SPT? – A better approach to site characterization of residual soils using other In-Situ tests

Roger A. Failmezger[1], Daniel Rom[2], Stacy B. Ziegler[3]

Sound geotechnical design requires a thorough quantification of soil properties. Engineers must determine the average values and variability of those properties. They must use tests that assess the site variability but minimize the parasitic test variability. The more variable the site is, the higher the risk is and therefore the more conservative the design should be. The contrary is also true. After determining the average and standard deviation values of the soil properties, the engineer can provide a design at a level of computed risk that is acceptable to the owner.

Where heterogeneous conditions prevail, which is often the case for residual soils, a large number of accurate tests is required. The chosen test should measure or model the property of interest. Heterogeneous conditions are best characterized using near continuous testing, such as dilatometer or piezocone. A dilatometer test (DMT) is a static deformation test and is useful for predicting settlement. The piezocone (CPTU) is a model of a pile and is good for predicting vertical capacity of piles.

Often exploration budgets are only large enough to perform a field program with associated laboratory testing consisting of routine index testing and a limited number of consolidation and triaxial tests. While consolidation and triaxial tests are practical for homogeneous conditions, it is not cost-effective to perform

[1] President of In-Situ Soil Testing, L.C., 2762 White Chapel Road, Lancaster, VA 22503, email: insitusoil @ prodigy.net

[2] President of Piedmont Geotechnical, Inc., 14735 Wrights Lane, Waterford, VA 20197, email: danrom @ ix.netcom.com

[3] Engineer at Duffield Associates, Inc., 5400 Limestone Road, Wilmington, DE 19808, email: stacy@duffnet.com

enough of these tests to be representative of heterogeneous soils. However, such tests can be beneficial for characterizing a critical soft or loose area that has been identified through near continuous dilatometer or piezocone soundings.

This paper summarizes several in-situ testing methods that are used for characterizing soils. The use of the in-situ test data in predicting shallow foundation settlements is also discussed, along with several case histories in which in-situ testing results were used in foundation design. Finally, the application of probability methods in quantifying risk as an important part of a foundation design is discussed.

IN-SITU SAMPLING AND TESTING METHODS

Standard Penetration Test (SPT)

Although standard penetration tests (SPT) are commonly used for evaluating subsurface conditions, there are many problems with using them to numerically characterize the static properties of residual soils. The dynamic penetration of the sampler severely remolds the soil and destroys the important latent rock structure of residual soils. Low N-values are often recorded and may indicate that the soil is much more compressible than it actually is. With SPT, the engineer cannot separate the parasitic test variability from true site variability. The real dilemma for the engineer is evaluating whether the low N-value is indicative of a soft zone or whether it is a result of destroying the latent rock structure. This uncertainty forces the engineer to use very conservative values for soil properties and assume the site has high variability. The engineer must use low allowable bearing pressures for foundation design, whether they are needed or not. When the foundation design is overly conservative, the engineer has wasted the owner's money.

The SPT is commonly performed at 1.5 meter depth intervals. Often, a soft or loose zone can be missed between sampling intervals or identified as being thicker than it actually is due to an error in estimating the location of strata changes. The soil stratification is a subjective interpretation in the field by the driller or logger. Although lab testing can be used to verify the classification of the samples, the thicknesses of the different strata as well as determining whether the sample obtained is truly representative of a given stratum cannot be checked. Not accounting for existing soft layers that were missed in sampling can result in an unconservative design, while identifying soft layers as thicker than they actually are results in a conservative design.

BACK

The SPT is a dynamic test and does not directly measure static soil properties. More importantly, the energy applied to the sampling system is rarely calibrated in practice, and can vary by a magnitude of 3 as documented by several researchers. Energy variability causes significant error to any numeric interpretation of SPT results. With energy calibrations, correlations with SPT data can be good but they are very site specific.

Some of the variability of the SPT N-value can be eliminated if the N-values are corrected to a specific energy (Skempton, 1986). Good drilling techniques will further reduce testing variability. Many of the SPT design methods are based on research performed from the 1940's to 1960's. Energy levels were not measured then because the necessary instrumentation had not been developed. Most experts believe that approximately 55 to 60 percent of the theoretical energy should be used with those correlations. The SPT methods used today are different than when the original research was done. Mud rotary drilling was used then instead of today's commonly used hollow stem augering. The mud rotary method does not remove as much of the in-situ stresses as hollow stem augering, and thus more representative N-values can be obtained using mud rotary methods. Today's spoon has an inside diameter to accommodate a liner but usually liners are not used. To correct the N-values for the lack of friction along the inside of the split spoon, Skempton suggests increasing those N-values by 20%. However, the most important correction is the energy correction. This value should be determined through system energy calibration. Skempton suggests as a preliminary guide the following delivered energy as a percentage of theoretical potential energy (30 inches x 140 lbs) for different hammer systems: 45% for donut hammers, 60% for safety hammers, and 95% for automatic hammers.

