P • A • R • T • 1

FOUNDATION AND CIVIL ENGINEERING SITE DEVELOPMENT

Site hydrology and land planning are two initial factors that influence land use and foundation design. Part 1 addresses these concerns. Site hydrology involves both subsurface and surface water content and movement. Land planning develops construction techniques intended to accommodate hydrologic problems and provide best use of the parcel. Coverage of the topic will be rather cursory—as a rule, foundation engineers are not involved with the early stages of development, but an awareness of the potential problems is beneficial.

SECTION 1A
WATER BEHAVIOR IN SOILS

ROBERT WADE BROWN

Site hydrology and land planning are two initial factors that influence land use and foundation design. This section addresses these concerns. Site hydrology involves both subsurface and surface water content and movement. Land planning develops construction techniques intended to accommodate hydroponic problems and provide best use of a parcel of land. The coverage will be rather cursory. As a rule, foundation engineers are not initially involved with the early stages of development. An awareness of the potential problems is, however, beneficial.

1A.1 MOISTURE REGIMES

The regime of subsurface water can be divided into two general classifications: the *aeration zone* and the *saturation zone*. The saturation zone is more commonly termed the *water table* or *groundwater*, and it is, of course, the deepest. The aeration zone includes the capillary fringe, the intermediate belt (which may include one or more perched water zones), and, at the surface, the *soil water belt*, often referred to as the *root zone* (Fig. 1A.1). Simply stated, the soil water belt provides moisture for the vegetable and plant kingdoms; the intermediate belt contains moisture essentially in dead storage—held by molecular forces; and the perched ground water, if it occurs, develops essentially from water accumulation either above a relatively impermeable stratum or within an unusually permeable lens. Perched water occurs generally after heavy rain and is relatively temporary. The capillary fringe contains capillary water originating from the water table. The soil belt can contain capillary water available from rains or watering; however, unless this moisture is continually restored, the soil will eventually desiccate through the effects of gravity, transpiration, and/or evaporation. When it does so, the capillary water is lost. The soil belt is also the zone that most critically influences both foundation design and stability. This will be discussed in the following sections. As stated, the more shallow zones have the greatest influence on surface structures. Unless the water table is quite shallow, it will have little, if any, material influence on the behavior of foundations of normal residential structures. Furthermore, the surface of the water table, the *phreatic boundary*, will not normally deflect or deform except under certain conditions, such as when it is in the proximity of a producing well. Then the boundary will *draw down* or recede.

Engineers sometimes allude to a "natural" buildup of surface soil moisture beneath slab foundations due to the lack of evaporation. This phenomenon is often referred to as *center doming* or *cen-*

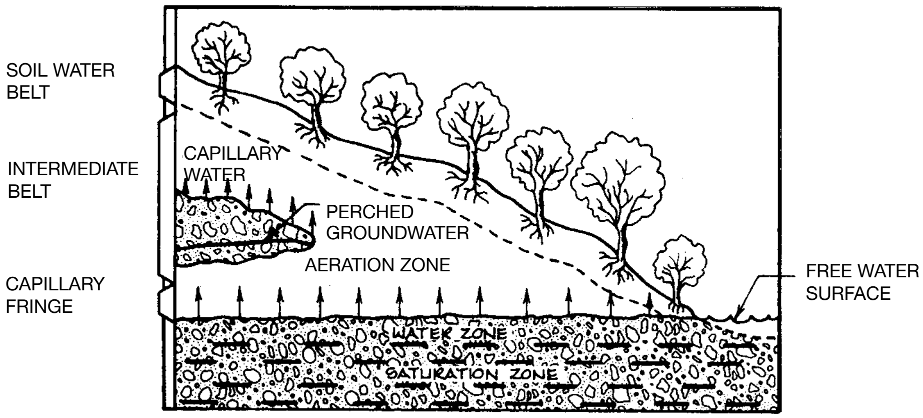


FIGURE 1.A1 Moisture regimes.

ter lift (refer to Sec. 7A.3). If the source for this moisture is assumed to be the water table and if the water table is deeper than about 10 ft (3 m),* the boundary (as well as the capillary fringe) is not likely to "dome"; hence, no transfer of moisture to the shallow soils would be likely. The other source of moisture could involve the capillary or osmotic transfer from underlying soils to the dryer, more shallow soils. When expansive soils are involved, this intrusion of moisture can cause the soil to swell. This swell is ultimately going to be rather uniform over the confined area. (This expansive soil has a much greater lateral than vertical permeability.) Again no "natural doming" is likely to occur. Refer to Sec. 1A.8.

