# 18

# Difficult Soils

***An approximate solution to the right problem is more desirable than a precise solution to the wrong problem.***

U.S. Army, et al., 1971



Certain soil conditions are especially problematic and require extra effort from geotechnical engineers. These are sometimes called *difficult soils*. This chapter discusses some of the more common difficult soil conditions and examines methods of accommodating them in design and construction.

## 18.1 WEAK AND COMPRESSIBLE SOILS

Many construction sites are underlain by soils that are both weak and compressible. These include soft clays, highly organic soils, and others. Such soils are often found near the mouths of rivers, along the perimeter of bays, and beneath wetlands. They are prone to shear failure and excessive settlements. In addition, the areas underlain by such soils frequently are subject to flooding, so construction projects often require placing a fill to raise the ground surface to a suitable elevation. Unfortunately, the weight of such fills can cause large settlements. For example, Scheil (1979) described a building constructed on fill underlain by varved clay in the Hackensack Meadowlands of New Jersey. About 250 mm (10 in) of settlement occurred during placement of the fill, 12 mm (0.5 in) during construction of the building, and an additional 100 mm (4 in) over the following ten years.

Sometimes land that is underwater is *reclaimed* by placing fills that raise it above the water level. Many waterfront cities, including Boston and San Francisco, have been extended into the water using this method. Such sites are usually underlain by soft soils that compress under the weight of such fills. In addition, many of these fills were placed many years ago using poor construction methods. For example, in the 1930s, the LaGuardia Airport in New York City was expanded into the adjacent bay by placing a fill made of incinerated refuse. This fill material is very compressible, and is underlain by a compressible organic clay deposit. As a result, parts of the airport have settled more than 2 m (7 ft)! This settlement is continuing, even more than half a century later, and poses significant problems in maintenance of runways and in construction of buildings.

Fills placed for bridge abutments can cause similar settlement problems. However, the bridge, which is probably supported on a deep foundation, generally settles much less than the approach fill, thus producing the "bump at the end of the bridge." Figure 11.2 shows the result of such a condition.

Fortunately, engineers and contractors have developed methods of coping with weak and compressible soils, and have successfully built large structures, highways, and other facilities on very poor sites. Most of these methods focus primarily on the settlement problem, because it often has the biggest impact on design. These methods include the following, either individually or in combination:

- Delay the construction of structures and other sensitive facilities until after most of the fill-induced settlement has occurred.
- Reduce the amount of settlement by using lightweight fill materials.
- Support structures on deep foundations that penetrate through the weak soils.
- Accommodate the settlement using specially designed structures or by accepting maintenance costs.
- Improve the engineering properties of the soils using special construction methods.

### Delaying Construction

The consolidation process continues only until the soil reaches equilibrium under the new loading condition. Chapter 12 discussed methods of assessing the rate of consolidation and the time required to achieve a specified degree of consolidation. If the required time is not excessive, it may be economical to place the fill, then wait before constructing the buildings, roads, or other improvements.

This option does not necessarily require waiting until 100 percent consolidation has been achieved. For example, if the fill will produce 500 mm of settlement, but the proposed construction can accommodate only 100 mm, then construction can begin after 400/500 = 80% of the ultimate settlement is complete.

The primary advantage of this method is that it requires the lowest direct costs. However, in many cases the time required to achieve the required settlement is excessive, so this option often is not viable. However, there are methods of accelerating the settlement, as discussed in Chapter 19, and these methods often are cost effective.

### Using Lightweight Fills

The majority of the settlement is usually due to the weight of fills placed on the site. Although these fills are usually made of soil, other materials are available that have a much lower unit weight and thus induce less settlement. These include geofoam (large blocks of styrofoam), special cementitious materials, and others, as discussed in Chapter 6. This option is generally cost effective only for small areas, such as backfills of bridge abutments.

### Using Deep Foundations

If structures, such as buildings or bridges, are to be built on sites underlain by weak and compressible soils, they often must be supported on deep foundations that penetrate through these soils and into more competent underlying soils. This type of foundation isolates the structure from most of the settlement, and avoids overstressing the weak soils. Although this design may be reliable, it needs to account for the following two special problems:

1. If the site is in the process of settling, perhaps due to the weight of a fill, the ground surface will sink away from the structure, which will not experience significant settlement because of the deep foundation. This can cause access problems for pedestrians and vehicles, and thus can be a maintenance problem. The bridge in Figure 11.2 illustrates this problem.
2. If the upper soils are settling, they impart a downward load onto the foundations. This load, called *downdrag*, can be quite large, and needs to be added to the structural loads. This additional load capacity requirement increases the cost of the foundations.

### Accommodating the Settlement

Sometimes it is possible to simply accommodate large settlements in the design, construction, and maintenance of the facility. For example, an airport terminal building at LaGuardia Airport (originally built to serve Eastern Airlines) is underlain by 24 m (77 ft) of soft organic clay which was covered by 6 to 12 m (19–38 ft) of incinerated refuse fill that had been placed in the 1930s. The organic clay has $C_c/(1+e_0) = 0.29–0.33$, which makes it "highly compressible" according to Table 11.1. When construction of this building began in 1979, the ground surface had already settled more than 2 m (7 ft), and was expected to settle an additional 450 mm (18 in) over the following 20 years.

