Dilatometer Use in Geotechnical Investigations

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ABSTRACT: The authors describe their considerations in determining when to use the dilatometer in their geotechnical investigations, either in combination with Standard Penetration Test (SPT) borings or without the former, and the results when they are used. Most of their studies are in the Chesapeake Bay area where Coastal Plain soils predominate the profile. Many of the soils are soft/medium stiff Clays (CL) or loose/medium dense Sands (SC-SM) with "N" values from below 10 to the low teens. In cases where the proposed building will have high loads, such as multi-story structures, limiting settlement to acceptable amounts based on current methods using SPT results usually requires use of a relatively low bearing capacity. Use of dilatometer results at the same site has allowed use of significantly higher bearing capacities. Several considerations need to be made, however, in determining when the added cost of the dilatometer is justified. These include the need to make SPT borings, in addition to dilatometer probes, so that soil samples can be obtained for accurate soil classification and other uses. This can double the field costs for a specific study. Another is the expected economic benefit of using a higher bearing capacity when the building loads are relatively low. Specific studies are described and detailed, including one where preloading and settlement monitoring were recommended.

1 WHEN DO WE USE THE DILATOMETER?

Our first use of the dilatometer was in the year 1999 when we were asked to investigate a site for a proposed multi-building self-storage business. The property had previously been used for mining Sand and Gravel which included use of sediment ponds to collect spoil from screening operations. The ponds and overall site were subsequently filled and rough graded to the relatively level condition that existed when we began our study. We were told that none of the backfill was compacted and that the sediment in the ponds was not removed prior to the backfilling. The proposed new grades were generally the same as the existing and the ideal foundation system would be conventional spread footings and slab-on-grade construction supported on the old backfill. We were somewhat familiar with the dilatometer and decided that the existing site conditions could best be evaluated by its use. We performed our study and concluded that conventional foundations could be used. The project was subsequently built and put into use and there have been no known foundation problems since completion several years ago.

Since that study, we have used the dilatometer on over a dozen other projects. Some of these studies are discussed in following sections of this paper. On most studies, we make SPT borings at the usual locations and to the usual depths. If those results indicate potentially excessive settlement, based on the "N" values and visual classification, and the probable recommendation of a low bearing capacity (usually less than 2000 psf) and if the proposed structure is relatively heavy (loads of over about 200 kips), we will contact the Structural Engineer or other affected person and inform them of our preliminary conclusions. At that time, we recommend the addition of dilatometer probes to more accurately evaluate the profile. Most of our dilatometer investigations fall in this category. On some studies, we may have knowledge of the general subsurface conditions at a specific site before we make borings. If we expect that excessive settlement may be a consideration in the study, we may recommend dilatometer probes as part of the initial investigation. A few of our investigations have also been in this category. One of our projects involved apartment building sites where the results of a geotechnical investigation by another firm several years earlier indicated the use of piles. That study included settlement analyses using laboratory consolidation test results on undisturbed samples. Based on our review of the previous borings, we recommended dilatometer probes at the site and subsequently determined that conventional spread footings could be used after a short period of preloading. A few of the buildings have since been constructed and occupied and there have not been any known foundation problems.

2 FIELD INVESTIGATION PROCEDURES & CONSIDERATIONS

Our soil borings are usually made with a drill rig using hollow stem augers. Split spoon samples are typically obtained at 2.5 to 5-foot intervals of depth by the Standard Penetration Test (SPT) Procedure. A representative portion of each sample is sealed in a glass jar and subsequently inspected and visually classified by our geotechnical staff. The dilatometer soundings are made by hydraulically pushing a dilatometer probe into the ground and recording miscellaneous geotechnical parameters at incremental depths below the surface, usually about 8-inch increments. This provides us with a very complete profile for settlement analysis purposes as compared to other existing methods (SPT borings with a few undisturbed samples and laboratory consolidation tests). We note here that our analysis using SPT data must consider the effects on the "N" values during the sampling process due to liquefaction in Sands and remolding in Clays. These conditions do not develop during the insertion process with the dilatometer. A disadvantage to the dilatometer, however, is that soil samples are not obtained and soil classification is limited accordingly. We also note that dense/hard soils can cause refusal to the penetration of the dilatometer which can be a problem in cases where these conditions are within foundation depth influence and may only be thin layers.