<u>Pressuremeter Test (PMT)</u>

The pressuremeter test is a calibrated static deformation test and can accurately evaluate the deformation characteristics of the soil. The single most important part of obtaining good quality pressuremeter test data is making a high quality borehole by minimizing disturbance to the sidewalls. This is particularly true in the sensitive residual soils. Mud rotary techniques can generally make the best quality holes. Rock coring tends to oversize the borehole in decomposed or weathered rock and should only be used in sound rock when rotary drilling refusal occurs (i.e.: good quality rock). Quartz layers or seams can be a nuisance for pressuremeter testing, often puncturing the membrane.

The closest test intervals that pressuremeter tests can be conducted are about 1.5 meters (5 feet). If the soil has significant vertical variability, the test spacing may be too great for accurate characterization. Additionally, most subsurface exploration budgets do not allow for the performance of enough PMT testing to accurately evaluate variable stratigraphy.

Electric Cone Penetrometer Test (CPTU)

The electric cone penetrometer test with pore pressure measurements, or piezocone test, is a calibrated quasi-static penetration test. Data from the tip and friction sleeve strain gauges and the pore pressure transducers in the cone are collected at depth intervals between 0.01 and 0.05 meters. An advantage of CPTU testing is that a large amount of data can be collected quickly. Sites can be rapidly characterized with CPTU and critical soft zones can be identified as locations where deformation or shear strength tests should be performed. Determining the approximate depth to rock can be quickly evaluated. The vertical capacity of deep foundations are reasonably well predicted using CPTU data. The soil's deformation modulus can also be computed, but site specific or local correlation factors should be used.

Dilatometer Test (DMT)

The dilatometer test is a calibrated static deformation test that is typically performed at 0.2 meter depth intervals. In thin soft zones the testing interval can be reduced to 0.1 meters for better characterization. The geometry and quasi-static push of the dilatometer minimize disturbance to the soil structure, allowing the DMT to measure the significance of latent rock structure. The volumetric strain and shear strain induced during penetration of the DMT are significantly lower than CPTU and SPT. As with pressuremeter tests, quartz layers can tear membranes.

Dr. Marchetti attempted to correlate many important soil properties with dilatometer test results. Some correlations were very good and some were not. He chose to use only the good correlations. The constrained tangent deformation modulus correlated very well and is calculated from each test. Figure 1 shows a comparison of the deformation modulus obtained from dilatometer tests with oedometer test data in residual soils. It is often difficult to collect undisturbed samples in residual soil and thus we do not have as many laboratory oedometer tests as we would like. Additionally, there was significant variability observed in modulus values from samples from the same tube and between dilatometer tests. Settlement predictions can be accurately made using dilatometer data. DMT results can also be used to evaluate the drained friction angle in cohesionless soil or undrained shear strength in cohesive soil.

BACK

These shear strength parameters can be useful in performing slope stability analyses when short-term conditions are critical.

Iowa Borehole Shear Test (BST)

The Iowa borehole shear test can be used to measure the in-situ drained shear strength parameters. Researchers have shown that BST results compare very well with laboratory triaxial shear test results. The borehole shear test is performed similarly to a laboratory direct shear test but is conducted along the borehole sidewalls. A pore pressure transducer can be used to assure that consolidation at each normal stress has occurred and that the rate of strain is slow enough so that drained conditions exist. Similar to pressuremeter tests, it is important to minimize sidewall disturbance of the borehole.

Predicting Settlement of Shallow Foundations

To predict settlements, the engineer needs to evaluate the soil's stiffness or deformation modulus. The dilatometer and pressuremeter tests are preferred because they are calibrated static deformation tests. Often, residual soil is heterogeneous and thin compressible layers will be critical for design. Because pressuremeter tests are conducted at 1.5 m or larger depth intervals, compressible layers, if thin, may be missed with PMT. DMT tests are performed at 0.2m intervals and, as a result, thin compressible layers can be detected. Additional data can be obtained in these thin zones by performing DMT at 0.1 m intervals.

With the DMT, settlement is calculated by dividing the soil profile into layers of similar stiffness and computing the settlement of each layer. The total settlement is the sum of all the layers. With a spreadsheet template, each test depth interval can be used as a layer. Settlement is computed using Schmertmann's ordinary method (1986) with the following formula:

$S = (\Delta\sigma)(h)/M$

where S = settlement,
$\Delta\sigma$ = vertical stress increase,
h = layer thickness, and
M = constrained deformation modulus.

BACK

Schmertmann's special method takes the soil's preconsolidation pressure into account and generates a M versus p curve. For typical foundation loads on reasonably stiff soils the two methods often predict settlements within 10% of each other, and the more rigorous special method is not needed. Additional details and numerical examples can be found in the above reference.