Other buildings at the airport are supported on pile foundations, and require continual maintenance to preserve access for aircraft, motor vehicles, and people. To avoid these problems, this building was built on spread footing foundations, and included provisions for leveling jacks between the foundations and the building (York and Suros, 1989). As differential settlements occurred, the building could then be periodically releveled using the jacks. In addition, the building was designed to accommodate large differential settlements.

By 1988, the building had settled as much as 315 mm (12 in), with differential settlements of up to 56 mm (2 in). However, because of the settlement-tolerant design, the structure was performing well even though no releveling had yet been performed.

This design was at least $2 million less expensive than a pile foundation, and has performed better. This savings in construction cost was much greater than the cost of periodically releveling the building.

### Improving the Soil

Another option is to improve the engineering properties of the soils before construction. Many special construction methods have been developed to do this, as discussed in Chapter 19. Once the soils have been improved, normal construction can proceed because the difficult soil conditions have been eliminated.

## 18.2 EXPANSIVE SOILS

Certain types of clayey soils expand when they are wetted and shrink when dried. These are called *expansive soils*, and are very troublesome. In the United States alone, they inflict about $9 billion per year in damages to buildings, roads, airports, pipelines, and other facilities—more than twice the combined damage from earthquakes, floods, tornados, and hurricanes (Jones and Holtz, 1973; Jones and Jones, 1987). The distribution of these damages is approximately as shown in Table 18.1.

Sometimes the damages from expansive soils are minor maintenance and aesthetic concerns, but often they are much worse, even causing major structural distress, as illustrated in Figure 18.1. According to Holtz and Hart (1978), 60 percent of the 250,000 new homes built on expansive soils each year in the United States experience minor damage and 10 percent experience significant damage, some beyond repair. Although the statistics for new houses built today are probably better, expansive soils continue to be a significant problem.

**TABLE 18.1** ANNUAL DAMAGE IN THE UNITED STATES FROM EXPANSIVE SOILS (Jones and Holtz, 1993; Jones and Jones, 1987. Used with permission of ASCE.)

| Category | Annual Damage |
|---|---|
| Highways and streets | $4,550,000,000 |
| Commercial buildings | 1,440,000,000 |
| Single-family homes | 1,200,000,000 |
| Walks, drives and parking areas | 440,000,000 |
| Buried utilities and services | 400,000,000 |
| Multi-story buildings | 320,000,000 |
| Airport installations | 160,000,000 |
| Involved in urban landslides | 100,000,000 |
| Other | 390,000,000 |
| Total annual damages (1987) | $9,000,000,000 |

These soil movements and the damage they cause generally occur very slowly, and thus are not nearly as dramatic as hurricanes and earthquakes. In addition, they cause only property damage, not loss of life, and this damage is spread over wide areas rather than being concentrated in a small locality. Nevertheless, the economic loss is large and much of it could be avoided by proper recognition of the problem and incorporating appropriate preventive measures into the design, construction, and maintenance of new facilities.

**Figure 18.1** Heaving of an expansive soil caused this brick wall to crack. The $490,000 spent to repair this and other walls, ceilings, doors, and windows represented nearly one-third of the original cost of the six-year-old building (Colorado Geological Survey).

### Physical Causes of Expansion and Shrinkage

There are many different clay minerals, as discussed in Chapter 4, and each has a different susceptibility to swelling, as shown in Table 18.2. Swelling occurs when water infiltrates between and within the clay particles, causing them to separate. Kaolinite is virtually nonexpansive because of the presence of strong hydrogen bonds that hold the individual clay particles together. Illite contains weaker potassium bonds that allow limited expansion, and montmorillonite particles are only weakly linked. Thus, water can easily flow into montmorillonite clays and separate the particles. Field observations have confirmed that the greatest problems occur in soils with a high montmorillonite content.

**TABLE 18.2** SWELL POTENTIAL OF PURE CLAY MINERALS (Adapted from Budge, et al. (1964).

| Surcharge Load | | Swell Potential (%) | | |
|---|---|---|---|---|
| ($lb/ft^2$) | (kPa) | Kaolinite | Illite | Montmorillonite |
| 200 | 9.6 | Negligible | 350 | 1500 |
| 400 | 19.1 | Negligible | 150 | 350 |

### Sources of Wetting and Drying

The shrinking and swelling potential in a soil becomes reality only when its moisture content changes. Such changes in moisture content can be due to natural processes, such as changes in the groundwater table and infiltration of rainwater. However, moisture changes due to human activities are often much larger and more extensive than those caused exclusively by natural causes, and thus are more often a source of problems.

Irrigation of landscaping is one of the most important causes of increased moisture content in soils, especially in arid and semi-arid areas. For example, irrigation of lawns and shrubs often is the equivalent of about 2000 mm (80 inches) of rain per year, a significant increase over the 200–500 mm/yr (8–20 in/yr) that naturally occurs in such places.

Other sources of excessive moisture and the associated soil expansion include:

- Changes in surface drainage patterns that prevent water from running off and allow water to percolate into the ground.
- Removal of vegetation that brings an end to transpiration.
- Placement of slab-on-grade floors, pavements, or other impervious materials on the ground, which stops both evaporation and the direct infiltration of rain water.

Some activities can have the opposite effect by removing moisture from the soil and causing shrinkage. Poorly placed trees with aggressive roots have caused such problems, especially in areas with moist climates.

