Redesign of Shallow Foundations using Dilatometer Tests—more Case Studies after DMT'06 Conference

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ABSTRACT: Geotechnical engineers have the duty and obligation to the owner to prove that shallow spread footings will not work before recommending more expensive deep foundations. Unfortunately, too often engineers recommend deep foundations because they do not accurately measure the deformation properties of the soil or thicknesses of softer compressible soils. Their engineering study should not end due to inadequate geotechnical information, but should continue with a second phase investigation using dilatometer tests. We present case studies where the first engineer stopped after obtaining inadequate information, recommended an expensive foundation solution and irritated the owner. The owner then hired us to reevaluate the site using dilatometer tests. Dilatometer tests carefully measure the soils' deformation properties and for seven case studies we safely redesigned the foundations supporting the buildings on shallow spread footings.

1 INTRODUCTION

Unfortunately, too often engineers do not perform tests that measure the soil's stiffness but still make foundation design recommendations on limited and poor quality information. While most of these poor recommendations are overly conservative and the structures do not settle or crack, owners pay the high price for constructing a foundation system that was unnecessarily costly. Fortunately, the dilatometer test allows the engineer to economically measure the soil's stiffness and accurately design shallow spread footings. We present several case studies that show large cost savings to the owner by using dilatometer tests instead of other cruder tests for the foundation design.

2 GEOTECHNICAL RISKS

2.1 *Structural/Performance*

Through formal education, geotechnical engineers design foundations so that they will perform adequately for the life of the structure. In the United States, lawyers have forced the engineer to become keenly aware of this duty. Unfortunately, to minimize their risk, engineers often design conservatively and often overly conservatively and costly.

2.2 *Financial*

The owner needs the foundation to adequately and safely support the column loads but with minimal foundation costs. When the owner wastes money on foundations that are not needed due to overly conservative engineering design, he significantly reduces his profits or incurs losses. The engineer may overlook the financial risks because the money lost belongs to the owner—not him.

2.3 *Reducing Uncertainty/Risks*

To best serve the project, the geotechnical engineer must consider both structural and financial risks in his design. To accurately design shallow foundations for settlement, the engineer must measure the deformation properties of the underlying soil. The dilatometer test accurately measures the constrained deformation modulus of the soil. The DMT strains the soil to an intermediate level similar to what the structure will impose on the soil. The engineer performs tests at close depth intervals (10 or 20 centimeters) and creates a depth profile of modulus values that he uses for the settlement analyses. The modulus from each test represents a layer or row in an Excel spreadsheet for settlement computation. Because of the close test depth intervals, for each layer the engineer accurately calculates the increase of applied vertical stress to the soil using Boussinesq, Westergaard or other stress distribution solution. The engineer predicts the total settlement by summing each row's settlement. Therefore, each dilatometer sounding becomes a settlement prediction, which could be used for a site contour map of settlement or identify unacceptable high settlement areas.

While in the field the engineer will detect any thin and soft layers as he performs the tests. Because soft layers are critical to settlement predictions, he should decrease the testing depth interval to 10 cm, particularly when the layers are soft and thin. When the engineer uses a load cell to measure the downward thrust, he will often find soft layers, where the thrust is less than 500 kgf.

For the perfect foundation solution, each footing will settle exactly the same amount and no cracking will occur. But the supporting soils are not perfectly homogeneous and the column loads are not the same, applying different stresses to the soil. Figure 1 illustrates the effect of the size of the stress bulb on settlement prediction when the footing applies a constant bearing pressure of 3000 psf (144 kPa) and the site has a constant deformation modulus of 100 bars (104 tsf).

