Settlement analyses from dilatometer test data justify supporting parking garage on spread footings

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Keywords: Settlement, dilatometer, parking garage

ABSTRACT: For heavily loaded structures, the cost of the foundation system can be quite large. Therefore, owners seek the most economical foundation that will safely support the structure's loads. Because the dilatometer is a calibrated static deformation test, data from these tests will accurately predict the amount of settlement that is likely to occur. Its accuracy enables the engineer to use probability design charts to explain the probability of success in simplistic terms to the owner and contractor. Consequently, they can make informed decisions regarding risk as demonstrated in this case study.

1 INTRODUCTION

A 6-level, precast concrete, parking garage was planned overlying approximately 35 to 50 feet (10 to 15 m) of residual soils further underlain by weathered metamorphic bedrock. A preliminary foundation design study based on six (6) soil test borings recommended the parking structure be founded on drilled piers (caissons) bearing on the weathered rock or on shallow spread foundations using a reduced soil bearing pressure to control settlement. Prior to construction, the design/build contractor retained Whitlock Dalrymple Poston & Associates, Inc. (WDP) and In-Situ Soil Testing, LC to re-evaluate the foundation design alternates and settlement potential; consequently, six (6) dilatometer test (DMT) soundings were performed. Settlement analyses were performed for varying column loads (850 to 2000 kips [3780 to 8900 kN]) using the closest DMT sounding. Probability analyses were done to evaluate the risk of settlement exceeding the owner's desired maximum value of 1 inch [25 mm] total settlement and 0.5 inch [12.5 mm] differential settlement criteria. The owner and contractor accepted the calculated risk and the parking garage was supported on shallow spread footings using allowable soil bearing pressures of 6,000 psf and 8,000 psf [287 to 383 kPa]. This foundation redesign saved the project about $200,000 to $300,000.

2 PREVIOUS GEOTECHNICAL INVESTIGATION

The parking garage is about 200 feet by 400 feet [61 by 122 m] in plan view. Six soil test borings were performed to depths of 50 to 60 feet [15 to 18 m] at the corners and the middle of the long sides. Geologically, the site contained residual soils overlying decomposed metamorphic rock of the Sykesville Formation. Limited laboratory tests performed on random soil samples indicated the residual soils contain approximately 52 to 81% silt/clay fraction and 19 to 48% sand. The liquid limits were less than 45, and the plasticity index was less than 7.

The results from the soil test borings are summarized in the Table 1. A Central Mine Equipment (CME) automatic standard penetration test hammer was used to drive the split spoon sampler. Notably, the correction of the raw N-values to N_{60}-values (Skempton, 1986) is quite significant due to the high efficiency of the automatic hammer (Schmertmann, 1984). Additionally, the split spoon barrel that was used could accommodate liners, but liners were not used. This correction increased the N_{60}-values by 20%. Robertson (2004) shows that the resistance of the soil for N-values exceeding 50 blows per foot is no longer linear. In soils with an N-value of 100 their CPT tip resistance was only 10 to 20% higher than the tip resistance for soils with an N-value of 50.

Soil Test Boring Number	Nearest Dilatometer Sounding	Elevation	Uncorrected N-value	N_{60}-value
B-1	D-5	380-361 Below 361	21 - 41 > 50	34 - 78 > 50
B-2	D-4	380 - 354 Below 354	7 - 12 21 - 28	11 - 22 40 - 53
B-3	D-1	380 - 350 350- 335 Below 335	7 - 15 27- 62 > 50	11 - 26 > 50 > 50
B-4	D-6	380 - 349 Below 349	22 - 42 > 50	41 - 80 > 50
B-5	D-3	380 - 370 370- 355 Below 355	20 - 31 32 - 61 > 50	32 - 44 > 50 > 50
B-6	D-2	380 - 366 366 - 348 Below 348	6 - 26 24 - 52 > 50	9 - 37 41 - 93 > 50

Table 1: Summary of SPT N-values at site

Based on the SPT N-value results, the initial geotechnical engineer preliminarily recommended using an allowable bearing pressure of 3 to 4 ksf [144 to 192 kPa] for footings near Borings B-2 and B-3 and 6 to 8 ksf [288 to 384 kPa] elsewhere. Alternatively, drilled piers into the weathered rock were recommended.

3 DILATOMETER RESULTS

Six (6) dilatometer test soundings were performed near the soil borings shown on Table 1 but about 30 feet [9 m] closer to the center of the parking garage. Tests were performed at 20-cm depth intervals until penetration refusal occurred, which ranged from 7.8 to 14.8 m. The results of the tests are plotted on Figures 1 to 3.