### Identifying, Testing, and Evaluating Expansive Clays

When working in an area where expansive soils can cause problems, geotechnical engineers must have a systematic method of identifying, testing, and evaluating the swelling potential of troublesome soils (Nelson and Miller, 1992). The ultimate goal is to determine which preventive design measures, if any, are needed to successfully complete a proposed project.

Experienced geotechnical engineers usually can identify potentially expansive soils based on a visual examination. To be expansive, a soil must have a significant clay content, probably falling within the unified symbols CL or CH (although some ML, MH, and SC soils also can be expansive). When dry, expansive soils often have distinct shrinkage cracks and other evidence of previous swelling and shrinking. However, any such visual identification is only a first step; we must obtain more information before we can develop specific design recommendations.

The next stage of the process—determining the degree of expansiveness—is more difficult. A wide variety of testing and evaluation methods have been proposed, but none of them are universally or even widely accepted. Some assessment techniques are as simple as performing Atterberg limits tests and classifying the expansiveness based on the results of these tests. Table 18.3 shows one such classification method. Alternatively, we could conduct a *swell test* by placing a sample in a device similar to a consolidometer and wetting it. The resulting swell can then be used as a semi-empirical assessment of expansion potential. Snethen (1984) suggested the following definition of potential swell:

Potential swell is the equilibrium vertical volume change or deformation from an oedometer-type[1] test (i.e., total lateral confinement), expressed as a percent of original height, of an undisturbed specimen from its natural water content and density to a state of saturation under an applied load equivalent to the in-situ overburden pressure.

Snethen also suggested that the applied load should consider any applied external loads, such as those from foundations. Using Snethen's test criteria, we could classify the expansiveness of the soil, as shown in Table 18.4.

**TABLE 18.3** CORRELATIONS WITH COMMON SOIL TESTS (Adapted from Holtz, 1969, and Gibbs, 1969)

| Percent Colloids | Plasticity Index | Shrinkage Limit | Liquid Limit | Swelling Potential |
|---|---|---|---|---|
| < 15 | < 18 | < 15 | < 39 | Low |
| 13 - 23 | 15 - 28 | 10 - 16 | 39 - 50 | Medium |
| 20 - 31 | 25 - 41 | 7 - 12 | 50 - 63 | High |
| > 28 | > 35 | > 11 | > 63 | Very high |

**TABLE 18.4** TYPICAL CLASSIFICATION OF SOIL EXPANSIVENESS BASED ON SWELL TEST RESULTS AT IN-SITU OVERBURDEN STRESS (Adapted from Snethen, 1984)

| Swell Potential (%) | Swell Classification |
|---|---|
| < 0.5 | Low |
| 0.5 - 1.5 | Marginal |
| > 1.5 | High |

The *expansion index test* [ASTM D4829] (ICBO, 1991b; Anderson and Lade, 1981) is a standardized loaded swell test. In this test a soil sample is remolded into a standard 4.01 in (102 mm) diameter, 1 in (25 mm) tall ring at a degree of saturation of about 50 percent. A surcharge load of 1 lb/in$^2$ (6.9 kPa) is applied, and then the sample is saturated and allowed to stand until the rate of swelling reaches a certain value or 24 hours, whichever is longer. The amount of swell is expressed in terms of the *expansion index*, or EI, which is defined as follows:

$$\boxed{EI = 1000\,h\,F} \tag{18.1}$$

[1] The terms *oedometer* and *consolidometer* are synonymous.

where:

EI = expansion index

$h$ = expansion of the soil (in)

$F$ = percentage of the sample by weight that passes through a #4 sieve

Table 18.5 gives an interpretation of EI test results.

Because the expansion index test is conducted on a remolded sample, it may mask certain soil fabric effects that may be present in the field.

**TABLE 18.5** INTERPRETATION OF EXPANSION INDEX TEST RESULTS (ICBO, 1997)

| EI | Potential Expansion |
|---|---|
| 0 - 20 | Very Low |
| 21 - 50 | Low |
| 51 - 90 | Medium |
| 91 - 130 | High |
| > 130 | Very High |





## Preventive Measures

Once the expansion potential has been evaluated, we develop preventive design, construction, and maintenance measures. These measures are intended to reduce the potential impact of expansive soils.

### Building Foundations and Floors

Buildings, especially those that are lightweight, are prone to damage from expansive soils. The magnitude of heaving and shrinking generally varies across the building, thus causing problems similar to those associated with excessive differential settlements. These include cracks, inoperative doors and windows, etc. Common preventive measures include:

- Extending the foundations to greater depths, thus bypassing the zone of greatest moisture change and supporting the building on more stable soil.
- Adding extra reinforcing steel to foundations and slabs. In some cases, prestressed or post-tensioned slabs are used.
- Avoiding the use of slab-on-grade floors.
- Being especially careful to provide and maintain good surface drainage around the building.
- Avoiding the placement of irrigated landscaping close to the building
- Pre-moistening the soil prior to construction, thus causing it to expand before the building is erected.

### Pavements

Highway pavements also are prone to damage from expansive soils. Common preventive measures include:

- Providing extensive surface and subsurface drainage to keep water away from the subgrade soils.
- Providing a non-expansive sub-base material.
- Treating the subgrade soils with lime or some other material to reduce their expansive properties.
- Providing more steel reinforcement.