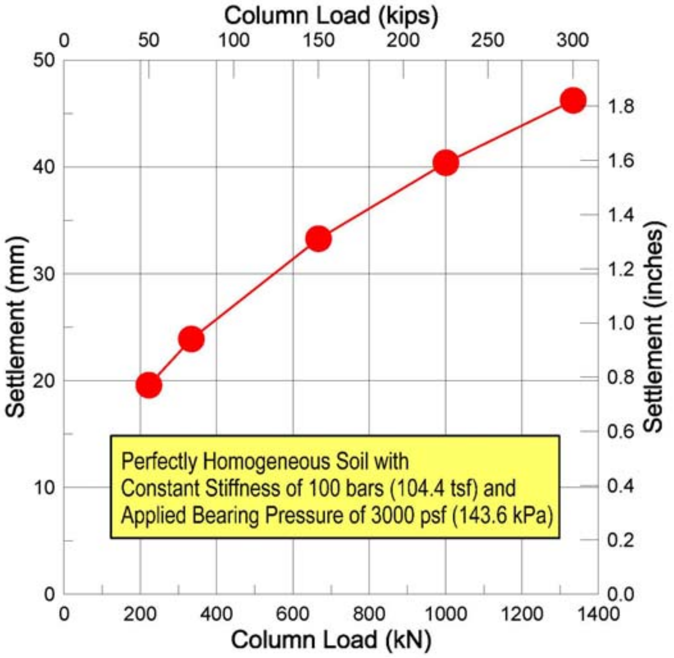

Figure 1: Effect of size of stress bulb on settlement

Therefore, the engineer should design footing individually to achieve uniform settlement. (Failmezger & Bullock, 2004) Where the soils compress, the engineer can design these footings larger, pre-load the soils or improve the ground to stiffen them before constructing footings or relocate the structure away from compressible soil areas. The engineer must know what the deformation moduli of subsurface soils are to make these important design decisions. He needs more modulus measurements for heterogeneous sites than homogeneous sites. Fortunately, the engineer can make many measurements with dilatometer tests, and then can accurately and confidently design shallow spread footings.

2.4 *Quantifying Uncertainty*

A bell-shaped curve best represents uncertainty in civil engineering design. The area under all probability distribution curves equals exactly 1.000. A steep and narrow curve depicts low uncertainty, while a flat and wide curve depicts high uncertainty. Poor and inaccurate measurements follow the high uncertainty curve, but accurate measurements from dilatometer tests tend to follow the low uncertainty curve. Measurements from tests that do not accurately predict the soil's deformation modulus should never be the source of uncertainty.

Figure 2 illustrates the low uncertainty (knowing) and the high uncertainty (unknowing) probability curves. In both cases, the risk for structural/performance failure was identical and equal to 5%--the area under both curves to the left of a factor of safety of 1.0 equaled 0.05. The average factor of safety for the low uncertainty case equaled 1.2 and for the high uncertainty case equaled 2.0. In this example, a design that has a factor of safety greater than 1.6 is entirely unnecessary and wasteful and represents financial failure because accurate measurements would have led the engineer to design using in the narrower curve that is less than 1.6. For the low uncertainty curve, the probability of financial failure equals 0%, while for the high uncertainty curve, the probability of financial failure equals 72.9%--the area under that curve to the right of 1.6.

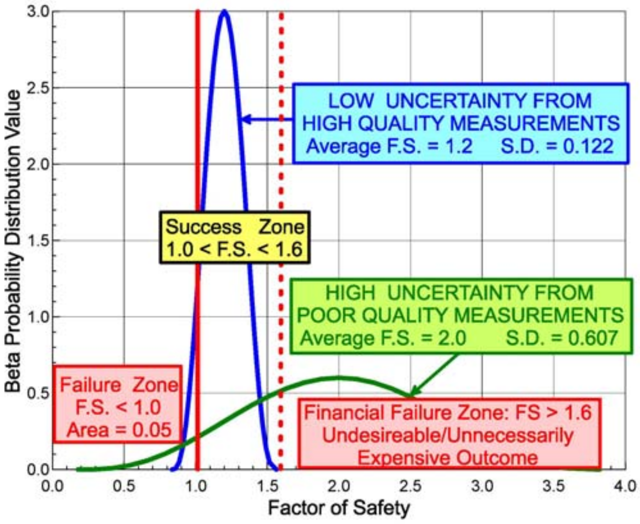

Figure 2: Quantifying risks for high and low uncertainty cases

3 TESTS USED TO MEASURE DEFORMATION MODULUS

Engineers use a variety of tests to measure the deformation moduli of soil. They often choose tests based on their experience and comfort with a particular test instead of which test most accurately measures the deformation moduli. The following sections discuss how well different test results correlate with the soil's deformation moduli.

3.1 *Standard penetration test (SPT)*

The driller dynamically drives a 2-inch (50-mm) diameter split barrel sampler into the soil and counts the counts the number of blows to penetrate the soil 1.0 foot (30 cm). Different hammer types deliver different energies to the sampler, but the engineer rarely calibrates or measures the energy. Essentially, the engineer precisely counts the number of blows, but does not know how hard the hammer hits the sampler. The engineer uses the blow count or N-value and a correlation factor to determine the soil's deformation modulus. Figure 3 shows the scatter when using SPT data to predict settlement in sand with N_{60} measurements (corrected N-values for 60% energy), considered the best case scenario for SPT. Duncan (2000), Failmezger (2001) show that the engineer needs an average settlement of 0.3 inches to be 95% certain that settlement will not exceed 1.0 inch due the prediction error of the SPT method.