Case Studies

The authors have been involved with several projects where the data from dilatometer and piezocone testing were used for foundation design. The engineers' more accurate design produced significant cost savings. In some of the case studies, in-situ testing was used in addition to conventional SPT borings and laboratory tests. However, in one of the case studies presented, the subsurface conditions were accurately defined using dilatometer and/or piezocone tests and no standard penetration tests were performed.

<u>Route 460 Bypass – Blacksburg, Virginia</u>

Several retaining walls were proposed along the right-of-way for this project. Initially, SPT borings were conducted and the proposed foundation design was steel HP piles driven to rock supporting concrete cantilever retaining walls. Settlement estimates for a mechanically stabilized earth (MSE) wall based on SPT data were more than 4 inches (100 mm). A senior Virginia Department of Transportation (VDOT) engineer requested dilatometer tests. Settlement predictions for the MSE walls were 1.07 inches (27.2 mm) or less based on DMT data. Undisturbed tube samples were then obtained in the softer areas identified by DMT and used for laboratory oedometer tests. Settlement predictions based on the oedometer tests were 1.1 inches (27.9 mm). The design was changed to MSE walls and the owner (VDOT) saved more than $500,000!

<u>Parking Garage – Wilmington, Delaware</u>

A geotechnical evaluation was performed for a proposed five-story pre-cast concrete parking garage structure. Long spans within the structure resulted in anticipated loads of up to 1200 kips per column. The initial evaluation consisted of standard penetration test borings, with Shelby tube sampling and subsequent laboratory testing of a soft silt stratum. Based on this evaluation, spread footing settlements of up to 3 inches were estimated, primarily due to the presence of a slightly overconsolidated silt stratum that was believed to be up to 15 feet in thickness. The estimated settlement exceeded the settlement tolerances of the structure; therefore, a drilled pier system founded on rock was recommended.

BACK

At the suggestion of the geotechnical engineer, dilatometer testing was performed at the site in the areas where the silt stratum was encountered. Based on the dilatometer test results, it was determined that the soft silt stratum was more overconsolidated and not as thick as originally estimated, thus allowing the engineer to use less conservative consolidation parameters. The result was a shallow foundation settlement estimate within the tolerable limits of the structure. This allowed the owner to construct the parking garage on a shallow foundation system instead of the originally proposed drilled pier system, resulting in significant cost and construction time savings.

<u>Hydropillar Water Tank - Eldersburg, Maryland</u>

A one-million-gallon elevated water storage tank was proposed to be supported in virgin Piedmont residual soils. Given the magnitude of the loading, 8950 kips, in addition to lateral loads and moments, DMT soundings were recommended to optimize foundation design with respect to settlement. The DMT data provided the geotechnical engineer with good design information, and thus standard penetration test borings were determined to be unnecessary and were not performed. It was determined that using an allowable design soil bearing pressure of 4500 psf resulted in economically-sized foundations, with total settlements less than one-half inch. The Owner was able to use a standard foundation design consisting of a ring-shaped spread footing with assurance that tolerable settlements would result.

<u>Forest Oak Middle School - Gaithersburg, Maryland</u>

A middle school structure with column loads of 250 kips was erected on virgin Piedmont residual soils of various quality and texture. The underlying rock included schist and serpentinite. The weathered soil ranged from loose to very dense, and rock elevations varied significantly. Settlement estimates based on the initial SPT borings were variable. For a final exploration, CPT and DMT soundings were used. It was determined that a conventional spread footing design of 3000 psf bearing satisfactorily addressed fill and natural soil conditions, with total settlements less than three-quarters of an inch, which met the structural engineer's standard. The settlement tolerance would not have been assured solely on the basis of the initial SPT tests.

<u>Bethesda-Chevy Chase High School</u>

Three 3-story school building structures with column loads of 30 to 1005 kips were proposed as infill where pre-existing buildings were to be razed. The original masonry structures, dating to the 1930's, were reportedly supported by spread footings proportioned for 6000 psf. The underlying strata included

BACK

residual soil derived from the decomposition of schist. Below two of the proposed structures, grades were to be lowered and support would be on decomposed rock.

A conventional geotechnical evaluation using standard penetration testing resulted in conservative foundation recommendations and an allowable soil bearing pressure value of 2000 psf, because an isolated area of loose fill soil was encountered at the edge of a planned building footprint. The heavier columns would require drilled pier or pile support, resulting in cost overruns of about $400,000.

A dilatometer study was authorized, and it was determined that two of the structures could safely be supported on spread footings bearing on decomposed rock at 20,000 psf. The remaining structure could safely be supported on conventional spread footings with a 6000 psf design bearing. Settlement tolerances were determined to be within tolerable limits established by the structural engineer, and the deep foundation alternate was deleted. The foundation cost overruns were eliminated.

Quantifying Risk

Geotechnical engineers should quantify the risk associated with their designs. With the factor of safety design approach, the engineer arbitrarily assumes a value for the factor of safety based on the engineer's "experience" or local codes. Experience is gained by analyzing failures. Harr (1987) reminds us that with the possible exception of the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation, other engineering firms or organizations have not experienced enough failures to quantify risk with values of factors of safety. Christian (1997) illustrates how design of a site with homogeneous subsurface conditions can have lower risk than a site with heterogeneous conditions that uses a higher factor of safety. Poor quality data can falsely mislead an engineer to believe a site is heterogeneous when it is actually fairly homogeneous.