Following paragraphs will provide further discussion concerning water migration in various soils as represented by several noted authorities.

1A.2 SOIL MOISTURE VERSUS WATER TABLE

Alway and McDole [1]† conclude that deep subsoil aquifers (e.g., water table) contribute little, if any, moisture to plants and, hence, to foundations. Upward movement of water below a depth of 12 in (30 cm) was reportedly very slow at moisture contents approximating field capacity. *Field capacity* is defined as the residual amount of water held in the soil after excess gravitational water has drained and after the overall rate of downward water movement has decreased (zero capillarity). Soils at lower residual moisture content will attract water and cause it to flow at a more rapid rate. Water tends to flow from wet to dry in the same way as heat flows from hot to cold—from higher energy level to lower energy level.

Rotmistrov [1] suggests that water does not move to the surface by capillarity from depths greater than 10 to 20 in (25 to 50 cm). This statement does not limit the source of water to the water table or capillary fringe. Richards [1] indicates that upward movement of water in silty loam can develop from depths as great as 24 in (60 cm). McGee [1] postulates that 6 in (15 cm) of water can be brought to the surface annually from depths approaching 10 ft (300 cm). Again, the source of water is not restricted in origin.

The seeming disparity among results obtained by these hydrologists is likely due to variation in

*The abbreviations of units of measure in this book are listed in Appendix C.
†Numbers in brackets indicate references at the end of the sections.

experimental conditions. Nonetheless, the obvious consensus is that the water content of the surface soil tends to remain relatively stable below very shallow depths and that the availability of soil water derived from the water table ceases when the boundary lies at a depth exceeding the limit of capillary rise for the soil. In heavy soils (e.g., clays), water availability almost ceases when the water source is deeper than 4 ft (120 cm), even though the theoretical capillary limit normally exceeds this distance. In silts, the capillary limit may approximate 10 ft (300 cm), as compared to 1 to 2 ft (30 to 60 cm) for sands. The height of capillary rise is expressed by Eq. (1A.1).

$$\pi\gamma_T r^2 h_c = T_{\mathrm{st}}\, 2\pi r \cos\alpha$$

or (1A.1)

$$h_c = \frac{2T_{\mathrm{st}}}{r\gamma_T}\cos\alpha$$

where h_c = capillary rise, cm
T_{st} = surface tension of liquid at temperature T, g/cm
r = radius of capillary pore, cm
α = meniscus angle at wall or angle of contact
γ_T = unit weight of liquid at temperature T, g/cm^2

For behavior in soils, the radius r is difficult, if not impossible, to establish. It is dependent upon such factors as void ratio, impurities, grain size and distribution, and permeability. Since the capillary rise varies inversely with effective pore or capillary radius, this value is required for mathematical calculations. Accordingly, capillary rise, particularly in clays, is generally determined by experimentation. In clays, the height and rate of rise are impeded by the soil's swell (loss of permeability) upon invasion of water. Fine noncohesive soils will create a greater height of capillary rise, but the rate of rise will be slower. More information on soil moisture, particularly that dealing with clay soils, will be found in Parts 6, 7, and 9 of this volume.

1A.3 SOIL MOISTURE VERSUS AERATION ZONE

Water in the upper or aeration zone is removed by one or a combination of three processes: Transpiration, evaporation, and gravity.