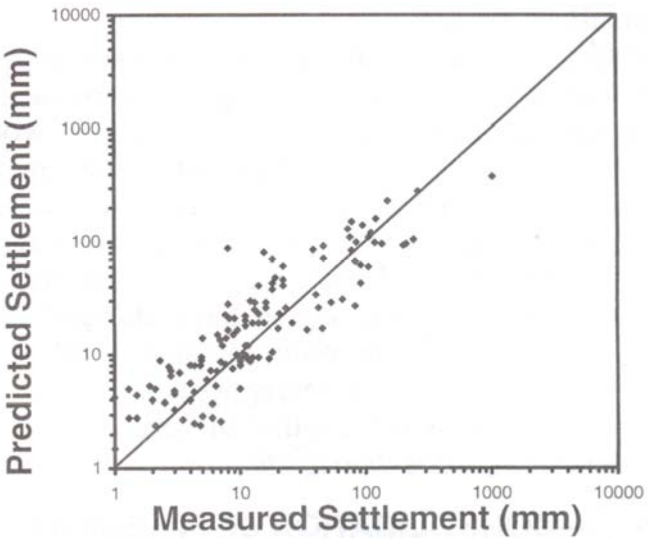

Figure 3: Settlement prediction using SPT data in sand with N_{60} values

The SPT correlation factors have wide scatter and thus lead to poor predictions of deformation modulus. Their scatter comes from 1) the energy not being measured, 2) dynamically penetrating the soil, 3) the soil being strained to failure, and 4) remolding of the soil. Measurements from dynamic tests do not correlate well with static soil properties. The deformation modulus should be determined at an intermediate strain level similar to what the structure will apply to the soil. Variability occurs when extrapolating from a high strain level to an intermediate level. In residual soil and sensitive cohesive soil, the dynamic SPT penetration destroys the soils' structure, usually resulting in low values. The automatic hammer delivers more than 60% of the theoretical potential energy (N_{60} values), resulting in lower uncorrected N-values, which make designs more conservative.

3.2 *Cone penetration test (CPT)*

The cone penetrometer quasi-statically pushes into the soil at a constant rate of 2 cm/second. Calibrated strain gauges accurately measure the pore pressure corrected tip resistance, q_T, and the computer records those values at depth intervals of 1 to 5 cm, depending on its acquisition system. CPT correlations to deformation modulus suffer from 1) straining the soil to failure and 2) remolding the soil. Because of the accurate tip resistance measurement, the engineer can make good modulus predictions if he knows what correlation value to use. While those values tend to be constant, they depend on both the site and geology. The CPT does not measure the stress history of the soil, which affects the correlation values. Figure 4 illustrates the wide range of correlation values in cohesionless soils due to stress history.

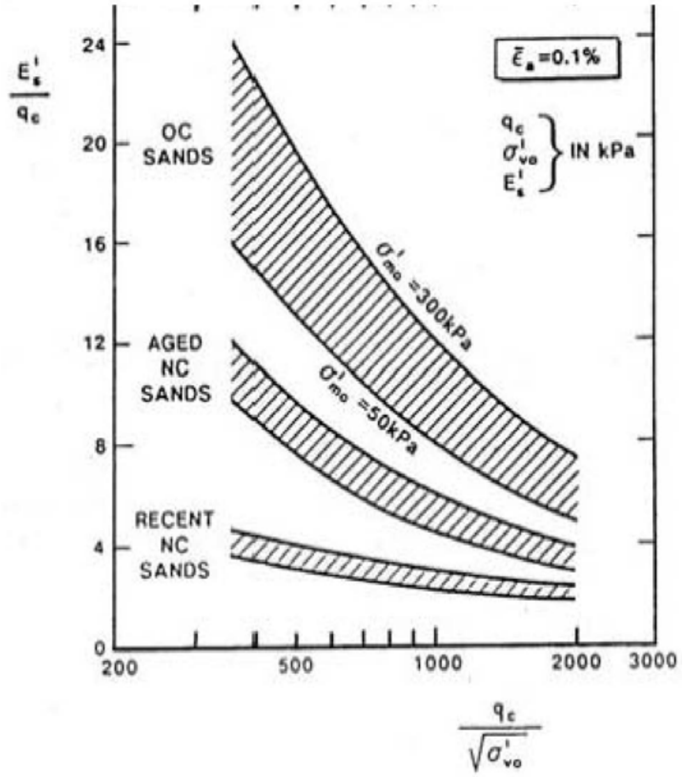

Figure 4: CPT Correlation coefficients for deformation moduli in cohesionless soil

3.3 *Laboratory consolidation test*

The consolidation test accurately measures the deformation modulus of the soil. This test requires a high quality undisturbed sample. A driller can use a piston sampler to collect high quality samples in cohesive soils. The sample needs to be transported from the field to the laboratory carefully to avoid disturbance. Unless costly soil freezing is done, undisturbed samples of cohesionless soil cannot be obtained. Unfortunately the cost per test is high and the engineer cannot perform enough tests to determine the variability of the soil's deformation modulus across the site. The results from cone penetrometer or dilatometer tests can aid in selecting the best locations to get samples for consolidation tests.