Engineering design should focus on the extreme or threshold limits rather than average values. For example, the engineer should be more interested in the chances or risks that settlement will exceed a threshold limit, for example, of 1.0 inch (25 mm) rather than what an average settlement will be. For slope stability analyses, the engineer must evaluate the risk that the factor of safety will be less than 1.0, and not that the average value is above a somewhat arbitrarily chosen minimum value. For heterogeneous subsurface conditions, an average factor of safety should be higher than for homogeneous conditions. Site variability needs to be accurately quantified to evaluate these extremes.

A probability approach can be used to evaluate the risk of exceeding threshold limits. Probability analysis involves determining the probability under the tail ends of the probability function. The normal probability function has values ranging from negative infinity to positive infinity and the log normal distribution ranges from zero to positive infinity. The beta probability function is recommended for the analysis because its minimum and maximum values are chosen by the engineer. Harr (1987) recommends using 3 standard deviations on each side of the average value as the minimum and maximum values for civil engineering design. The Beta probability function is defined below (Harr, 1977):

$$f(x) = C \cdot (x-a)^{\alpha}(b-x)^{\beta}$$

$$D = (\mu-a)/(b-a)$$

$$V = [S_x/(b-a)]^2$$

$$\alpha = \frac{D^2}{V}(1 - D) - (1+ D)$$

$$\beta = \frac{\alpha + 1}{D} - (\alpha + 2)$$

where: μ = average value
S_x = standard deviation
a = design minimum value,
b = design maximum value, and
C,D,V,α, β are all constants.

$$C = \frac{(b - a)^{-1-\alpha-\beta}}{B(\alpha+1,\beta+1)}$$

where $B(\alpha+1,\beta+1) = \dfrac{(\alpha!)\,(\beta!)}{(\alpha+\beta+1)!}$, and

! = factorial of the number

Spreadsheets can be created to quickly perform beta probability calculations. After generating the formula for the Beta probability curve, the engineer should verify that the formula is correct. The area under the probability curve must be 1.0. The trapezoidal method provides sufficiently accurate computations of area when the widths of the trapezoids are small.

BACK

To quantify the risk of exceeding a threshold acceptable value, the engineer computes the area under the tail end of the curve either above the threshold value for settlement or below the threshold value of 1.0 for slope stability. The probability of success equals 1.0 minus the probability of failure. Additionally, the engineer can generate the cumulative distribution function by summing the area beneath the probability distribution curve from the minimum value to the maximum values. When the cumulative distribution function is plotted, the engineer can directly read the probability of success.

Settlement Probability Design

With the presented approach, geotechnical engineers need to determine 1) how well the test and design methods predict field performance and 2) the spatial variability of the soil properties over the project site. Point #1 can be quantified using case study data that determine the average and standard deviation values of the predicted-to-measured ratio. The design method to compute settlement should accurately predict what is measured in the field with a low standard deviation. Point #2 can be quantified by collecting enough good quality data to numerically characterize the subsurface conditions.

The dilatometer test (DMT) is a static deformation test that is performed at 0.1 or 0.2 meter depth intervals. As documented by Schmertmann (1988) the DMT accurately predicts the soil's constrained deformation modulus (M) in peats, clays, silts and sands. Schmertmann (1986) shows that DMT data can be used to accurately predict settlement of shallow foundations. As illustrated by his case study data, the predicted-to-measured ratio for settlement was 1.18 with a standard deviation of 0.38. Where the dilatometer was pushed and excluding quick clayey silts, the average value of DMT predicted-to-measured settlement is 1.07 with a standard deviation of 0.22. The method's coefficient of variation is defined as the standard deviation divided by the average value and is 0.38/1.18 = 32% for all cases or 0.22/1.07 = 21% without special cases.

Most significant projects should allow the engineer to perform at least 5 and preferably 10 or more dilatometer test soundings. From each sounding, the engineer can predict settlement using Schmertmann's method. Each prediction becomes a data point for the probabilistic analysis. The project's average and standard deviation can then be computed for that data set. More accurate average and standard deviation values for the data set can be obtained by dividing those values by the measurement bias (average predicted-to-measured values), either 1.18 or 1.07.

Standard deviation from the testing error and Schmertmann's settlement prediction method can be computed by multiplying its coefficient of variation

BACK

(either 0.32 for all cases or 0.21 without special cases) by the average settlement. There may also be other intangible items that cannot be directly accounted for in the engineer's settlement prediction. Examples of these items may include lack of dilatometer soundings, uncertainty of the structural foundation loads, the contractor not being prequalified or another firm less familiar with the project or with less experienced people monitoring the construction. The overall standard deviation is the square root of {(project deviation)^2 + (method deviation)^2 + (other deviation)^2}.