1A.3.1 Transpiration

Transpiration refers to the removal of soil moisture by vegetation. A class of plants, referred to as *phreatophytes*, obtain their moisture, often more than 4 ft (120 cm) of water per year, principally from either the water table or the capillary fringe. This group includes such seemingly diverse species as reeds, mesquite, willows, and palms. Two other groups, *mesophytes* and *xerophytes*, obtain their moisture from the soil water zone. These include most vegetables and shrubs, along with some trees. In all vegetation, root growth is toward soil with greater available moisture. Roots will not penetrate a dry soil to reach moisture. The absorptive area of the root is the tip, where root hairs are found. The loss of soil moisture by transpiration follows the root pattern and is generally somewhat circular about the stem or trunk. The root system develops only to the extent necessary to supply the vegetation with required water and nutrition. Roots not accessible to water will wither and die. These factors are important to foundation stability, as will be discussed in following sections.

In many instances, transpiration accounts for greater loss of soil moisture than does *evaporation*.

In another process, *interception*, precipitation is caught and held by foliage and partially evaporated from exposed surfaces. In densely planted areas, interception represents a major loss of rainfall, perhaps reaching as high as 10 to 25% of total precipitation [1].

1A.3.2 Gravity and Evaporation

Gravity tends to draw all moisture downward from the soil within the aeration zone. *Evaporation* tends to draw moisture upward from the surface soil zone. Both forces are retarded by molecular, adhesive, and cohesive attraction between water and soil as well as by the soil's capacity for capillary recharge. If evaporation is prevented at the surface, water will move downward under the forces of gravity until the soil is drained or equilibrium with an impermeable layer or saturated layers is attained. In either event, given time, the retained moisture within the soil will approximate the "field capacity" for the soil in question.

In other words, if evaporation were prevented at the soil surface, as, for example, by a foundation, an "excessive" accumulation of moisture would initially result. However, given sufficient time, even this protected soil will reach a condition of moisture equilibrium somewhere between that originally noted and that of the surrounding uncovered soil. The natural tendency of covered soil is to retain a moisture level above that of the uncovered soil, except, of course, during periods of heavy inundation (rains) when the uncovered soil reaches a temporary state at or near saturation. In this latter instance, the moisture content decreases rapidly with the cessation of rain or other sources of water.

The loss of soil moisture from beneath a foundation caused by unabated evaporation might tend to follow a triangular configuration, with one leg vertical and extending downward into the bearing soil and the other leg being horizontal and extending under the foundation. The relative lengths of the legs of the triangle would depend upon many factors, such as the particular soil characteristics, foundation design, weather, and availability of moisture (Fig.1A.2).

Davis and Tucker [2] reported the depth as about 5 ft (1.5 m) and the penetration approximately 10 ft (3 m). In any event, the affected distances (legs of the triangle) are relatively limited. As with all cases of evaporation, the greatest effects are noted closer to the surface. In an exposed soil, evaporation forces are ever present, provided the relative humidity is less than 100%. The force of gravity is effective whether soil is covered or exposed.

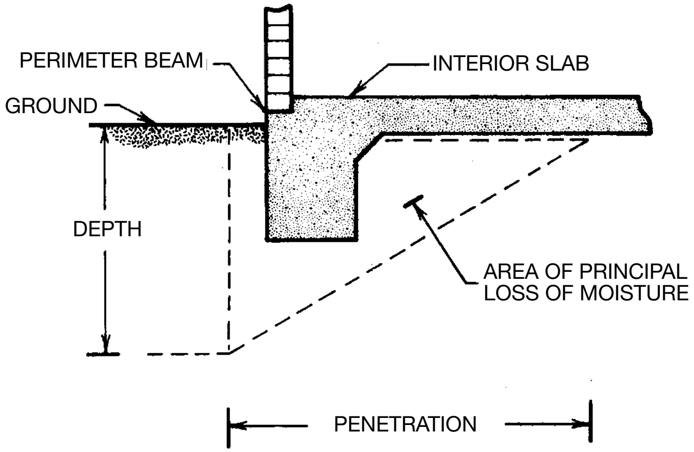


FIGURE 1A.2 Typical loss of soil moisture from beneath a slab foundation during prolonged drying cycle.