Consolidation tests can often confirm deformation moduli for other test methods. For the Skyway Sunshine Bridge in Tampa, Florida, Schmertmann (1986) showed through settlement measurements that consolidation tests significantly underpredicted the deformation modulus while the DMT predicted it more accurately. He states that consolidation tests suffered due to the difficulty collecting "undisturbed" samples in these highly over-consolidated clays. He also suggested that the dilatometer predictions would have been even better if they could have pushed the blade into the clays rather than drive it.

3.4 *Pressuremeter tests (PMT)*

The pressuremeter tests accurately measure the soil's deformation modulus in all types of soil and rock. In gravel and cobble formations, the engineer should use a pressuremeter inside a slotted steel casing. The accuracy of the tests depends on the quality of the sidewalls of the borehole. Highly experienced drillers make the best quality pressuremeter test holes drilling with mud rotary methods.

Pressuremeter tests must be performed at depth intervals of at least 1 meter, which can potentially miss thin soft zones of soil. The PMT takes about 1 to 4 hours to perform, which increase its cost. In France, experienced drillers use machines specifically for pressuremeter testing to perform tests efficiently.

3.5 *Dilatometer tests (DMT)*

Like the pressuremeter, the dilatometer test is a calibrated deformation test. For his Ph. D. research, Silvano Marchetti performed dilatometer tests at ten well-documented research sites, where the soil properties were known. He developed accurate correlations with soil properties, including the deformation modulus. These correlations have remained the same since his research in the late 1970s, which demonstrates how well he conducted his research. Schmertmann (1986) and Hayes (1986) predicted settlement at numerous sites and confirmed their predictions with measurements of the built structures, shown on Figure 5.

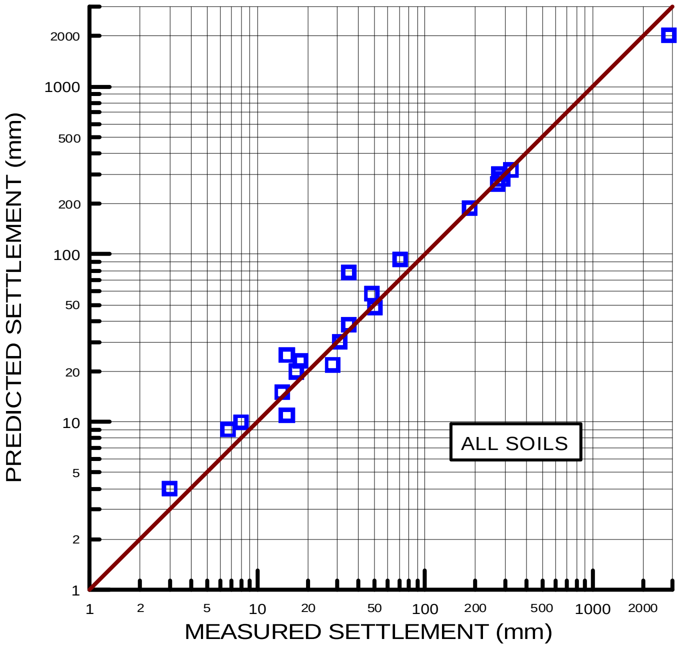

Figure 5: DMT predicted versus measured settlement

When the engineer performs dilatometer tests, he instantly notices how the test senses subtle changes in the soil properties. Because the engineer performs tests at close depth intervals (10 to 20 cm), he often observes trends in the processed data of the different soil properties, giving the engineer a good understanding of the behavior of the site's subsurface conditions. Having numerous high quality data gives the engineer confidence that he has found any critical soft layers that affect his design.

The dilatometer test provides accurate results in cohesive soil and sand. Gravel often creates point loads against the membrane and can give misleading results. Also gravel can tear the membrane, which stops testing of the sounding until the blade can be repaired.