In the following numeric example, 10 dilatometer soundings were performed and settlement computations were made at each sounding location. Table 1 shows the spreadsheet computations for the probability analysis of total settlement. In addition to inputting the 10 values from the settlement analysis, the engineer also must decide what values to input for the following parameters (the example values are in parenthesis):

- measurement bias (1.07),
- coefficient of variation for the design method (0.21),
- coefficient of variation for other intangible items (0.25),
- minimum value of the probability curve (0.0), and
- maximum value of the probability curve (32.84 mm).

Integrating the area under the Beta probability curve, the engineer checks to confirm that its area equals 1.0 verifying that the formula is correct. In the example, we have assumed a threshold value of 25.4 mm for the total settlement. Figure 2 shows the probability curve for total settlement. As shown on Table 1, the area of the tail above the threshold value, or probability of failure, is computed as 0.032. The probability of success is 1.0 minus the failure probability, or 0.968. This value can be read directly from the cumulative distribution graph (Figure 3).

Slope Stability Probability Design

The traditional factor of safety approach for slope stability analysis does not consider the variability of the soil parameters. The Monte Carlo probability approach is a brute force method that uses a random number generator to vary the soil parameters and numerous trials are used. Christian (1997) provides simpler approach whereby each parameter uses a value of either its average value plus or minus one standard deviation. Slope stability analyses are conducted for each possible combination. There are 2^n combinations or permutations, where n is the number of variables. For example, if there are 4 variables, there will be 16 different analyses performed. With this method the critical variables can be easily determined. The minimum factor of safety from each analysis becomes a data point for generating the probability distribution curve, as previously described, with the x-axis being factor of safety. The probability of success is the area under the probability distribution curve that exceeds a factor of safety of 1.0.

The most important task with this approach is determining the average and standard deviation values for the slope parameters. The shear strength of each soil layer can be determined using either laboratory shear tests or insitu dilatometer/piezocone (undrained conditions) or borehole shear tests (drained conditions). An advantage of insitu tests is that many more tests can be conducted than laboratory tests within the same budget. With more but also accurate tests the average and standard deviation values can be better defined. Preliminary dilatometer or piezocone tests can assist the engineer by identifying average or minimum strength zones where the more refined laboratory or borehole shear tests should be performed. When only a limited number of refined tests can be conducted, DMT/CPTU can be used to evaluate standard deviation values.

SUMMARY AND CONCLUSIONS

The engineer should ideally focus on the variability of the subsurface conditions rather than the variability of the test or design method. The engineer should select tests that accurately predict the soil parameters of interest and that accurately reflect the heterogeneity of the soil profile.

The presented probability methods offer engineers straightforward approaches to quantify risk. The owner and the engineer should work together to decide what is acceptable risk. The engineer can then design to satisfy the risk criteria. When risk is not quantified and the design is based on the engineer's "experience", the engineer assumes all the risks and the owner usually receives a conservative and expensive design, which does not serve either party. Designs should be less conservative for homogeneous subsurface conditions than for heterogeneous conditions.

ACKNOWLEDGEMENT

The authors thank Mr. David Kaulfers for providing laboratory test data for the Virginia Department of Transportation projects used in this paper. We also thank Dr. Paul J. Bullock for his constructive review of the paper.

KEYWORDS: Dilatometer, standard penetration test, pressuremeter, electric

cone penetrometer, borehole shear test, probability, settlement, slope stability

APPENDIX. REFERENCES

Briaud, Jean-Louis, (1992), The Pressuremeter, A.A. Balkema, Rotterdam.

Christian, John T. (1997), "Reliability Approaches in Design of Slopes." Excellence in Geotechnical Engineering. Central Pennsylvania Section, ASCE and Pennsylvania Department of Transportation.

Handy, Richard L. (1986), "Borehole Shear Test and Slope Stability" Proceedings of In Situ' 86 ASCE Specialty Conference on Use of In Situ Tests and Geotechnical Engineering, Virginia Tech, Blacksburg, Virginia, pp. 161-175.

Handy, R.L., Schmertmann, J.H. and Lutenegger, A.J. (1985), "Borehole Shear Tests in a Shallow Marine Environment", Strength Testing of Marine Sediments Laboratory and In-Situ Measurements, ASTM STP 883, R.C. Chaney and K.R. Demars, Eds., American Society for Testing and Materials, Philadelphia, pp. 140-153.

Harr, Milton E. (1977), Mechanics of Particulate Media: A Probabilistic Approach. McGraw-Hill, New York.

Harr, Milton E. (1987), Reliability-Based Design in Civil Engineering. McGraw-Hill, New York.

Janbu, N., "Settlement Calculations Based on the Tangent Modulus concept". Three guest lectures at Moscow State University, Bulletin No. 2, Soil Mechanics, Norwegian Institute of Technology, 1967, pp. 1-57.