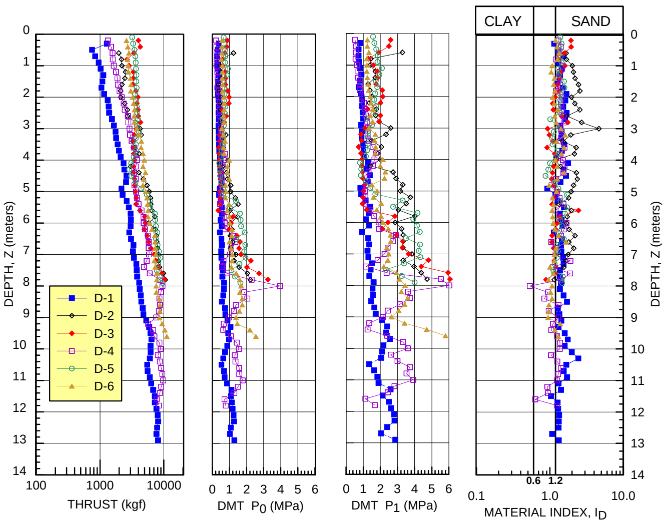

Figure 1: Summary of dilatometer results for soundings D-1 to D-6

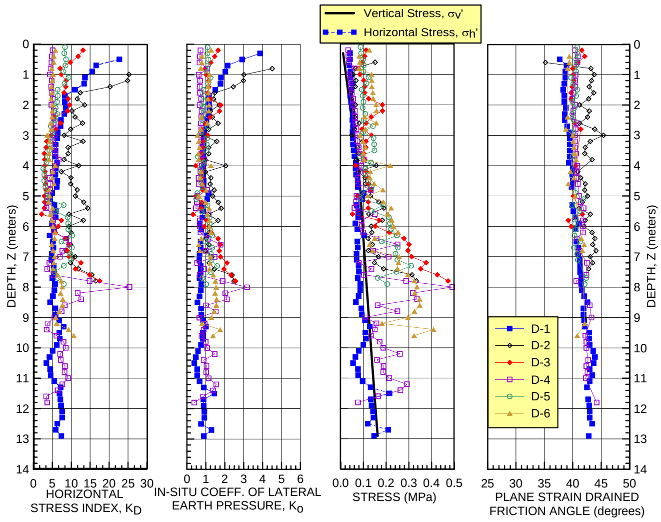

Figure 2: Summary of dilatometer lateral stress and strength parameters for soundings D-1 to D-6

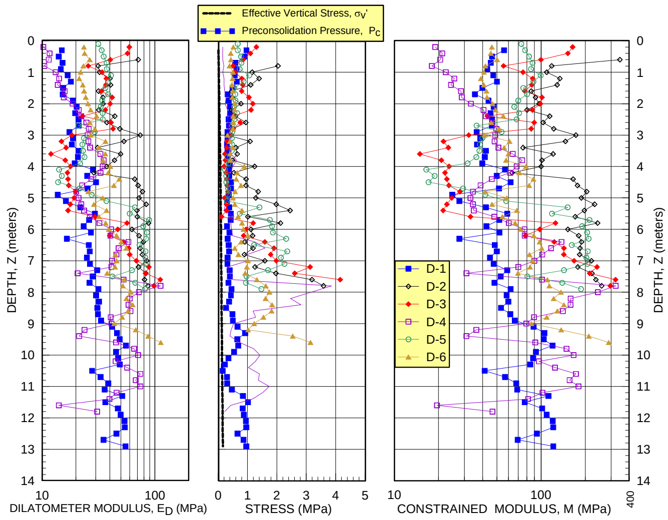

Figure 3: Summary of dilatometer modulus parameters for soundings D-1 to D-6

As indicated by the dilatometer test results, the residual soils are overconsolidated to highly overconsolidated. Their strengths and stiffness generally improve with depth as the chemical weathering decreases. The dilatometer soil classification (I_D) correlates well with the laboratory test results.

4 SETTLEMENT ANALYSES

The structural engineer provided the various loads for each column. We overlaid six zones that corresponded to our six dilatometer test sounding locations on the structural plan sheet. We performed settlement analyses using Schmertmann's (1986) ordinary and special methods. The ordinary method is simply the stress increase multiplied by the layer thickness divided by the constrained deformation modulus. The special method considers the preconsolidation pressure and uses the recompression modulus for stress less than the preconsolidation pressure and the virgin modulus for stress above the preconsolidation pressure. However, if the stress increase is less than the preconsolidation pressure, the special method does not adjust the constrained modulus from the dilatometer correlations and uses the same modulus as the ordinary method. Because the residual soils were, in general, overconsolidated, there was little difference in the settlement predictions between the ordinary and special methods. We initially sized the footings based on an applied soil bearing pressure of 10 ksf [479 kPa]. However, the resulting settlements exceeded the strict tolerable total settlement criterion of 1 inch [25 mm] that was established for the parking garage by the owner. We recomputed the settlement for footings sized based on an applied bearing pressure of 8 ksf [383 kPa]. For the footings near Sounding D-1, an applied bearing pressure of 6 ksf [287 kPa] was used for design to keep the settlements within acceptable tolerance. The results of our analyses are presented in Table 2.