1A.4 PERMEABILITY VERSUS INFILTRATION

The infiltration feature of soil is more directly related to penetration from rain or water at the surface than to subsurface vertical movement. The exceptions are those relatively rare instances in which the ground surface us within the capillary fringe. Vertical migration or permeation of the soil by water infiltration could be approximately represented by the single-phase steady-state flow equation, as postulated by Darcy [3].

$$Q = -\left(\frac{Ak}{\mu}\right)\left(\frac{\Delta P}{L} + g_c \sin \alpha\gamma\right) \tag{1A.2}$$

where Q = rate of flow in direction L
A = cross-sectional area of flow
k = permeability
μ = fluid viscosity
$\frac{\Delta P}{L}$ = pressure gradient in direction L
L = direction of flow
γ = fluid density
α = meniscus angle at wall or angle of contact = angle of dip ($\alpha > 0$ if flow L is up dip)
g_c = gravity constant

If $\alpha = 90°$, $\sin \alpha = 1$, and, simplified, Eq. (1.2) becomes

$$Q = -\left(\frac{Ak}{\mu L}\right)(\Delta P + g_c h\gamma)$$

where $h = L \sin \alpha$ and $g_c h\gamma$ is the hydrostatic head.

If $H = \Delta P + g_c h\gamma$, where H is the fluid flow potential, then

$$Q = -\left(\frac{Ak}{\mu}\right)\left(\frac{H}{L}\right)$$

When flow is horizontal, the gravity factor g_c drops out. Any convenient set of units may be used in Eq. (1A.2) so long as the units are consistent. Several influencing factors represented in this equation pose a difficult deterrent to mathematical calculations. For example, the coefficient of permeability k can be determined only by experimental processes and is subject to constant variation, even within the same soil. The pore sizes, water saturation, particle gradation, transportable fines, and mineral constituents all affect the effective permeability k.

In the instance of expansive clays, the variation is extremely pronounced and subject to continuous change upon penetration by water. The hydraulic gradient ΔP and the distance over which it acts, ΔL, are also elusive values. For these reasons, permeability values are generally established by controlled field or laboratory tests in which the variables can be controlled. In the case of clean sand, the variation is not nearly as extreme, and reasonable approximations for k are often possible.

In essence, Eq. (1A.2) provides a clear understanding of factors controlling water penetration into soils but does not always permit accurate mathematical calculation. The rate of water flow does not singularly define the moisture content or capacity of the soil. The physical properties of the soil, available and residual water, and permeability each affect infiltration. A soil section 3 ft (90 cm) thick may have a theoretical capacity for perhaps 1.5 ft (0.46 m) of water. This is certainly more water than results from a serious storm; hence, the moisture-holding capacity is seldom, if ever, the limiting criterion for infiltration. That is as it would appear from the foregoing paragraphs.

To better comprehend the variations in the permeability coefficient *k*, consider the following values, sometimes considered "typical" for various soils (after Terzaghi and Peck, *Soil Mechanics in Engineering*, 2nd Ed., Wiley, New York, 1967):

Sand: 10^{-3} to 10^{-5} cm/s (1000 to 10 ft/year)

Silty Clay: 10^{-5} to 10^{-7} cm/s (10 to 0.1 ft/year)

Clay: less than 10^{-7} cm/s (less than 0.1 ft/year)

In a more specific vein, Dr. Malcomb Reeves reported permeability values for London clay of 1 cm/day (2.78×10^{-4} cm/s or 278 ft/year); refer to Sec. 6A.6. In the case of expansive soils, the horizontal permeabilities K_h often exceed the indicated values K_v by a factor of 10 or more. This is because of the presence of fissures, roots, induced fractures, bedding planes, etc.

In addition to the problems of permeability, infiltration has an inverse time lag function. Figure 1A.3 is a typical graphical representation of the relationship between infiltration and runoff with respect to time. At onset of rain, more water infiltrates, but over time, most of the water runs off and little is added to the infiltration.