The shape of the blade causes less soil disturbance than the conical shape of the CPT or SPT as illustrated on Figure 6. Because of less soil disturbance, the dilatometer results sense the stress history of the soil. As a result, the dilatometer test provides accurate results in residual soils that have latent rock structure and in sensitive cohesive soils.

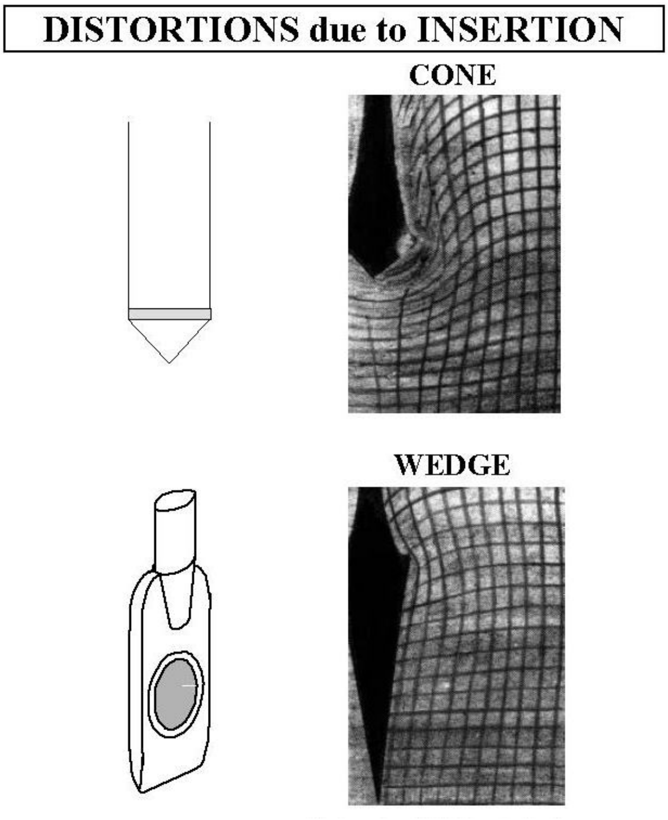

Figure 6: Less disturbance pushing the DMT blade than conical probe (CPT or SPT)

3.6 *Plate load tests/conical test load/settlement plates*

The engineer can prove his settlement prediction before the structure is built using plate load test, conical test load or settlement plates. These tests increase the engineer's knowledge and reduce uncertainty in his design and thus reduce the financial risk of the project. With these tests the engineer can fine tune his design.

4 CASE STUDIES

In the following sections we present several case studies that demonstrate the benefit of using dilatometer tests to correctly and accurately evaluate settlement of shallow spread footings. Earlier designs based on SPT and basic laboratory tests recommended overly conservative and costly foundation recommendations. Designs based on dilatometer tests saved the owner significant amount of money as shown on Table 1:

Project Name	Cost Savings Using DMT
MD Live!	$2,000,000
Towson Circle	$200,000
Retirement Community, Glen Mills, PA	Significant but unknown
Xfinity Live!	$500,000
Obery Court	$200,000
Residences at Rivermarsh	Significant but unknown
Residences at River Place	$80,000

Table 1: Summary of project cost savings from using DMT data instead of previous recommendations based on other less accurate data

4.1 *MD Live! – Hanover, MD (Casino/Parking)*

The casino site is located in what was previously a parking lot for the Arundel Mills Mall. The parking lot was constructed on what was known to be fill. Although there was no geotechnical report recommending deep foundations, the owner was aware of the fill and the possible need for piles. They were interested in looking into less costly alternatives, i.e. shallow foundations. A preliminary investigation consisting of 7 borings was conducted. The preliminary borings verified that fill was present, to depths ranging from approximately 8 to 29 feet (2.4 to 8.8 m). The borings indicated that the fill was likely placed in a controlled manner, however, isolated loose conditions were observed. Based on only the SPT data, shallow foundations designed for an allowable bearing pressure of only 2,000-4,000 psf (96-192 kPa) could be recommended. Since maximum column loads were on the order of 3,300 kips (13.3 MN), these allowable pressures would require unreasonably large and costly spread footings.

The final investigation consisted of 28 borings, 7 DMT soundings and 1 PMT sounding. The results of the DMT tests indicated settlement ranging from 0.47 to 0.81 inches (11.9 to 20.6 mm) for an applied bearing pressure of 10,250 psf (491 kPa). This eliminated the need for deep foundations, and allowed for the spread foundations to be designed for 10,000 psf (479 kPa). Due to the isolated loose conditions, dynamic compaction was utilized to improve the fill in selected areas. Figure 7 shows the completed structure.