Column Load (kips/kN)	Footing Width (ft/m)	Applied Bearing Pressure (ksf/kPa)	Sounding	Predicted Settlement (inch/mm)
850/3780	10.5/3.2	7.71/369	D-5	0.24/6.1
850/3781	10.5/3.2	7.71/369	D-6	0.37/9.4
1000/4448	13/4	5.92/283	D-1	0.70/17.8
1000/4448	11/3.4	8.26/396	D-2	0.33/8.4
1400/6227	15/4.6	6.22/298	D-1	0.84/21.3
1400/6227	13/4	8.28/397	D-2	0.38/9.7
1400/6227	13/4	8.28/397	D-3	0.57/14.5
1400/6227	13/4	8.28/397	D-4	0.82/20.8
1400/6227	13/4	8.28/397	D-5	0.40/10.2
1400/6227	13/4	8.28/397	D-6	0.51.13.0
1500/6672	16/4.9	5.86/281	D-1	0.84/21.3
1500/6672	13.5/4.1	8.23/394	D-2	0.38/9.7
1500/6672	13.5/4.1	8.23/395	D-5	0.42/10.7
1500/6672	13.5/4.1	8.23/396	D-6	0.53/13.5
2000/8896	18/5.5	6.17/296	D-1	0.98/24.9
2000/8896	16/4.9	7.81/374	D-2	0.41/10.4
2000/8896	16/4.9	7.81/375	D-3	0.72/18.3
2000/8896	16/4.9	7.81/376	D-4	0.89/22.6
2000/8896	16/4.9	7.81/377	D-5	0.50/12.7
2000/8896	16/4.9	7.81/378	D-6	0.57/14.5

Table 2: Summary of settlement analyses used for design

5 PROBABILITY ANALYSES

Failmezger et al. (2004) discovered that the average value of settlement and its standard deviation have linear relationships with risk provided that the probability distribution curve is bell-shaped. The average value of settlement can be easily computed from the values in Table 2. The computed standard deviation from the values in Table 2 represents the standard deviation due the subsurface heterogeneity (spatial standard deviation). There is also some uncertainty as to how well Schmertmann's method predicts settlement based on dilatometer test data. Based on Schmertmann's and Hayes' case study data bases, the coefficient of variation, which equals the standard deviation divided by the average, is 0.18 (Failmezger and Bullock, 2004). This value is low, demonstrating the accuracy of the design method. There may be other sources of uncertainty that contribute to the overall standard deviation. In our case, we considered that there was a lack of dilatometer soundings in the analyses as an additional source of uncertainty. If the contributory sources of uncertainty are considered to be independent of each other, then the overall standard deviation is the square root of the sum of each standard deviation squared. In Table 3, we show the computations for the average and overall standard deviations.

		(inch)	(mm)
Average Settlement		0.57	14.48
Spatial Standard Deviation		0.22	5.48
Method Coefficient of Variation =	0.18	(Failmezger, 2004)	
Method Standard Deviation		0.10	2.61
Intangible Coefficient of Variation =	0.20	(Lack of Soundings)	
Intangible Standard Deviation		0.11	2.90
Overall Standard Deviation		0.26	6.72

Table 3: Summary of average and overall standard deviation computations

After determining the average and overall standard deviation, one simply plots those x-y values (standard deviation = 6.72, average settlement = 14.48 mm) on the settlement design summary figure as shown below.

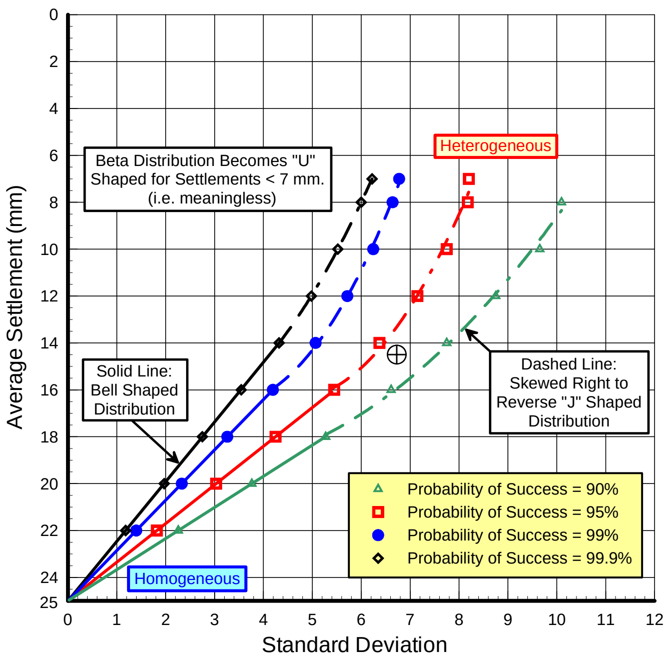

Figure 4: Probability settlement design summary chart showing probability of success for the foundation design for this site

As one can readily observe from Figure 4, the probability of success for this design was 93%. The owner and design/build contractor agreed that this foundation design sufficiently addressed their concerns, tolerable settlement criteria, and was subsequently approved for construction.

6 CONCLUSIONS

1. Settlement analyses based on dilatometer test data can be used to accurately size spread footings for structures.
2. Schmertmann's dilatometer design method is accurate enough to enable the engineer to assess risk using probability analyses.
3. The probability analyses and design chart enabled the owner and design/build contractor to understand the project risk and make an informed decision regarding the foundation design.

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