Driveways, sidewalks, and other exterior *flatwork concrete* can have similar problems.

## 18.3 COLLAPSIBLE SOILS

Another moisture-driven phenomena, often seen in arid regions, is *collapse* (Clemence and Finbarr, 1981; Dudley, 1970; Houston and Houston, 1997). Soils prone to this behavior are called *collapsible soils*. In their natural state, these soils have a high void ratio and a low moisture content. They are usually alluvial or aeolian, and have a "honeycomb" or highly porous structure that is maintained by water-soluble interparticle bonds. These soils can cause problems when structures, highways, or other improvements are built on them, and the soil subsequently becomes wetted. The influx of water breaks down these bonds and causes the soil to compress.

Geotechnical engineers usually assess the collapse potential by placing an undisturbed sample in a consolidometer at its in-situ moisture content, loading it to a normal stress comparable to that in the field, then applying water. The amount of strain that occurs due to wetting is a measure of its collapse potential. Some soils experience strains in excess of 10 percent simply due to wetting.

Unlike expansive soils, which can heave or shrink as the moisture content changes, collapse is a one-way process. Therefore, preventive measures often attempt to pre-collapse the soil prior to construction. This may be accomplished by pre-wetting the soil, by excavating it and replacing it as a compacted fill, or by compacting the soil in place. Other techniques, such as grouting, deep foundations, and avoidance of wetting also have been used (Houston and Houston, 1989).

## 18.4 FROZEN SOILS

The temperature of soils near the ground surface reflects the recent air temperatures. Thus, when the air temperature falls below 0°C (32°F) for extended periods, the soil temperature drops to a comparable level and the pore water turns to ice. This transformation has significant impacts on civil engineering works built on such soils, and thus is an important aspect of geotechnical engineering in regions with cold climates.

## Ground Freezing and Frost Heave

The depth of freezing in the ground depends on how far the air temperature falls below freezing, how long it remains there, and other factors. This depth is negligible in warm climates, such as Florida, but can extend to depths of 2 m (7 ft) or more when the winters are very cold, such as in Minnesota. In arctic and sub-arctic regions, the depth of freezing is even greater. In North America, problems with ground freezing are most common in the northern United States and in Canada. However, areas farther south also can be affected. For example, underground water pipes in Atlanta have frozen during exceptionally cold winters.

For geotechnical engineers, the most significant consequence of ground freezing is a phenomenon called *frost heave*, which is an upward movement in the ground due to the formation of underground ice. There are two causes of frost heave: The first occurs because the pore water expands about 9 percent in volume when it freezes. Thus, if the soil is saturated and has a typical porosity (say, 40 percent), it will expand about $9\% \times 40\% \approx 4\%$ in volume. In climates comparable to those in the northern United States, this could correspond to surface heaves of as much as 25–50 mm (1–2 in). Although such heaves are significant, they would probably be fairly uniform and cause relatively little damage.

The second cause of frost heave is more insidious and capable of producing much more damage to civil engineering works. If the groundwater table is relatively shallow, capillary action can draw water up to the frozen zone where it forms ice lenses as shown in Figure 18.2. In some situations, this mechanism can move large quantities of water, so it is not unusual for these lenses to produce ground surface heaves of 300 mm (12 in) or more. Such heaves are likely to be very irregular and create a hummocky ground surface that can cause extensive damage.

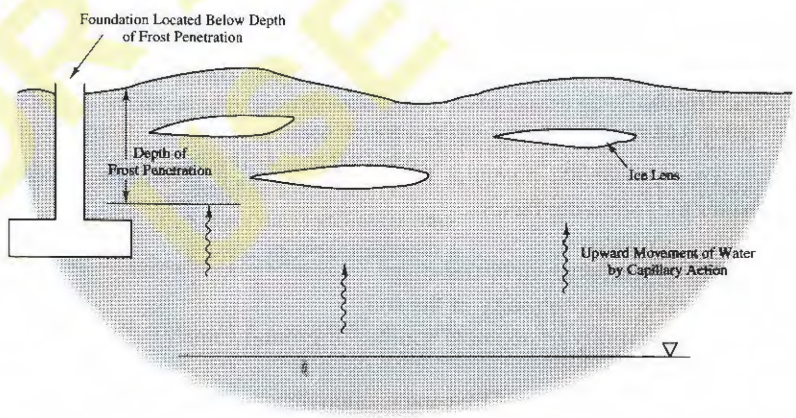


**Figure 18.2** Formation of ice lenses. Water is drawn up by capillary action and freezes when it reaches the frozen soil, which is located within the depth of frost penetration. The frozen water forms ice lenses that cause heaving at the ground surface. Foundations placed below the depth for frost penetration are not subject to heaving.

Additional damage can occur when the frozen ground begins to thaw, especially if ice lenses are present. As the upper soils and ice lenses thaw, the resulting soil has a much greater moisture content than it originally had. However, the deeper soils have not yet thawed, so this excess water cannot drain away, resulting in a very soft and weak soil as shown in Figure 18.3. This condition is especially troublesome when it occurs beneath highways, and is often the cause of ruts and potholes. Once the soil completely thaws, the excess water drains down and the soil regains much of its original strength.