Estimated cost savings of shallow foundations over piles was $2,000,000

Figure 7: Completed MD Live! Casino

4.2 *Towson Circle III – Towson, MD (Cinema/Parking)*

This project consists of a cinema over 3 levels of concrete parking garage, with maximum column loads on the order of 1,700 kips (7.6 MN). The first engineer performed an investigation that included 27 SPT borings. Due to fill and natural soils with low "N" values in some areas, they recommended that aggregate piers be used to improve the soils, and that the shallow foundations on the improved soils be designed for 4,000-6,000 psf (192-287 kPa). We performed additional borings as well as 7 DMT test sounding. Although we also recommended that the materials be improved with aggregate piers, the DMT results allowed us to recommend that the foundations be designed for an allowable bearing pressure of 10,000 psf (479 kPa), with 6,000 psf (287 kPa) in isolated locations. The higher bearing pressures allowed for a significant reduction in the footing size. Figure 8 shows the completed structure.

Estimated cost savings due to increased allowable bearing pressure was $200,000

Figure 8: Photo of completed Towson Circle III building

4.3 *Retirement Community in Glen Mills, PA (4-story, wood frame residential buildings)*

For the recent investigation, 11 SPT borings and 4 DMT soundings were performed (numerous borings and soundings have been performed for the buildings prior to 2006, which yielded conservative recommendations). The natural soils consist of loose to medium dense sandy silts. Based on only the SPT results, an allowable soil bearing pressure of about 2,500-3,000 psf (120-144 kPa) could be recommended. The DMT results indicate about 0.4 to 0.8 inches (10 to 20 mm) of settlement using 5,000 psf (239 kPa) bearing pressure. Therefore, we were able to recommend shallow footings proportioned for 5,000 psf (239 kPa), significantly reducing the size of the footings. Figure 9 shows the constrained deformation modulus versus depth for one of the soundings and the isolated softer zones.

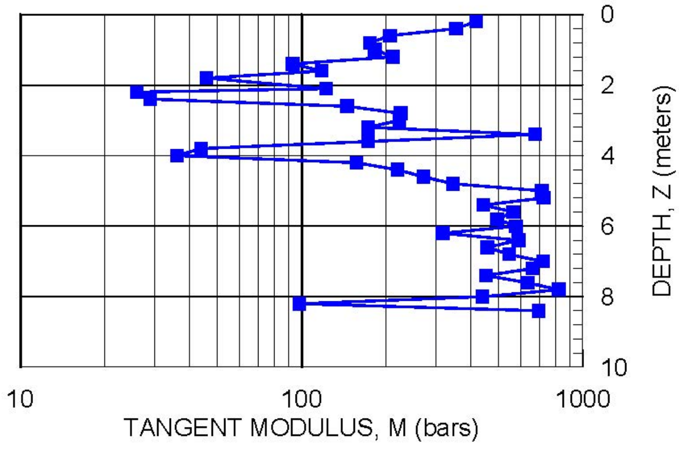

Figure 9: DMT M values versus depth for the Glen Mills site showing that the soft zones were quite limited

These buildings have not been built yet and the estimated savings is not known.

4.4 *Xfinity Live! – Philadelphia, PA (2-story Commercial Buildings)*

This project consists of 2-story commercial buildings adjacent to the Wells Fargo center, which is to be demolished and replaced by Xfinity Live! Casino. Old geotechnical reports for the Wells Fargo center indicated that the entire area contained uncontrolled fill with debris. Piles were generally considered to be needed for the project. Our investigation consisted of 10 SPT borings and 5 DMT soundings. The investigation confirmed the presence of up to 15 feet (4.6 m) of fill, very loose in some areas, over soft natural clay. The DMT results indicated settlement ranging from 0.72 to 4.6 inches (18 to 117 mm). However, the results showed that most of the settlement would be in the fill. Therefore, we were able to recommend improvement of the fill with dynamic compaction and an allowable bearing pressure of 3,000 psf (144 kPa) for shallow spread footings on the improved fill. Figure 10 shows this building.

Using of spread footings instead of piles saved the project $500,000.