Clays have a greater tendency for runoff, as opposed to infiltration, than sands. The degree of the slope of the land has a comparable effect, since steeper terrains deter infiltration. Only the water that penetrates the soil is of particular concern with respect to foundation stability. The water that fails to penetrate the soil is briefly discussed in Section 1A.5.

1A.5 RUNOFF

Any soil at a level above the capillary fringe tends to lose moisture through the various forces of gravity, transpiration, and evaporation. Given sufficient lack of recharge water, the soil water belt

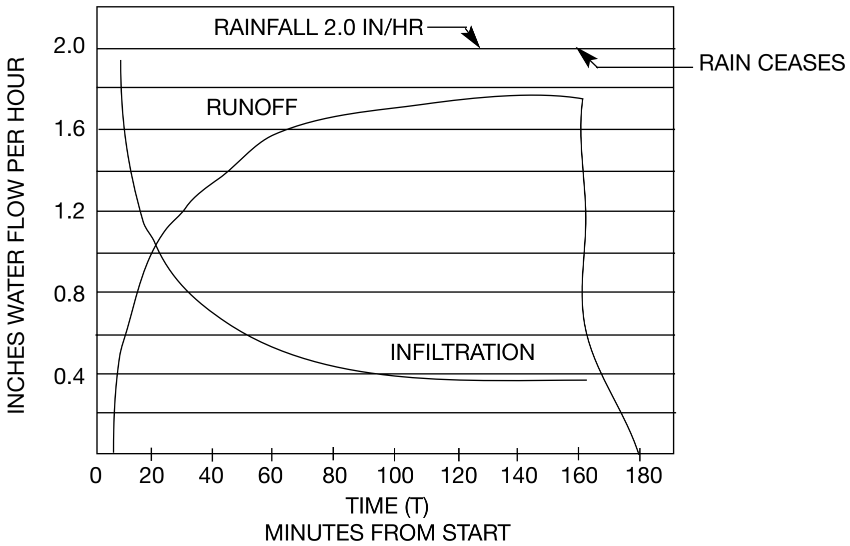


FIGURE 1A.3 Typical case of infiltration versus runoff after a 2 in/h rainfall.

will merge with and become identical in character to the intermediate belt. However, nature provides a method for replenishing the soil water through periodic rainfall. Given exposure to rain, all soils absorb water to some varying degree, dependent upon such factors as residual moisture content, soil composition and gradation, and time of exposure. The excess water not retained by the soil is termed *runoff* (Fig. 1A.3).

As would be expected, sands have a high absorption rate and clays have a relatively low absorption rate. A rainfall of several inches over a period of a few hours might saturate the soil water belt of sands, but penetrate no more than 6 in in a well-graded, high-plasticity soil. A slow, soaking rain would materially increase penetration in either case. The same comparison holds whether the source of water is rain or watering. Parts 7 and 9 also develop the importance of maintaining soil moisture to aid in preventing or arresting foundation failures.

1A.6 GROUNDWATER RECHARGE

Even in arid areas, an overabundance of water can occur sporadically due, principally, to storm runoff. If these surpluses can be collected and stored, a renewable resource is developed that involves conservation during periods of plenty for future use during times of shortage. Generally, this storage can be in the form of surface reservoirs or recharged aquifers [5].

Surface reservoirs suffer losses from evaporation, as well as occasional flooding, and are somewhat limited because of topographical demands.

Underground storage can be realized through natural groundwater recharge or artificial recharge. The obvious advantage to either form of underground storage is high capacity, simplicity, no evaporation losses, and low costs. Natural groundwater recharge occurs when aquifers are unconfined, surface soils are permeable, and vadose (aeration) zones have no layers that would restrict downward flow. When and where the foregoing conditions do not exist, artificial recharge is necessary. The latter requires that a well be drilled into the aquifer. Such wells can be used to inject water into or remove water from the aquifer, or both, depending on supply and demand. The prime storage zones include limestone, sand, gravel, clayey sand, sandstone, and glacial drift aquifers. The quality of the aquifers and recharge water depends mostly upon availability. Under the most adverse conditions, appropriate thought, well design, and operation procedures can produce potable water. Additional detail on this topic can be found in Ref. 5.