Kottegoda, Nathabandu T. and Rossa, Renzo (1997), Statistics, Probability, and Reliability for Civil and Environmental Engineers, McGraw-Hill, New York.

Kulhawy, Fred H. and Trautmann, Charles H. (1996), "Estimation of In-Situ Test Uncertainty", Uncertainty in the Geologic Environment: From Theory to Practice, Vol. 1, Charles D. Shackelford, Priscilla P. Nelson, and Mary J.S. Roth, editors, ASCE, New York, NY, pp. 269-286.

Lutenegger, Alan J., Remmes, Bernard D. and Handy, Richard L. (1978), “Borehole Shear Test for Stiff Soil” Proceedings of the American Society of Civil Engineers, Journal of the Geotechnical Engineering Division, Vol. 104, No. GT11, ASCE, pp. 1403-1407.

Lutenegger, Alan J. and Tierney, Kevin F. (1986), “Pore Pressure Effects in Borehole Shear Testing” Proceedings of In Situ’ 86 ASCE Specialty Conference on Use of In Situ Tests and Geotechnical Engineering, Virginia Tech, Blacksburg, Virginia, pp. 752-764.

Marchetti, S. (1980), “Insitu Tests by Flat Dilatometer”, Proceedings of the American Society of Civil Engineers, Journal of the Geotechnical Engineering Division, Vol. 106, No. GT3, pp. 229-241., discussion and closure (1981), Vol. 107, No. GT6, pp. 831-837.

Schmertmann, J. H. (1978), “Use the SPT to Measure Dynamic Soil Properties? – Yes, But..!” Dynamic Geotechnical Testing, ASTM STP 654, American Society for Testing and Materials, pp. 341-355.

Schmertmann, John H. (1979), “Statics of SPT”, Proceedings of the American Society of Civil Engineers, Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT5, pp. 655-670.

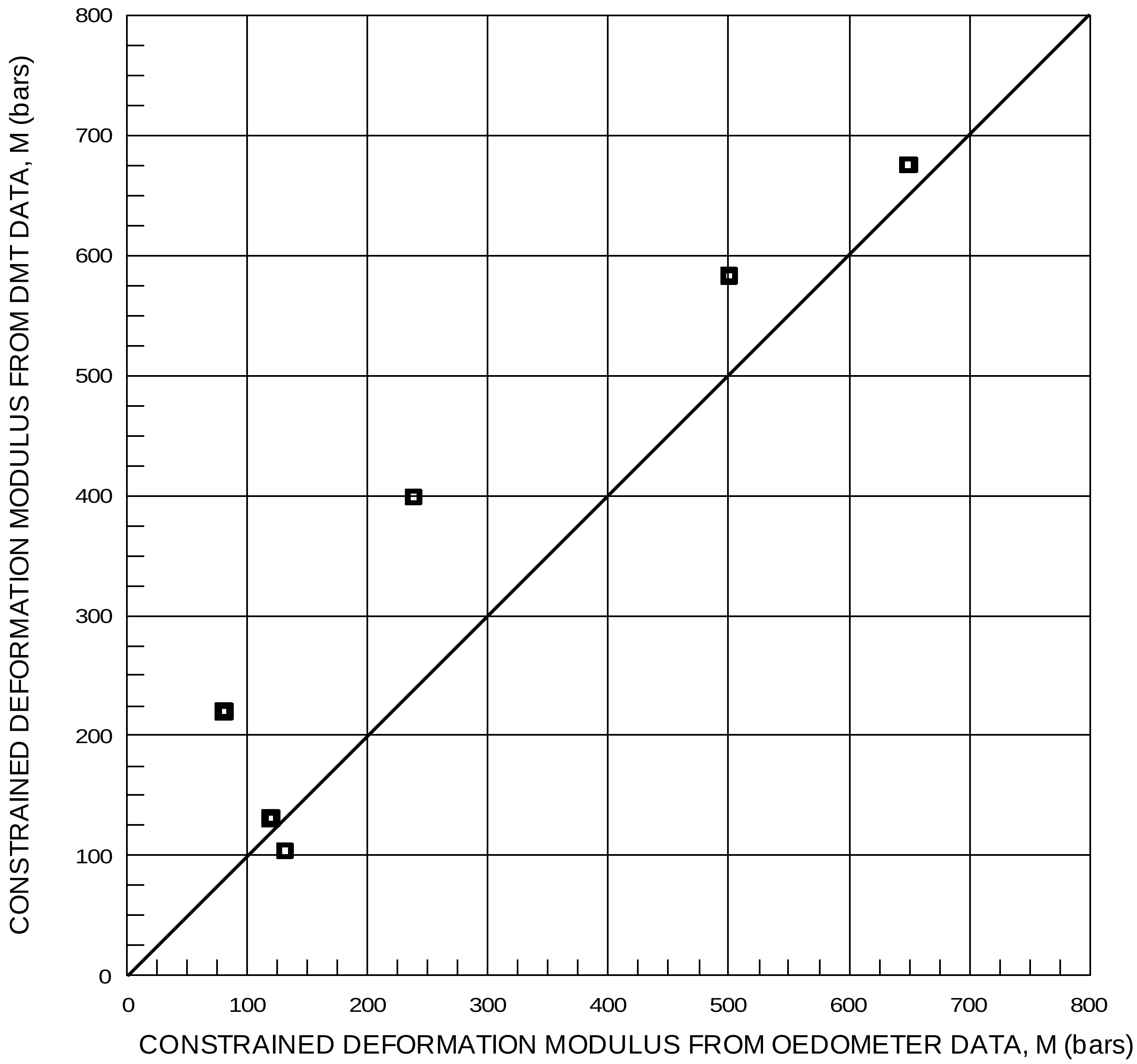
Schmertmann, John H. (1986), “Dilatometer to Compute Foundation Settlement.” Proceedings of In Situ’ 86 ASCE Specialty Conference on Use of In Situ Tests and Geotechnical Engineering, Virginia Tech, Blacksburg, Virginia, pp. 303-321.

