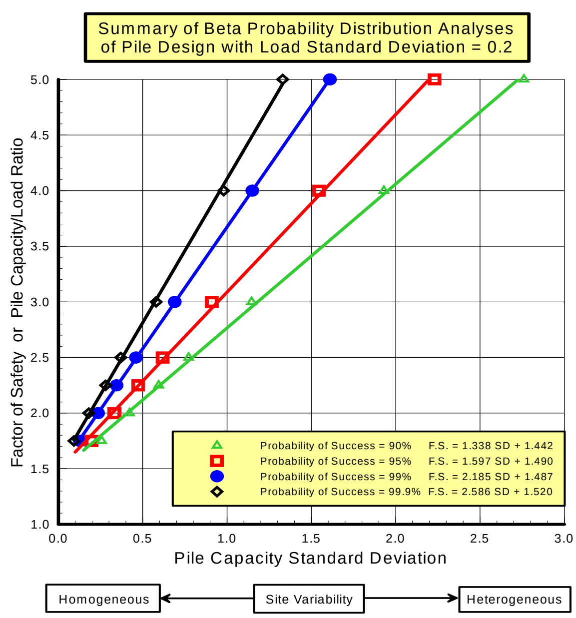

Figure 8. Probability of success for pile capacity

6. Computing the standard deviation

Table 1 provides some guidance for determining the standard deviation for the test/method based on case study data and load testing. The engineer should multiply the coefficient of variation by the average value to get the standard deviation for the test/method. If the standard deviation from the test/method and the subsurface variability are independent of each other, then the maximum standard deviation can be computed with the following equation:

$$\sigma_{\text{maximum}} = \text{square root}(\sigma_{\text{test/method}}^2 + \sigma_{\text{subsurface}}^2)$$

If the engineer does not believe that the two sources of standard deviation are independent, then he/she should reduce the design standard deviation using engineering judgment.

Duncan (2000) recommends that the engineer determine the minimum and maximum possible values and divide their difference by 6 to get the standard deviation.

For the factor of safety analyses, Christian (1997) recommends the point estimate method. For this method the engineer determines the variables the affect his/her design. Factor of safety analyses are performed using the average value and either plus or minus one standard deviation for each variable. The total number of analyses that are performed equals 2^n, where n is the number of variables. The average and standard deviation are computed from this data set. Additionally, the engineer can determine the variables are more important for the design, as they change the factor of safety more.

7. Computing financial failure

Financial failure occurs when the prediction is not a good as it should be due to the incorrect test/method used for analyses or not enough tests are preformed. Figure 9 illustrates probability distribution functions for the factor of safety case for the accurate analyses and the overly conservative or inaccurate analyses. The area where the inaccurate analyses exceeds the accurate analyses is the probability of financial failure. In this example, the probability of financial failure equals 0.786 or 78.6%. Because not many owners are willing to pay for the geotechnical engineering costly solution, they should request that the engineer perform only the most accurate test and method for the design solution. This risk analysis helps the owner understand the benefit of accurate analyses.

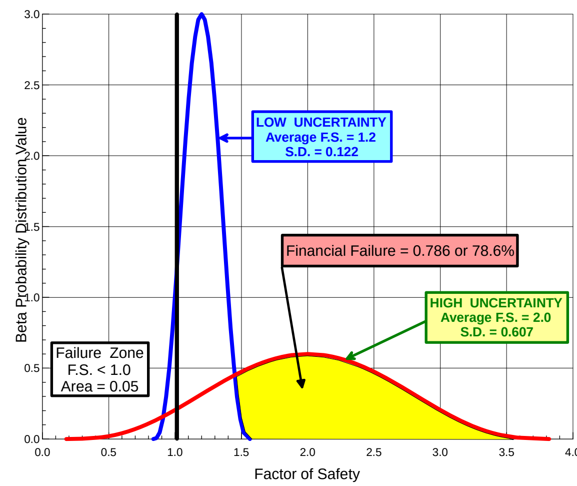

Figure 9. Computing Probability of Financial Failure

8. Conclusions

1. Engineers should choose the most accurate test and design method to safely design the most economical foundation system.
2. Using another test to get parameters of the more accurate test only results in an additional unnecessary layer of uncertainty. The engineer should simply use the most accurate test for the design need.
3. If the site's subsurface conditions are not homogeneous or the column loads are not the same throughout the structure, the engineer should design foundation for each column separately so that settlement is the same or the allowable pile capacity matches the load for the entire structure. This approach minimizes differential movement.
4. The beta probability distribution more accurately represents geotechnical engineering design than either the normal probability distribution or log-normal probability distribution because the engineer chooses its end limits.
5. The area under the beta probability distribution curve must equal 1.0.
6. When plotting the average factor of safety, settlement or pile capacity versus its standard deviation, the probability of success has a linear relationship.
7. Financial failure occurs when the engineer uses a less accurate test and method for analyses. The area under the probability distribution curve that exceeds the most accurate test/method analyses equals the probability of financial failure**.**
8. Some engineers do not use tests because they are not familiar or comfortable with them. Good engineers can easily get comfortable with the tests that provide the most accurate predictions.

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