3 DESIGN CONSIDERATIONS

In selecting a foundation bearing capacity magnitude, we consider both the shear strength and compressibility parameters of the soils below the foundation level. The former is related to the shear failure of the subgrade soils under the foundation and the latter to the magnitude of settlement of the foundation both in terms of total amount and relative to adjacent foundations, referred to herein as differential settlement. Based on the subsurface conditions at all sites referenced in this paper, settlement is the governing consideration. Concerning magnitude of settlement, we generally limit the total predicated amount to 1-inch or less. Differential settlements are usually chosen to limit angular distortion to a ratio of about 1/500 or less, or about 0.5-inch over a distance of 20 feet. We usually note in our reports, when applicable, that our computations consider reduction of overburden pressure resulting from excavations to a lower design level and reduction of the applied footing pressure with depth below footing (pressure distribution). We further note that the dilatometer measures the compressibility at depth increments of about 8 inches for the entire depth penetrated and our computations are based on all of those measurements.

4 COMPLETED PROJECT SUMMARIES

Following are descriptions of projects where the dilatometer was used and the results of those studies. It is noted that these descriptions are based on the conditions at the time our investigation was performed. The first project (4.1) was under construction and almost completed at the time this paper was written. The last (4.4) has not been constructed. The other projects are still in design stage.

4.1 *Office Building – Annapolis, Maryland*

This building will have a footprint of about 30,000 sq.ft. and will be five stories above ground and one level below ground when completed. The west portion of the building will be a parking garage and retail space and a restaurant area are planned for the ground floor level of the other portion of the structure. The project site is generally open except for a few trees and bushes. Existing ground surface levels vary from about El 47' to El 42'. The proposed lower level slab grade is El 35.5' and first floor level is El 46'. The garage levels are generally the same. Based on these grades, the entire site will be excavated to a level about 9 to 14 feet below the existing grade. Lateral bracing, possibly solder beams and lagging, will be used to retain the earth outside the excavated area. The proposed column layout for the entire structure was provided. Typical column loads as shown on that plan are summarized below.

Column Load Range

Interior	Exterior
623 kips (max.)	345 kips (max.)
342 kips (min.)	180 kips (min.)

To determine the subsurface conditions, we made eleven soil test borings and four dilatometer soundings. The soil borings extended to depths of between 22 and 40 feet below the existing ground surface and the dilatometer soundings extended to depths of about 40 feet.

The soils at the site are Coastal Plain deposits identified as the Aquia Formation by the Maryland

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Geological Survey. They are fine to medium grained Sands that vary from Clayey to Silty (SC-SM) in classification. The condition of the soils in the profile as measured by the Standard Penetration Test (SPT) Procedure was found to be variable. Generally below about El 15' to El 20', the soils were found to be medium dense to dense. The "N" values were generally over 20 below this level indicating relatively low compressibility. Above these soils the "N" values were generally between 5 and 15 with many below 10 indicating loose conditions and generally higher compressibility than the deeper soils. The results of the dilatometer probes generally confirm the profile condition as described above. The groundwater table ranged from about El 22' to El 25' at the time the borings were made (February-March 2002) or about 10 to 13 feet below proposed lower level building slab.

To determine the range of expected settlements under the foundation loadings for this project, we computed settlements using the range of column loads furnished by the Structural Engineer, several assumed bearing capacities and the compressibility parameters at each of the four dilatometer locations. We note here that the results of the dilatometer readings revealed that the "best" conditions relative to settlement exist at the location of D-2 and the "worst" at D-8. They also revealed that the most compressible zone exists generally in the depth range of about El 35' to El 20'. Based on our review of the furnished column loads and our computed settlements, an allowable net bearing capacity of 4000 psf was recommended for preliminary design and cost estimate purposes. The following settlements were predicted using 4.0 ksf bearing.

Column Load	Footing Size	D-2	D-8
623^k (Int.)	12.5' x 12.5'	0.36"	0.64"
342^k (Int.)	9.5' x 9.5'	0.27"	0.51"
345^k (Ext.)	9.5' x 9.5'	0.52"	0.82"
180^k (Ext.)	7' x 7'	0.42"	0.70"

The computed settlement for a column footing is about 0.8-inch and the minimum about 0.3-inch. These numbers are considered within an acceptable range based on the criteria cited above.