Schmertmann, John H. (1988), “Guidelines for Using the CPT, CPTU and Marchetti DMT for Geotechnical Design.” U.S. Department of Transportation, Federal Highway Administration, Office of Research and Special Studies, Report No. FHWA-PA-87-023+24, Vol. 3-4.

Schmertmann, John H. and Palacios, Alejandro (1979), “Energy Dynamics of SPT”, Proceedings of the American Society of Civil Engineers, Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT8, pp. 909-926.

Skempton, A. W. (1986), “Standard penetration test procedures and the effects in sand of overburden pressure, relative density, particle size, ageing and overconsolidation”, Geotechnique 36, No. 3, pp. 425-447.

Figure 1: COMPARISON OF DMT vs. OEDOMETER CONSTRAINED DEFORMATION MODULUS



BACK

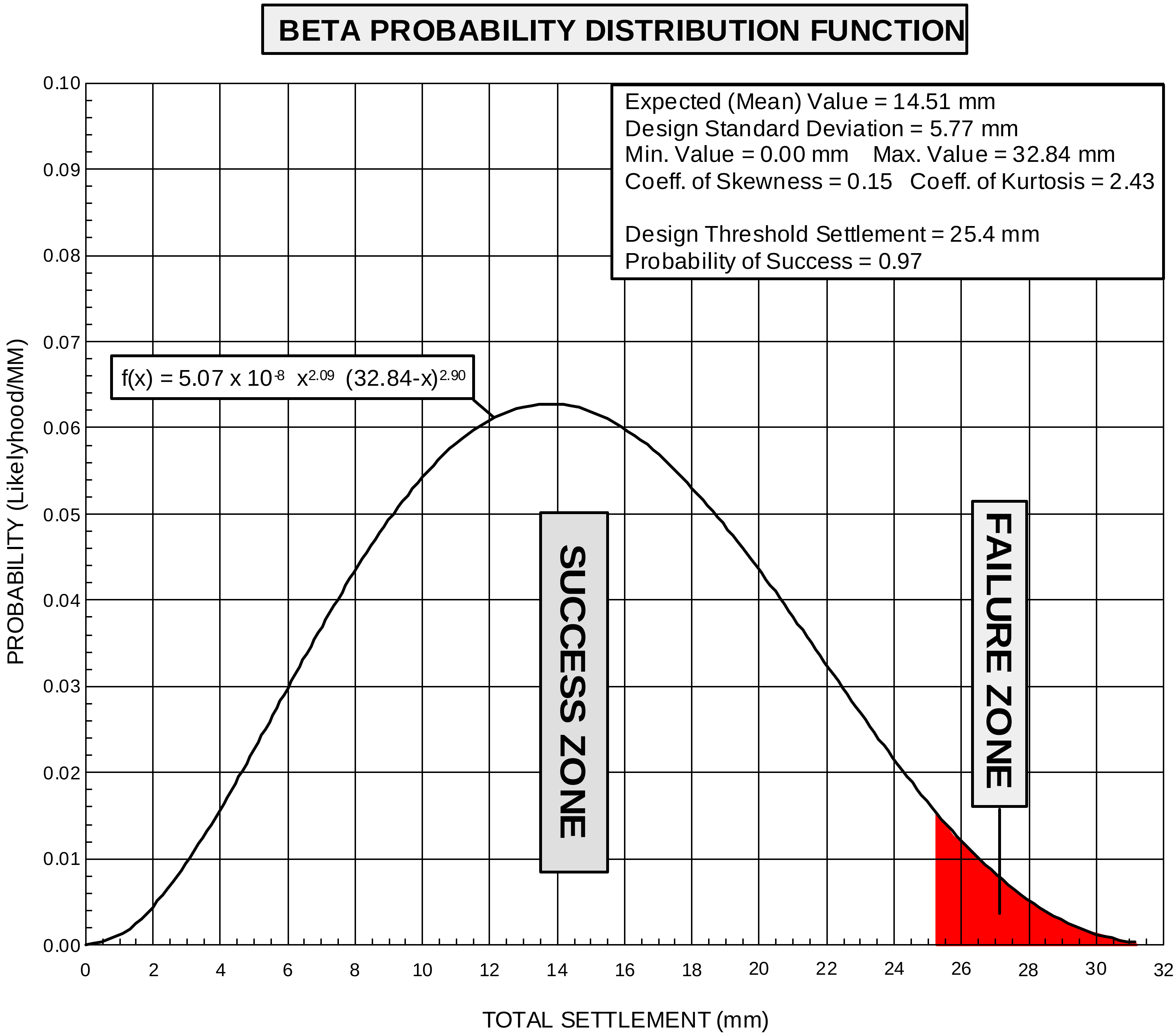


Figure 2: Total Settlement Probability Curve

BACK

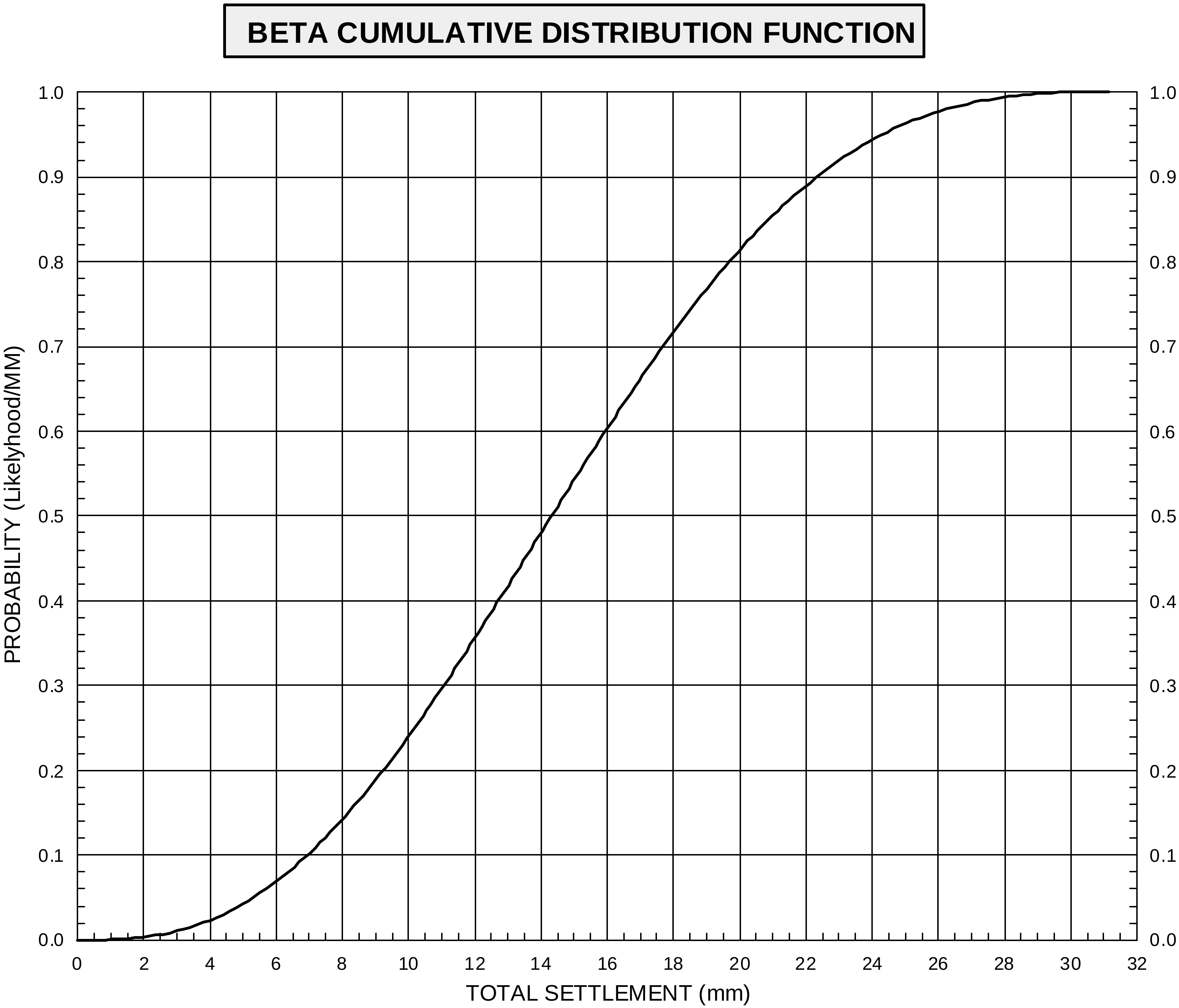


Figure 3: Cumulative Distribution Graph