1A.7 CLAY SOIL

Preceding sections have suggested the influence of groundwater hydrology on foundation stability. This is most certainly true when the foundation-bearing soil contains an expansive clay. One complex and misunderstood aspect is the effect roots have on soil moisture. Without question, transpiration removes moisture from the soil. Exactly how much, what type, and from where represent the basic questions. If the roots take only pore (or capillary) water and/or remove the moisture from depths deeper than about 3 to 7 ft (1 to 2 m), the moisture loss is not likely to result in shrinkage of the soils sufficient to threaten foundation stability.

1A.8 SOIL MOISTURE VERSUS ROOT DEVELOPMENT

Logically, in semiarid climates, the root pattern would tend to develop toward deeper depths. In wetter areas, the root systems would be closer to the surface. In that instance, the availability of moisture would be such that the roots' needs could be supplied without desiccation of the soil; see Figs.

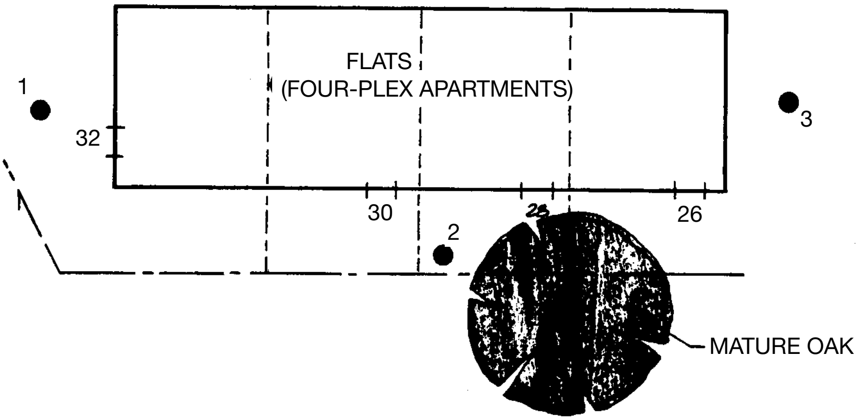


FIGURE 1A.4 Location plan.

1A.4 and 1A.5 and Table 1A.1. [An explanation of the Atterberg limits (LL, PL, and PI) is given in Sec. 2A.]

The soil in question is identified as a London clay with physical and chemical characteristics similar to many of the typical fat clays found in the United States. The London climate has a C_W factor* in range of 35 to 40, which is similar to that for Mississippi and Washington. Note that the soil moisture content remains constant from 2 to 5 m (6.6 to 16.4 ft) despite the close proximity of the mature oak tree (Table 1.1). Although this observation might be surprising, it is by no means an isolated instance. The test borings provided data on the loss of soil moisture, but there was nothing to indicate the root pattern. This information is not critical but would have been interesting. Note, however, that all tests commenced below the 2 ft (0.6 m) level, which seems to be the maximum depth from which roots remove moisture in this environment. (Refer to Sec. 6A.6, "Clay Mineralogy," and Sec. 7B.5, "Expansive Soils," for additional information concerning water behavior in clay soils.) In areas with more extreme climates and the same general soil, the root development pattern would more closely resemble that in Fig. 1A.6. It is worth mentioning that, during earlier growth stages, particularly if the tree is being conscientiously watered, the root system might be quite shallow—within the top 1 ft (30 cm) or so. Dry weather (lack of "surface" moisture) forces the roots to seek deeper soils for adequate water. The surface roots can remain dormant in a low-moisture environment for extended periods of time and become active again when soil moisture is restored.

Although the so-called *fat clays* are generally impermeable, thus limiting true capillary transfer of water, intrinsic fractures and fissures allow the tree or plant root system to pull water from soil a radial distance away somewhat in excess of the normal foliage radius. A side point worthy of mention is that when transpiration is active, evaporation diminishes (the shaded areas lose less moisture). The net result is often a conservation of soil moisture. The depth within which seasonal soil moisture varies is often referred to as the *soil active zone*. The total soil moisture change involves both evaporation and transpiration.