We noted in our report that once final column loads and locations are known, an evaluation of each individual pier foundation must be performed to verify that detrimental settlement or differential settlement will not occur. We noted that the bearing capacity of some column footings could probably be increased to 5000 psf and still maintain settlements within acceptable limits.

4.2 *Office Building – Anne Arundel County, Maryland*

This structure will be constructed in an existing building complex on the highest level of a landform that slopes down in all directions from that area. The highest ground surface is at about El 130'; most of the existing complex is at or above El 120'. Most of the land beyond the complex is undisturbed woodlands that slope down to existing roads, a ravine and wetlands. Ground surface levels along one road range from about El 75' to El 100' and along the other from about El 15' to El 20'.

The proposed building will consist of two 11-story towers located at the southwest and southeast corners of a rectangular lower structure consisting of a two to three-level parking garage under a plaza level. The "footprint" of the lowest level garage will be about 720 feet by 168 feet and it will have a slab level at about El 100'. It will be situated generally in the area of the existing office building and immediately north of the main parking lot east of that building. The next level garage above will cover the first level garage and extend south an additional 124 feet where it will be situated under the two towers. This area includes an existing swale south of the existing office building and the existing parking lot. This garage level is proposed at El 110' and will be the lowest level under the two towers and lower structure between. Existing ground surface levels within the proposed lower level garage vary from about El 100' in a small area near the northeast corner to most above El 110' and up to about El 132'. Most of the ground surface levels within the remaining building area range from about El 110' to El 132'. Final grades around the exterior of the structure will generally be the same as existing. Based on information provided by the Structural Engineer, maximum loads for a typical Plaza column will be about 800 kips and for typical interior and exterior Tower columns about 2500 and 2100 kips, respectively.

A total of eight SPT borings were made to depths of 70 to 100 feet below the existing ground surface and nine dilatometer soundings were made to depths of about 66 to 90 feet. The soils at this site are also Coastal Plain deposits identified as the Aquia Formation. The profile is predominated with interbedded layers of Sands that vary in classification from Silty (SM) to Clayey (SC). Isolated layers of Sandy and Silty Clays (CL) and Sandy and Clayey Silts (ML-CL) also exist randomly in the upper profile and pockets and layers of ironstone were also encountered at various locations and depths. Fill and possible fill [Fill?], defined herein as soil that had some visual evidence it might be fill but no positive indicator, were encountered at a few locations to depths of up to as much as about 12 feet. Based on the "N" values the soils were found to be generally loose to medium dense in the upper profile and

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dense at the deeper levels. At most boring locations, they were slightly below 10 to the teens to depths of between about El 100' and El 105' and averaged values of over 40 at most locations below those levels. The denser level was below about El 90' at Borings B-2 and B-102 and El 108' at Boring B-13. Groundwater was not encountered in any boring made at this site.

To determine the range of expected settlements under the foundation loadings for this project, we computed settlements using the range of column loads furnished by the Structural Engineer, assumed bearing capacities that ranged from 6,000 to 10,000 psf, and the compressibility parameters at the dilatometer locations.

It was concluded from this investigation that conventional spread footings located in the dense Sands could be used to support the proposed building. Analysis of the compressibility of the profile as determined by the dilatometer data indicates that settlement of spread footings designed for an allowable net bearing capacity of 8000 psf should be within tolerable limits for the proposed structure based on the proposed grades as described above. It was noted that the dense Sands exist below depths that range from about El 90' to El 110' depending on site location that will require relatively deep foundation excavations in some areas.

4.3 *School Building – St. Mary's County, Maryland*

This project site is mostly open and rolling in topography with ground surface levels ranging from about El 34' to El 24'. Surface drainage is generally to the west and southwest. Lower wetlands areas border the site on the north, south and east sides. The proposed building will be situated near the center of the property and will have a first floor level at El 38'. It is understood that the building will be one to two-story without a basement and that the subsurface conditions must be suitable for use of spread footing foundations designed for an allowable net bearing capacity of 2500 psf. Paved parking areas will be located north and west of the building and a new road is proposed west of both parking areas. Based on the proposed and existing grades, fill ranging in thickness from a few feet along the east side of the site to about 12 feet under portions of the building will be required to establish new site grades.