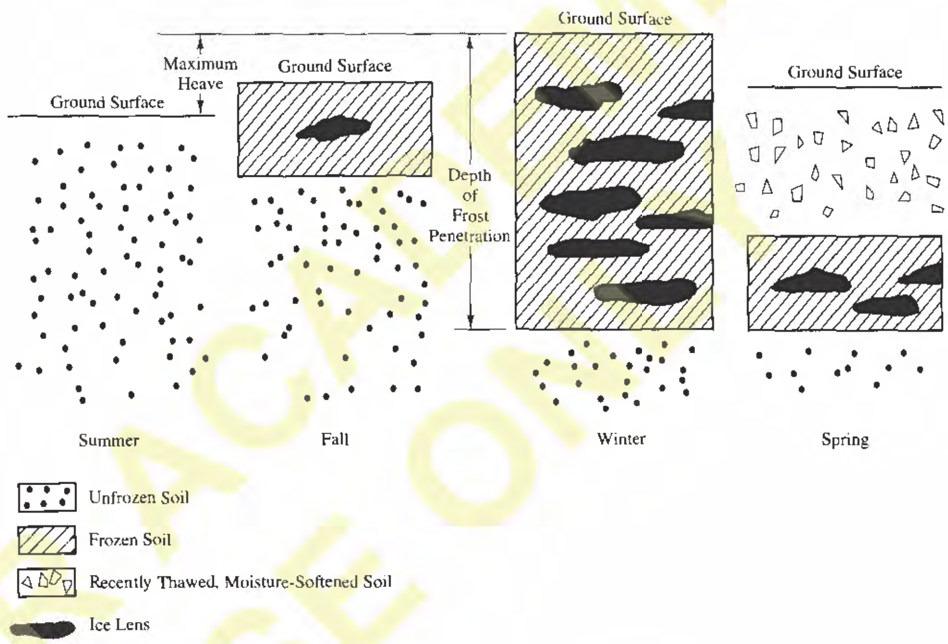


**Figure 18.3** Idealized freeze–thaw cycle in temperate climates. During the summer, none of the ground is frozen. Then, during the fall and winter it progressively freezes from the ground surface downward. Finally, in the spring, it progressively thaws from the ground surface downward.

To evaluate the potential for frost heave at a given site, geotechnical engineers consider the following factors:

- The potential depth of freezing
- The frost susceptibility of the soil
- The proximity of potential sources of groundwater

The potential depth of freezing is often dictated by local building codes. For example, the Chicago Building Code specifies a design frost penetration depth of 42 in (1.1 m). Special thermodynamic analyses might be used on special projects, such as ice skating rinks or cold-storage warehouses, but they would rarely be performed on more ordinary projects.

To be considered *frost-susceptible*, a soil must be capable of drawing significant quantities of water up to the frozen zone through capillary action. Clean sands and gravels are not frost-susceptible because they are not capable of significant capillary rise. Conversely, clays are capable of raising water through capillary rise, but they have a low hydraulic conductivity, so they are unable to deliver large quantities of water. Therefore, clays are capable of only limited frost heave. However, intermediate soils, such as silts and fine sands, have both characteristics: They are capable of substantial capillary rise and have a high hydraulic conductivity. Large ice lenses are able to form in these soils, so they are considered to be very frost-susceptible.

The U.S. Army Corps of Engineers has classified frost-susceptible soils into four groups, as shown in Table 18.6. Higher group numbers correspond to greater frost susceptibility and more potential for formation of ice lenses. Clean sands and gravels (i.e., <3% finer than 0.02 mm) may be considered non-frost-susceptible and are not included in this table.

**TABLE 18.6** FROST SUSCEPTIBILITY OF VARIOUS SOILS ACCORDING TO THE U.S. ARMY CORPS OF ENGINEERS (Adapted from Johnston, 1981)

| Group | Soil Types | USCS Group Symbols |
|---|---|---|
| F1 (least susceptible) | Gravels with 3 - 10% finer than 0.02 mm | GW, GP, GW-GM, GP-GM |
| F2 | a. Gravels with 10 - 20% finer than 0.02 mm | GM, GW-GM, GP-GM |
| | b. Sands with 3 - 15% finer than 0.02 mm | SW, SP, SM, SW-SM, SP-SM |
| F3 | a. Gravels with more than 20% finer than 0.02 mm | GM, GC |
| | b. Sands, except very fine silty sands, with more than 15% finer than 0.02 mm | SM, SC |
| | c. Clays with $PI > 12$, except varved clays | CL, CH |
| F4 (most susceptible) | a. Silts and sandy silts | ML, MH |
| | b. Fine silty sands with more than 15% finer than 0.02 mm | SM |
| | c. Lean clays with $PI < 12$ | CL, CL-ML |
| | d. Varved clays and other fine-grained, banded sediments | |

Finally, there must be a source of groundwater. Usually the source is a shallow groundwater table, but it also could come from water infiltrating from the ground surface.

### Preventive Measures

Once a potential frost heave problem has been identified, geotechnical engineers begin to consider preventive design measures. Many types of preventive measures are available, and the appropriate selection depends on the type of facility to be protected, the level of protection desired, cost, and other factors.