With respect to Fig. 1A.6, Dr. Don Smith, Botanist at The University of North Texas, Denton, suggests certain generalities:

1. D_1 is in the range of 2 ft (0.6 m) maximum.
2. W_r is in the range of $1.25XW$, where W is the natural canopy diameter (unpruned).

*C_W is the climatic factor developed by the Building Research Advisory Bulletin (BRAB). It is used in the design of slab-on-ground foundations.

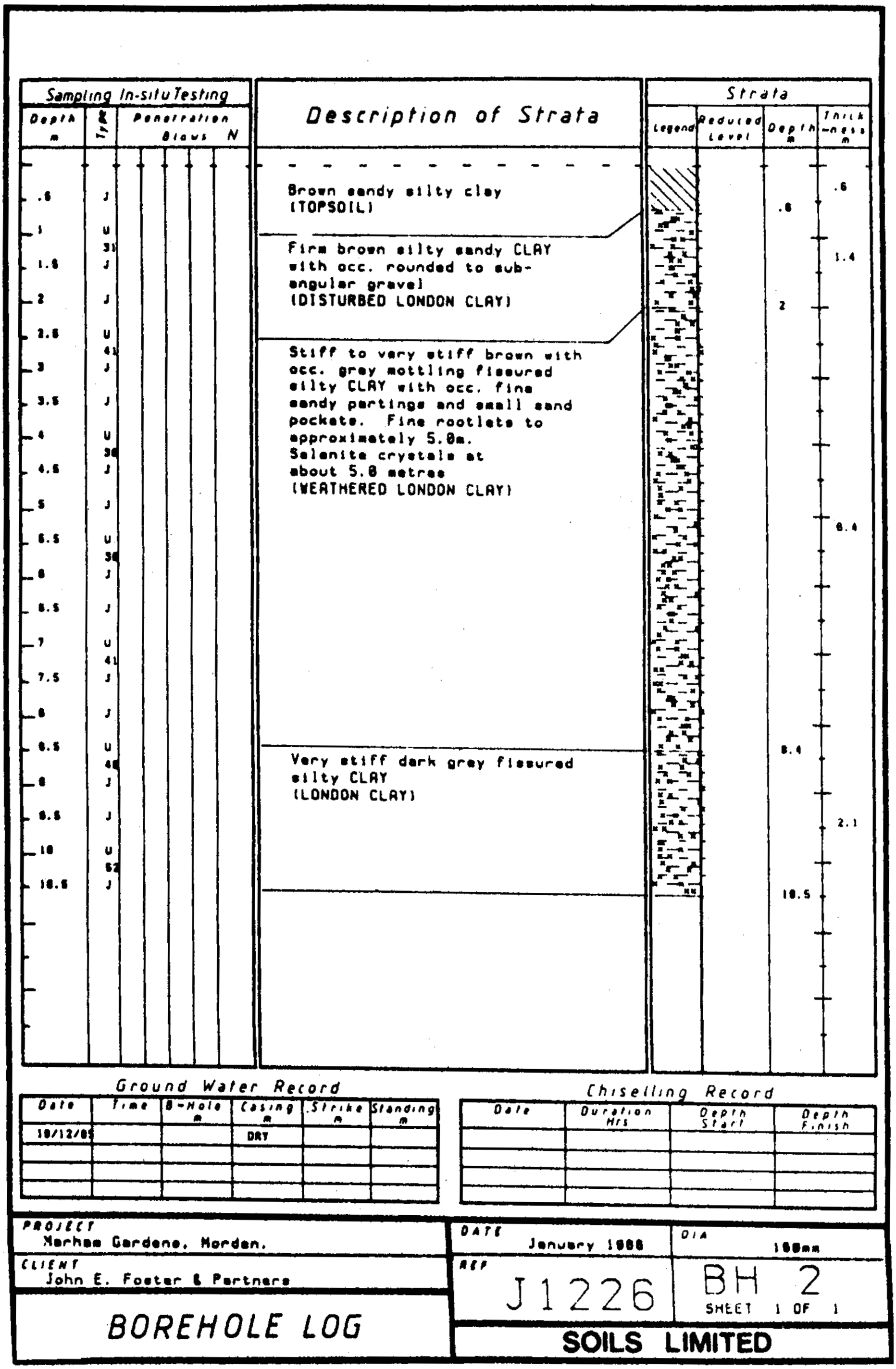
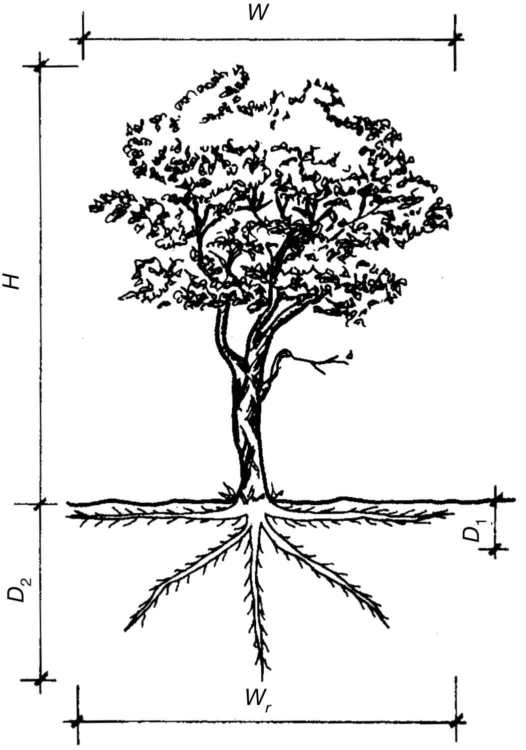