Based on the SPT borings, the subsurface profile was found to be quite variable. Two basic soil types exist, deposits of Sands and lesser deposits of fine-grained Silts and Clays that generally occur as layers within the more predominant Sands. The Sands range in classification from Silty (SM) and Clayey (SC) to Sands with Silt (SP-SM). They vary from very loose to medium dense in condition with "N" values ranging from many below 10 to a few over 20. Most were in the range of 5 to the low teens. The Silts and Clays generally classify as Sandy Clayey Silts (ML) to Silty and Sandy Clays (CL). These deposits exist randomly within the profile and generally vary from soft to stiff in consistency. Soil colors generally range from brown to gray and light gray in the higher levels to gray and dark gray at the deeper elevations. The water table was at a depth range of about 3 to 8 feet below existing grade at the time the borings were made which was in the month of January, a relatively "wet" time of year.

To determine the range of expected settlements under conditions assumed to be similar to final design conditions, reference is made to the following table.

Settlement (inches) Due to Given Loading Condition

Structural Fill to El 38'	Structural Fill & Pier Footing (1)	Structural Fill & Continuous Footing (2)	Preload to El 49' & Structural Fill
0.82	0.97	0.97	1.95+
0.44	0.47	0.48	0.85+
0.23	0.27	0.27	0.49+
0.71	0.73	0.75	1.26+
1.94 (3)	2.04 (3)	2.09 (3)	4.07+ (3)

(1) Assume 150 kip max pier load – Footing dimensions 8 ft. x 8 ft. (2500 psf design soil bearing capacity).

(2) Assume 5 kip/LF max continuous wall load – Footing dimensions 2 ft. wide (2500 psf design soil bearing capacity).

(3) Mud and soft clay layer encountered at 19.5 ft. to 21.5 ft.

We note here that our computations consider pressure increase due to filling the site to achieve final grade (El 38') and reduction of the applied footing pressure with depth below the footing (pressure distribution). As can be seen from these results, the computed total settlement is less than 1 inch at all dilatometer locations except one where it was 2.04 to 2.09 inches. The excessive settlement at this location is believed to be due to the presence of a very soft Clay layer at about 20-foot depth. The magnitude of settlement at all other locations is considered acceptable based on the criteria stated above, however, the settlement at the one is considered exces-

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sive. For that reason and assuming that other similar areas may exist within the limits of the site, it is concluded that the site should be preloaded to insure any excessive settlement occurs before building construction.

Concerning consolidation time-rate parameters, the table below summarizes the data obtained from this study.

Test Depth	Coefficient of Consolidation (1)	Time for Settlement to Occur (2)
26.2’	$C_h = 6.1$ ft.^{2}/day	31.3 days (3)
29.5’	$C_h = 6.1$ ft.^{2}/day	
32.8’	$C_h = 7.2$ ft.^{2}/day	
32.2’	$C_h = 5.5$ ft.^{2}/day	65.6 days (3)
10.5’	$C_h = 1.8$ ft.^{2}/day	5 days (4)
7.2’	$C_h = 1.2$ ft.^{2}/day	56.9 days (3)
23.6’	$C_h = 8.5$ ft.^{2}/day	
5.2’	$C_h = 12.7$ ft.^{2}/day	0.7 days (4)

NOTES:

1) Computed coefficient of consolidation (square feet/day) based on A-Reading vs. Square Root of Time plot.

2) For general discussion purposes, the computed time is based on dividing the square of the thickness of the compressible layer by the coefficient of consolidation.

3) General profile has deeper Silts & Clays.

4) General profile has shallow Sands.

It was concluded that conventional spread footings could be used to support the proposed building based on preloading the site as recommended. The analysis of the compressibility of the existing profile as determined by the dilatometer data and borings indicated that excessive differential settlement may occur in some areas of the site due to the combined loading of the proposed fill required to establish final grades and additional building loads. However, special site preparation to include placement of a shallow drainage system prior to filling the site and temporary placement of an additional preload fill to El 49’ should cause that magnitude of settlement to occur over a computed time period of about 90 days. The preload fill could then be removed and construction of the building proceed. Future building settlements should be minimal. It was recommended that settlement plates be installed prior to fill placement to monitor ground movement and confirm when the preload could be removed.