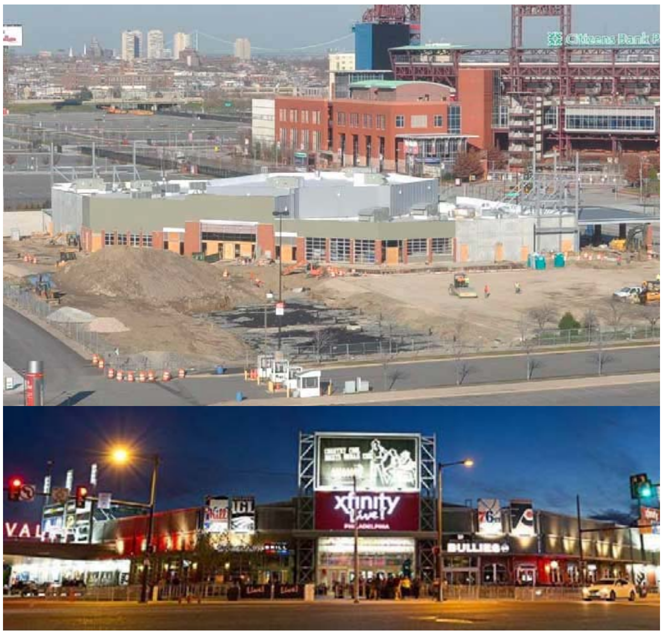

Figure 10: Photos of Xfinity Live!

4.5 *Obery Court Phase 1 - Annapolis, MD (Three Story wood Frame Townhouses)*

The initial investigation for this site included conventional standard penetration test borings. The site contains 30+ year old uncontrolled fill overlying soft clay-loose sand deposits. The first engineer recommended that the site be improved using vibrated aggregate piers extending through the fill and soft underlying soils and using a bearing pressure of 2,000 psf (96 kPa). DMT's were used to assess the compressibility of the underlying soils. The slab subgrade and footing excavations were compacted to insure the uniformity of the upper soils. The aggregate piers were eliminated and the buildings were supported on spread footings proportioned for an allowable soil pressure of 2,000 psf (96 kPa). The buildings have been in service for over five years. Figure 11 shows the constructed buildings for Obery Court.

Estimated cost savings for elimination of aggregate piers was $200,000.

Figure 11: Constructed Buildings for Obery Court

4.6 *Residences at Rivermarsh – Cambridge Maryland (Residential)*

This site was investigated using conventional standard penetration test borings and electric cone penetrometer tests. The site contains fill overlying interbedded, variably soft natural clay, and loose sand deposits. There was a wide variety of construction proposed including single family dwellings, townhomes, villas, and condominiums. In general the single family dwellings were proposed to be supported on spread footings proportioned for an allowable soil pressure of 1,500 psf (72 kPa). The townhouse and condominiums were proposed to be supported on timber piles with embedded lengths of 35 to 50 feet (10.7 to 15.2 m) and estimated capacities of 15 to 25 tons (133 to 222 kN). DMT's were conducted throughout the site. Based on the DMT results (estimated settlement of 0.25 to 1.0 inch (6 to 25 mm)), the footings for the single family dwellings were proportioned for an allowable soil pressure of 2,500 psf (120 kPa), instead of 1,500 psf (72 kPa), as previously recommended by others. It should be pointed out that loose near surface soils were compacted to reduce the settlement further. Only one condominium building and one townhouse group was constructed prior to the great recession. Both were supported on spread footings and proportioned for an allowable soil pressure of 2,500 psf (120 kPa) for the townhouses and 3,000 psf (144 kPa) for the four story condominium. The structures have been in service, satisfactorily since 2008.

The cost for the smaller footings and the eliminated piles was never determined.

4.7 *Residences at River Place – Seaford, Delaware (5 Level Apartment Buildings)*

This project consists of two, five level apartment buildings located on the Nanticoke River in Seaford, Delaware. The initial geotechnical investigation for this site included drilling standard penetration test borings. The conditions identified by the borings revealed a significant variation in soil conditions between the two building sites. The first engineer recommended that both buildings be supported with driven pile foundations. In order to more accurately access the soil conditions and better define the thickness and engineering properties of the underlying soft conditions identified with the borings, 10 DMT soundings (five for each building) were performed. Based on the DMT data, settlement estimates were conducted which provided justification to support one building with conventional spread footing foundations. Although the recommendations for the second building remain as driven timber piles, the DMT soundings provided data to better define the installation requirements for the driven pile system. Figures 13 and 14 show the constrained modulus values for buildings 1 and 2, respectively.

Estimated cost savings for elimination of driven piles under Building 1 was $80,000.