### Highways and Other Pavements

Highways, parking lots, airports, and other paved areas are especially susceptible to damage from frost heave. Some of this damage occurs during the winter as a result of differential heaving associated with ice lenses, but more damage often occurs in the spring when the soils have partially thawed and contain trapped water. Heavy wheel loads from trucks or large aircraft are especially troublesome during the spring thaw because they produce bearing capacity failures in the weak soil, which then causes the overlying pavement to sink into the ground. Figure 18.4 shows such a failure.

**Figure 18.4** The soils beneath this asphaltic concrete pavement in New York became wet and soft during the spring thaws. As a result, these soils failed under the weight of the heavy trucks that use this site. The pavement is now in very poor condition, with extensive alligator cracks and potholes.

Preventive design measures include:

- Excavating the upper soils and replacing them with non-frost-susceptible soils.
- Providing gradual transition sections between frost-susceptible and non-frost-susceptible subgrade soils.
- Restricting heavy traffic during the spring thaw.
- Installing thermal insulation between the pavement and the underlying soils (this method reduces the depth of frost penetration, but can enhance the formation of ice on the pavement surface, creating dangerous driving conditions).
- Increasing the thickness of aggregate base courses to spread out the wheel loads and to provide greater overburden pressure on the subgrade soil.
- Treating the subgrade soils with cement or lime.

Unfortunately, these preventive measures are often very expensive and may not be cost effective for all pavements. In addition, they are not always completely effective. Thus, maintenance crews are usually busy through the summer repairing these problems.

### Buildings and Other Structures

Preventive measures for buildings and other structures are usually more extensive than those for pavements because these facilities have higher standards of performance, and because they cover smaller areas and are thus easier to remediate.

Engineers definitely want to protect building foundations from the effects of frost heave. The most common method is to place foundations at a depth below the depth of frost penetration, as shown in Figure 18.2. This is usually wise in all soils, whether or not they are frost-susceptible and whether or not the groundwater table is nearby. Even "frost-free" clean sands and gravels will often have silt lenses that are prone to heave, and groundwater conditions can change unexpectedly, thus introducing new sources of water. The small cost of building deeper foundations is a wise investment in such cases. However, foundations supported on bedrock or interior foundations in heated buildings normally do not need to be extended below the depth of frost penetration.

Another alternative is to remove the natural soils and replace them with a compacted fill made of soil known to be non-frost-susceptible. This may be an attractive method for unheated buildings with slab-on-grade floors to protect both the floor and the foundation from frost heave.

Builders in Canada and Scandinavia sometimes protect buildings with slab-on-grade floors using thermal insulation. This method traps heat stored in the ground during the summer and thus protects against frost heave, even though the foundations are shallower than the normal frost depth. Both heated and nonheated buildings can use this technique (NAHB, 1988 and 1990).

A peculiar hazard to keep in mind when foundations or walls extend through frost-susceptible soils is *adfreezing* (CGS, 1992). This is the bonding of soil to a wall or foundation as it freezes. If heaving occurs after the adfreezing, the rising soil will impose a large upward load on the structure, possibly separating structural members. Placing a 10 mm (0.5 in) thick sheet of rigid polystyrene between the foundation and the frozen soil reduces the adfreezing potential.

### Ice Skating Rinks and Cold-Storage Warehouses

Although frost heave problems are usually due to freezing temperatures from natural causes, it is also possible to freeze the soil artificially. For example, refrigerated buildings such as cold-storage warehouses or indoor ice skating rinks can freeze the soils below and be damaged by frost heave, even in areas where natural frost heave is not a concern (Thorson and Braun, 1975; Duncan, 1992b). Heaves of up to 280 mm (11 in) have been observed in ice skating rinks in Minneapolis, which seriously impairs their usefulness. In some cases the deformation of the ice surface is so bad that hockey teams find it necessary to switch goals between periods and during the middle of the last period.

These facilities can freeze the soil to substantial depths because they usually operate year-round. For example, during nearly two years of continuous operation, an ice skating rink in Minnesota froze the soil to a depth of 6 m (20 ft), and might ultimately reach a depth of 12 m (40 ft) (Thorson and Braun, 1975).

Preventive design measures include excavating the upper soils and replacing them with non-frost-susceptible soils, placing thermal insulation or air passages between the building and the soil, and even placing heating tubes below the insulation.

### Underground Pipelines

Underground pipelines, especially water lines, can freeze if they are located within frozen soil. This can cause them to burst (because of the expansion of water when it freezes), or at least it becomes a nuisance in that the water does not flow. Solutions to these problems include placing the pipelines below the frost depth or surrounding them with thermal insulation. Sometimes it also is possible to avoid freezing by keeping a water faucet running continuously, thus continually drawing warmer water through the pipe.

## Permafrost

In areas where the mean annual temperature is less than 0°C, the penetration of freezing in the winter may exceed the penetration of thawing in the summer. This creates a zone of permanently frozen soil known as *permafrost* (Phukan, 1985; Andersland and Anderson, 1978). In the harshest of cold climates, such as Greenland, this permanently frozen ground is continuous, whereas in slightly "milder" climates, such as central Alaska, central Canada, and much of Siberia, the permafrost is discontinuous (i.e., the frozen zones are separated by seasonally frozen zones). Areas of seasonal and continuous permafrost in Canada are shown in Figure 18.5.