4.4 *Office Building – Prince Frederick County, Maryland*

The site contains an office building that will be demolished and replace with a new two-story building with a “walk-out” basement in the rear. Development of the project will require only minimal cuts and fills.

The generalized subsurface profile in the building area consists of a surface deposit of fill over deposits of natural Silty and Clayey Sand (SM-SC) and a deeper layer of Sandy Silt (ML). The fill generally classifies as Clayey fine to medium Sand (SC) and was found to be about 2.5 feet thick. Based on an “N” value of 4, the fill is very loose indicating it probably was not compacted when placed. The deeper natural deposits were found to be loose to medium dense with “N” values of 8 to 11.

It was initially recommended that all foundations exposed to outside temperatures be located at least 2.5 feet below final exterior grade for frost protection and that foundations not exposed to outside temperatures could be located as shallow as 1 foot below final grade. Foundations located at these depths and bearing either on approved natural soils or compacted fill could be designed for an allowable net bearing capacity of 1500 psf. It was also recommended that all footings should contain reinforcing steel as designated by a structural engineer.

A supplemental geotechnical study was later made using the dilatometer to determine if a higher bearing capacity could be used. Using the dilatometer results, we made a settlement analysis of the foundation system for the proposed structure using an allowable net bearing capacity of 3000 psf and a foundation layout as provided to us by the project Structural Engineer. That layout showed the bottom of footing elevations, slab level and structural loadings. A tabulation of computed settlements based on this data is given in the table below. As can be seen, the maximum settlement we computed was 0.87-inch (location D-2, continuous footing at El 126’, 6’ x 6’ square). All others were generally in the range of 0.3-inch to 0.7-inch for a differential of about 0.4-inch. This information was presented to the client and Structural Engineer without a recommendation.

Bottom of Footing Elev. Subgrade Elev.	Footing Typing and Dimension*	Computed Settlement
126’	(Col) 7’ x 7’	0.52”
126’	(Cont) 4’ Wide	0.63”
122’	(Col) 7’ x 7’	0.35”
122’	(Cont) 3’ Wide	0.35”
126’	(Col) 7’ x 7’	0.74”
126’	(Cont) 4’ Wide	0.87”
122’	(Col) 7’ x 7’	0.49”
122’	(Cont) 3’ Wide	0.49”
126’	(Col) 7’ x 7’	0.74”
126’	(Cont) 4’ Wide	0.87”
122’	(Col) 7’ x 7’	0.49”
122’	(Cont) 3’ Wide	0.49”
126’	(Col) 7’ x 7’	0.61”
126’	(Cont) 4’ Wide	0.71”
122’	(Col) 7’ x 7’	0.32”
122’	(Col) 6’ x 6’	0.28”
122’	(Cont) 3’ Wide	0.33”

* (Col) = Column
(Cont) = Continuous

5 OTHER DILATOMETER USES

We have also used the dilatometer for purposes other than obtaining data for settlement evaluation and foundation design recommendations as described in the examples above. Some are described briefly below.

5.1 *Retaining Wall – Anne Arundel County, Maryland*

The purpose of this investigation was to determine the in-situ condition of the subsurface profile along the alignment of a proposed 20 to 30 foot high Keystone retaining wall. Two SPT borings and three dilatometer probes were made for this purpose. The results were presented in the form of boring logs, dilatometer printouts and the following table.

Depth	General Soil Classification	Shear Strength	Angle of Internal Friction
0’ – 3’	Clayey Silt	1000 psf*	
3’ – 17’	Layered Silty Clayey Sand and Silty Clay		∅ = 33°*
17’ – 30’	Silty Clay	1200 psf*	
0’ – 8’	Clayey Silt/Silt	1400 psf	
8’ – 15’	Sandy Silt/Silty Sand		∅ = 35°*
15’ – 30’	Clayey Silt/Silty Clay	*1400 psf	
0’ – 25’	Silty Sand/Sandy Silt		∅ = 33°*
25’ - 30’	Clayey Silt	*2400 psf	
0’ – 6’	Clayey Sand		∅ = 33°*
6’ – 30’	Clayey/Silty Sand		∅ = 33°*
0’ – 20’	Silty Sand/Sandy Silt		∅ = 35°*
20’- 30’	Clayey Silt/Silty Clay	*1200 psf	