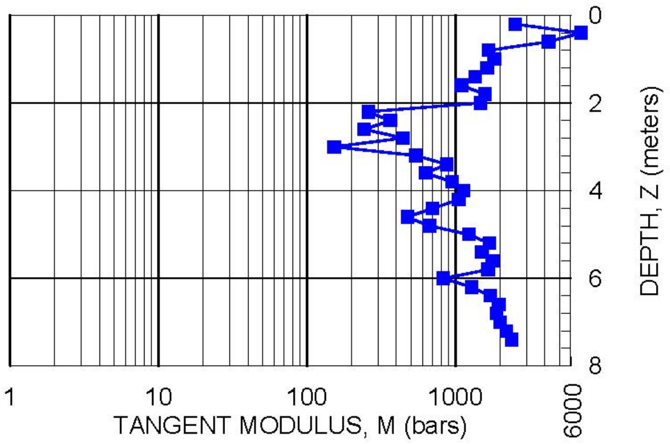

Figure 13: Constrained deformation modulus versus depth for a DMT sounding for Building 1

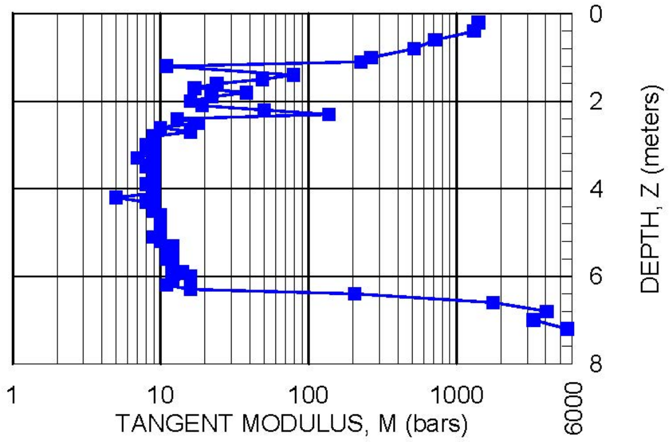

Figure 14: Constrained deformation modulus versus depth for a DMT sounding for Building 2

5 CONCLUSIONS

- We present seven case studies where the results from the additional dilatometer test investigations saved the owners significant amounts of money.
- Too often, geotechnical engineers recommend costly foundation solutions because they do not accurately define the subsurface deformation properties of the site. By performing dilatometer tests at 10 to 20 cm depth intervals, the engineer can quantify the thicknesses and deformation moduli of any soft layers and accurately predict settlement for shallow footings. Often cost effective shallow spread footings instead of the expensive alternative foundation recommendation can safely support the proposed structures.
- Geotechnical engineers have the duty to the owner to prove that cost effective shallow spread footing will not safely support the building loads before recommending more costly foundation solutions. DMT soundings enable the geotechnical engineer to prove the best solution.

6 REFERENCES

Baldi G., Bellotti R., Ghionna V., Jamiolkowski M., 1988, “Stiffness of sands from CPT, SPT and DMT—A critical review” ICE Proc. Conf. Penetration Testing in the UK, Univ. of Birmingham, July, Paper No. 42, pp. 299-305

Baligh M.M., Scott R.F., 1975, “Quasi-Static Deep Penetration in Clay”, ASCE Journal of Geotechnical Engineering, Vol. 101, No. GT11, 1119-1133.

Burland, J. B. and Burbridge, M. C., 1985, “Settlement of Foundations on Sand and Gravel”, Proc., Inst. of Civ. Engrs, Part 1, 78, 1325-1381.

Duncan, J. Michael, April 2000, “Factors of Safety and Reliability in Geotechnical Engineering”, ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol 126, No. 4, pp. 307-316.

Failmezger, Roger A., 2001, Discussion of “Factors of Safety and Reliability in Geotechnical Engineering.

Failmezger, Roger A., Bullock, Paul J., 2004, “Individual foundation design for column loads”, International Site Characterization ’02, Porto, Portugal

Failmezger, Roger A., Till, Paul, 2006, “DMT testing for redesign using shallow foundations”, Second International Conference of the Flat Plate Dilatometer, Washington, D.C.

Hayes, J.A., August 1986, “Comparison of flat dilatometer in-situ test results with observed settlement of structures and earthwork”, Proceedings 39th Geotechnical Conference, Ottawa, Ontario, Canada.

Marchetti, S., March 1980, “In situ tests by flat dilatometer, Journal of the Geotechnical Engineering Division, ASCE, Vol. 106, No. GT3, pages 299-321.

Mayne, P.W. (2001). Keynote: “Stress-Strain-Strength-Flow Parameters from Enhanced In-Situ Tests”, Proceedings, International Conference on In-Situ Measurement of Soil Properties & Case Histories (In-Situ 2001), Bali, Indonesia, 27-47.

Schmertman, 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, J. H., June 1986, “Dilatometer to compute foundation settlement”, Proceedings, ASCE Specialty Conference, In-Situ ’86, VPI, Blacksburg, Virginia, pages 303-321.

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