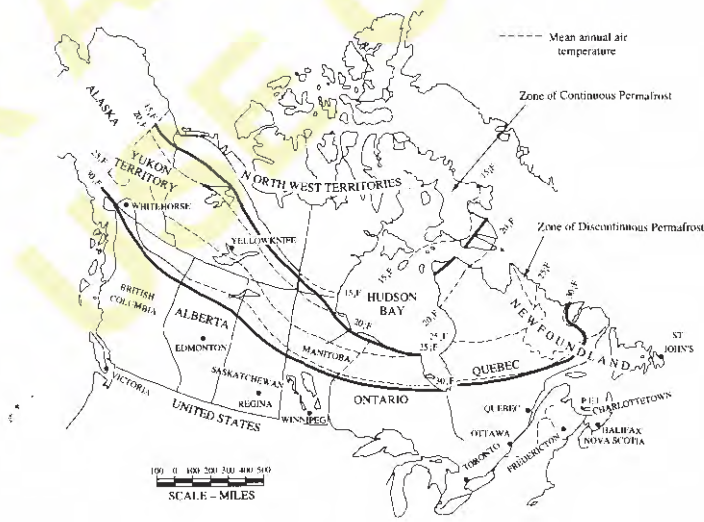


**Figure 18.5** Zones of continuous and discontinuous permafrost in Canada (Adapted from Crawford and Johnson, 1971).

In areas where the summer thaws occur, the upper soils can be very wet and weak and probably not capable of supporting any significant loads, while the deeper soils remain permanently frozen. Foundations must penetrate through this seasonal zone and well into the permanently frozen ground below. In addition, it is very important that these foundations be designed so that they do not transmit heat to the permafrost. Figure 18.6 shows the results of permafrost thawing beneath a heated building. To avoid such problems, buildings are typically built with raised floors and a ducting system to maintain subfreezing air temperatures between the floor and the ground surface.

The Alaska Pipeline project is an excellent example of a major engineering work partially supported on permafrost (Luscher, et. al, 1975).

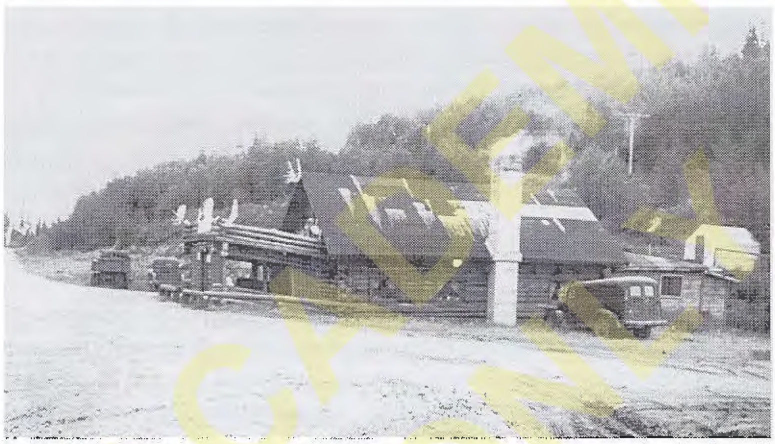

**Figure 18.6** Heat from this lodge in Alaska thawed the permafrost below, causing it to settle. However, the permafrost did not thaw beneath the unheated porch (Photo courtesy of Professor Richard L. Handy).

## 18.5 CORROSIVE SOILS

Soil can be a very hostile environment in which to place engineering materials. Concrete, steel, and wood placed in contact with soil may become the target of chemical and/or biological attack that can adversely affect their integrity.

### Steel and Iron

Corrosion is a nearly universal concern with steel and iron. In above-ground applications it generally can be kept under control by painting, galvanizing, and other measures, and visually monitored. Potentially hazardous conditions, such as heavily corroded bridges, usually can be detected by careful inspection. However, corrosion in underground facilities, such as tanks, pipelines, and pile foundations, is potentially much more troublesome and more difficult to monitor.

Sites where the elevation of the groundwater table fluctuates, such as tidal zones, are especially difficult because this scenario continually introduces both water and oxygen. Contaminated soils, such as sanitary landfills and shorelines near old sewer outfalls, are also more likely to have problems.

If the geotechnical engineer suspects that corrosion may be a problem, it is generally appropriate to retain the services of a corrosion engineer. Detailed assessments of corrosion and the development of preventive designs are beyond the expertise of most geotechnical engineers. Preventive measures might include:

- Applying protective coatings, such as coal tar enamel.
- Providing a *cathodic protection system*, which consists of applying a DC electrical potential between the item to be protected (the cathode) and a buried sacrificial metal (the anode). This system causes the corrosion to be concentrated at the anode and protects the cathode. These systems consume only nominal amounts of electricity, and in some cases can be self-energizing (i.e., generating their own electricity).
- Increasing the steel thickness by an amount equal to the anticipated deterioration.
- Using a different material. For example, underground tanks can be made of fiberglass.

## Concrete

Concrete in contact with soil, such as buried pipelines, foundations, retaining walls, and slabs, is usually very resistant to corrosion and will remain intact for many years. However, serious degradation can occur in concrete subjected to soils or groundwater that contains high concentrations of sulfates ($SO_4$). These sulfates can react with the cement to form calcium sulfoaluminate (ettringite) crystals. As these crystals grow and expand, the concrete cracks and disintegrates. In some cases, serious degradation has occurred within 5 to 30 years of construction. Although we do not yet fully understand this process (Mehta, 1983), engineers have developed methods of avoiding these problems.