*Selected by comparison of dilatometer data and visual soil classification of SPT samples and “N” values

5.2 *Existing Building – Annapolis, Maryland*

The purpose of this study was to determine the condition of the subsurface profile under the old portion of a structure with a newer addition relative to the impact of intended subsurface improvements as a result of a recent grouting operation. It was originally planned to perform 3 to 4 tests using a pressuremeter on the assumption that the grouting had densified and solidified the subsurface materials into a stable mass. The bore holes for the tests were made by the wash boring method using a rotary drill rig. A pressuremeter test was attempted at about 5-foot depth in the first boring, however, cave-in of the sides of the bore hole resulted in enlargement of the hole diameter to the extent that the pressuremeter could not reach the sides and that test was terminated. Based on that condition, it was decided to substitute dilatometer probes for the pressuremeter tests. The general procedure consisted of first advancing the hole by wash boring method and setting casing at the top to allow re-circulation of the drill water. Split spoon samples were then obtained continuously by the Standard Penetration Test (SPT) procedure until very soft conditions were encountered at which time testing with the dilatometer probe was begun. It was assumed that effective grouting would result in the creation of a stable mass of soil about 15 feet thick that would be dense-cemented in condition. It was, therefore, not expected that conditions would be encountered in the

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borings that included cave-in of the sides of the hole and very loose or soft zones where the split-spoon sampler and dilatometer could easily be hydraulically pushed with the light drill rig. It was also expected that veins of cement grout would be observed throughout the profile.

The Tangent Modulus ("M") obtained by the dilatometer after grouting was selected for comparison to "M" values measured prior to that operation. The "M" value generally reflects the "stiffness" of the profile which relates to both compressibility and strength. For general comparison purposes, a value less than 10 indicates a very low stiffness or high compressibility. A value between 10 and 100 indicates potential problem conditions. The results of this study indicated no significant difference between the stiffness of the profile before and after the grout operation.

It was, therefore, concluded that the subsurface profile under the old portion of the building was not improved to any noticeable degree by the grout operation. It was found that no voids were noted under the slab at any location indicating good contact between the slab and underlying subgrade. However, there was limited evidence of grout penetration and the comparison of the stiffness of the profile as measured by the "M" values from the dilatometer did not indicate any significant change in conditions after the grout operation.

6 COST COMPARISONS

The cost of making a dilatometer sounding, obtaining data and reducing that data to a useful form is somewhat higher than making soil test borings using hollow stem augers and obtaining SPT samples. Based on current prices, an investigation at an arbitrary site where ten SPT borings to 40 feet are to be made would cost about $6700.00 in drilling costs. The cost for making the same number of dilatometer probes to the same depth would be about $7200.00 which includes reduction of the data. As another example, the SPT drilling cost at a site where six 20 foot borings are required would be about $2500.00 compared to $3300.00 using the dilatometer. The cost difference becomes more significant when the dilatometer is used in conjunction with an STB boring program, which is usually the case, due to additional mobilization costs. The difference can be reduced by substituting SPT borings for dilatometer probes which is what we try to do on most projects.

7 CONCLUSIONS

It is our conclusion that the use of the dilatometer provides data and results that are substantially more detailed and accurate than can be obtained from the older methods that have been in use for many years and, therefore, worth the additional cost. Settlement computations using the dilatometer results considers a profile with data available in close increments as compared to wide gaps based on a few undisturbed samples and the results of laboratory consolidation test or SPT results. The in-situ parameters obtained more accurately represent the actual compressibility of the profile than is measured by the other methods. Time is also a positive factor in that the dilatometer data is available immediately whereas several weeks, at least, are lost between the time a boring is made, the undisturbed sample is obtained and consolidation test is completed. The dilatometer does have the disadvantages that samples are not obtained for classification purposes, groundwater information is limited and some subsurface conditions cannot be penetrated.

8 REFERENCES

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APPENDIX: UNIT CONVERSIONS

1 foot (ft) = 0.3048 m
1 kip = 4.4482 kN
1 lb/ft^2 (psf) = 0.04788 kPa
1 British ton-force/ft^2 (tsf) = 95.76 kPa