The subsurface conditions below the tower have been investigated, including an exhaustive program sponsored by the Italian government that began in 1965. The profile, shown in Figure 25, is fairly uniform across the site and consists of sands underlain by clay.

This problem has attracted the attention of both amateurs and professionals, and the authorities have received countless “solutions,” sometimes at the rate of more than fifty per week. Some are clearly absurd, such as tying helium balloons to the top of the tower, or installing a series of cherub statues with flapping wings. Others, such as large structural supports (perhaps even a large statue leaning against the tower?), may be technically feasible, but aesthetically unacceptable.

In 1990 the interior of the tower was closed to visitors, and in 1993 about 600 tons of lead ingots were placed on the north side of the tower as a temporary stabilization measure.
Then, in 1995, engineers installed a concrete ring around the foundation and began drilling tiedown anchors through the ring and into the dense sand stratum located at a depth of about 40 ft (see profile in Figure 25). The weights caused the underlying soils to compress and slightly reduced the tilt, but construction of the anchors disturbed the soil and produced a sudden increase in the tilt of the tower. In one night the tower moved about 1.5 mm, which is the equivalent to a year’s worth of normal movement. As a result, the work was quickly abandoned and more lead ingots were added to the north side.
A period of inactivity followed, but in 1997 an earthquake in nearby Assisi caused a tower in that city to collapse—and that tower was not even leaning! This failure induced a new cycle of activity at Pisa, and the overseeing committee approved a new method of stabilizing the tower: soil extraction.

The method of soil extraction consists of carefully drilling diagonal borings into the ground beneath the north side of the tower and extracting small amounts of soil. The overlying soils then collapse into the newly created void, which should cause the north side of the tower to settle, thus decreasing the tilt. The objective of this effort is to reduce the tilt from 5.5 degrees to 5.0 degrees, which is the equivalent of returning the tower to its position of three hundred years ago. There is no interest in making the tower perfectly plumb.

Soil extraction has been successfully used to stabilize structures in Mexico City, and appears to be the most promising method for Pisa. This process must proceed very slowly, perhaps over a period of months or years, while continuously monitoring the movements of the tower. When this book was published, the soil extraction work had begun and the tilt had been very slightly reduced. If this effort is successful, the temporary lead weights will no longer be necessary, and the life of the tower should be extended for at least three hundred years.


 tors, and should be used with engineering judgment. A vital ingredient in this judgement is an understanding of the sources of error in the analysis. These include:

- Uncertainties in defining the soil profile. This is the largest single cause. There have been many cases of unexpectedly large settlements due to undetected compressible layers, such as peat lenses.
- Disturbance of soil samples.
- Errors in in-situ tests (especially the SPT).
- Errors in laboratory tests.
- Uncertainties in defining the service loads, especially when the live load is a large portion of the total load.
- Construction tolerances (i.e., footing not built to the design dimensions).
- Errors in determining the degree of overconsolidation.
- Inaccuracies in the analysis methodologies.
- Neglecting soil-structure interaction effects.
Shallow Foundations—Settlement

We can reduce some of these errors by employing more extensive and meticulous exploration and testing techniques, but there are economic and technological limits to such efforts.

Because of these errors, the actual settlement of a spread footing may be quite different from the computed settlement. Figure 23 shows 90 percent confidence intervals for spread footing settlement computations.

We can draw the following conclusions from this data:

• Settlement predictions are conservative more often than they are unconservative (i.e., they tend to overpredict the settlement more often than they underpredict it). However, the range of error is quite wide.
• Settlement predictions made using the Schmertmann method with CPT data are much more precise than those based on the SPT. (Note that these results are based on the 1970 version of Schmertmann’s method. Later refinements, as reflected in this chapter, should produce more precise results.)
• Settlement predictions in clays, especially those that are overconsolidated, are usually more precise than those in sands. However, the magnitude of settlement in clays is often greater.

Many of the soil factors that cause the scatter in Figure 23 do not change over short distances, so predictions of differential settlements should be more precise than those for total settlements. Therefore, the allowable differential settlement criteria (which include factors of safety of at least 1.5) reflect an appropriate level of conservatism.

SUMMARY

Major Points

1. Foundations must meet two settlement requirements: total settlement and differential settlement.
2. The load on spread footings causes an increase in the vertical stress, $\Delta \sigma_z$, in the soil below. This stress increase causes settlement in the soil beneath the footing.
3. The magnitude of $\Delta \sigma_z$ directly beneath the footing is equal to the bearing pressure, $q$. It decreases with depth and becomes very small at a depth of about $2B$ below square footings or about $6B$ below continuous footings.
4. The distribution of $\Delta \sigma_z$ below a footing may be calculated using Boussinesq’s method, Westergaard’s method, or the simplified method.
5. Settlement analyses in clays and silts are usually based on laboratory consolidation tests. The corresponding settlement analysis is an extension of the Terzaghi settlement analyses for fills.
Shallow Foundations—Settlement

6. Settlement analyses based on laboratory tests may use either the classical method, which assumes one-dimensional consolidation, or the Skempton and Bjerrum method, which accounts for three-dimensional effects.

7. Settlement analyses in sands are usually based on in-situ tests. The Schmertmann method may be used with these test results.

8. Differential settlements may be estimated based on observed ratios of differential to total settlement.

9. Settlement estimates based on laboratory consolidation tests of clays and silts typically range from a 50 percent overestimate (unconservative) to a 100 percent underestimate (conservative).

10. Settlement estimates based on CPT data from sandy soils typically range from a 50 percent overestimate (unconservative) to a 100 percent underestimate (conservative). However, estimates based on the SPT are much less precise.

Vocabulary

<table>
<thead>
<tr>
<th>Allowable differential settlement</th>
<th>Differential settlement</th>
<th>Schmertmann’s method</th>
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</thead>
<tbody>
<tr>
<td>Allowable settlement</td>
<td>Distortion settlement</td>
<td>Settlement</td>
</tr>
<tr>
<td>Boussinesq’s method</td>
<td>Induced stress</td>
<td>Skempton and Bjerrum method</td>
</tr>
<tr>
<td>Classical method</td>
<td>Plate load test</td>
<td>Rigidity</td>
</tr>
</tbody>
</table>

COMPREHENSIVE QUESTIONS AND PRACTICE PROBLEMS

24 A 600-mm wide, 500-mm deep continuous footing carries a vertical downward load of 85 kN/m. The soil has \( \gamma = 19\text{kN/m}^3 \). Using Boussinesq’s method, compute \( \Delta \sigma_z \) at a depth of 200 mm below the bottom of the footing at the following locations:
- Beneath the center of the footing
- 150 mm from the center of the footing
- 300 mm from the center of the footing (i.e., beneath the edge)
- 450 mm from the center of the footing

Plot the results in the form of a pressure diagram.

Hint: Use the principle of superposition.

25 A 3-ft square, 2-ft deep footing carries a column load of 28.2 k. An architect is proposing to build a new 4 ft wide, 2 ft deep continuous footing adjacent to this existing footing. The side of the new footing will be only 6 inches away from the side of the existing footing. The new footing will carry a load of 12.3 k/ft. \( \gamma = 119\text{lb/ft}^3 \).