We can evaluate a soil's potential for sulfate attack by measuring the concentration of sulfates in the soil and/or in the groundwater and comparing them with those that have had problems with sulfate attack. If the laboratory tests indicate that the soil or groundwater has a high sulfate content, design the buried concrete to resist attack by using one or more of the following methods (Kosmatka and Panarese, 1988; PCA, 1991):

- **Reduce the water:cement ratio**—This reduces the hydraulic conductivity of the concrete, thus retarding the chemical reactions. This is one of the most effective methods of resisting sulfate attack.
- **Increase the cement content**—This also reduces the hydraulic conductivity. Therefore, concrete exposed to problematic soils should have a cement content of at least 6 sacks/yd$^3$ (564 lb/yd$^3$ or 335 kg/m$^3$).
- **Use sulfate-resisting cement**—Type II low-alkali and type V Portland cements are specially formulated for use in moderate and severe sulfate conditions, respectively. Pozzolan additives to a type V cement also help. Type II is easily obtained, but type V may not be readily available in some areas.
- **Coat the concrete with an asphalt emulsion**—This is an attractive alternative for retaining walls or buried concrete pipes, but not for foundations.

Unlike steel corrosion problems, which are generally passed on to corrosion engineers, sulfate attack problems are normally addressed by the geotechnical engineer.

### Wood

It is generally best to avoid placing wood in contact with soil because it becomes subject to decay and insect attack. The worst condition occurs when the wood is subjected to repeated cycles of wetting and drying. Therefore, building codes usually require all wood in wood frame buildings to be at least 150 mm (6 in) above the ground. However, there are situations where wood is placed in contact with soil or buried underground. These include:

- Timber piles
- Telephone poles
- Wood retaining walls
- Fence posts
- Railroad ties

To reduce problems of decay and insect attack, wood may be treated before it is installed. The most common treatment consists of placing the wood in a pressurized tank filled with creosote or some other preserving chemical. This *pressure treatment* forces some of the chemicals into the wood and forms a coating on the outside. Creosote leaves a black tar-like substance which is often seen on telephone poles and railroad ties. Some chemical treatments produce a greenish color. Another option is to use wood species that are naturally resistant to decay, such as redwood or cypress.



## SUMMARY

### Major Points

1. Certain soil conditions are especially problematic and require special attention. These are called difficult soils.
2. Soils that are weak and compressible, such as soft clays and highly organic soils, are common near the mouths of rivers, along the perimeter of bays, and in wetlands. These soils generally require special measures to control or accommodate large settlements. They also are subject to shear failure.
3. Expansive soils are those that expand when wetted and shrink when dried. They have caused extensive damage to buildings, highways, and other projects. Engineers have developed methods of recognizing and testing these soils, along with various remediation measures.
4. Collapsible soils are found in arid and semi-arid areas. They initially are very dry and have a loose "honeycomb" structure. This structure is maintained by water-soluble bonds. If these soils subsequently become wetted, these bonds weaken and the soil collapses, sometimes causing excessive settlements. Engineers have developed

methods of evaluating such soils. Once they have been recognized, appropriate preventive measures may be implemented.

5. Frozen soils are those that have a temperature less than 0° C. They can cause a variety of problems, and are most often a concern in areas with cold winters. Frost heave is one of these problems. Once again, engineers have developed methods of assessing the potential for heave and implementing preventive measures.
6. Permafrost is permanently frozen ground. In this case, problems occur when engineering projects cause it to thaw.
7. Corrosive soils are those that are hostile to buried materials. Steel and iron can be subject to rusting, concrete can be subject to sulfate attack, and wood can be subject to rotting. The effects of corrosion can be reduced, but not always eliminated.

### Vocabulary

collapsible soil
corrosive soil
expansion index test
expansive soil
frost heave
frost-susceptible soil
frozen soil
permafrost
swell test

## COMPREHENSIVE QUESTIONS AND PRACTICE PROBLEMS

**18.1** A 2.5 m thick fill is to be placed over a thick stratum of soft clay, then a one-story office building is to be built on top of the fill. According to a settlement analysis, the weight of this fill will cause 600 mm of total settlement over a period of 30 years. The differential settlement will probably be about 100 mm. Although the building could be supported on spread footing foundations in the fill, the design engineer has decided to support it on a system of pile foundations that penetrate through the fill and into the underlying soils, thus insulating this building from the settlement problem.

Other than cost considerations, what problems will probably occur as a result of this design? What methods might be used to overcome these problems?

**18.2** A one-story wood-frame house is to be built on a site in Texas that is underlain by a clay with a plasticity index of 40. Might this house be prone to distress due to expansive soils? Why or why not?

**18.3** A project specification requires all imported soils be "non-frost-susceptible." Some import is required, and three sources are available. Source A has a fine silty sand (ML), Source B has a well-graded sand (SW), and Source C has a lean clay (CL). Which of these soils would be most likely to satisfy the project specifications? Explain the reason for your answer.

**18.4** An underground steel pipeline is to be constructed in a soil that is mildly corrosive. What kinds of measures might be used to prevent failure due to excessive corrosion?