FIGURE 1A.5 Borehole log.

TABLE 1A.1 Atterberg Limits and Soil Moisture for London Clay BH No. 2: Brown-Gray Mottled Silty Clay

Depth						
m	ft	LL, %*	PL, %*	PI, %*	*W*, %*	Soil classification
2.0	6.6	93	27	66	30	CE
3.5	11.5	86	28	59	30	CV
4.5	14.8	89	28	61	30	CV
5.0	16.4	85	26	59	29	CV

*LL = liquid limit; PL = plastic limit; PI = plasticity index; *W* = natural moisture. The British Soil Classification uses CV for soils with an LL between 70 and 90 and CE for soils with an LL in excess of 90.



W - DIAMETER OF CANOPY (UNPRUNED) DRIP LINE
H - HEIGHT
D_1 - DEPTH OF LATERAL ROOTS
D_2 - DEPTH OF DEEP ROOTS (TAP ROOTS)
W_r - DIAMETER OF LATERAL ROOTS

FIGURE 1A.6 Root system.

3. When moisture is not readily available at D_1, the deeper roots D_2 increase activity to keep the tree's needs satisfied. If this is not possible, the tree wilts.
4. H has no direct correlation to W_R, D_1, or D_2 except the indirect relation that H is relative to the age of the tree.

T. T. Koslowshi [6] and the National House-Building Council [7] suggest values for D_2, and the effective D_1, as shown in Table 1A.2. Note that the depth of soil moisture loss due to the near surface feeder roots is not to be confused with depth of total soil moisture loss (activity zone). The important point is that soil moisture losses from either transpiration or evaporation normally occur from relatively shallow depths. Both Tucker and Davis [2] and Tucker and Poor [8] report test results that indicate that 84% of total soil moisture loss occurs within the top 3 to 4 ft (1 to 1.25 m) (Fig. 1A.7). The soil involved was the Eagle Ford (Arlington, Texas) with a PI in the range of 42. Other scientists, such as Holland and Lawrence [9], report similar findings. The last publication suggests soil moisture equilibrium below about 4 ft (1.25 m) from test data involving several different clay soils in Australia with PIs ranging from about 30 to 60.

It might be interesting to note that the data accumulated by Tucker, Davis, and others [2,8,10] seem to indicate both minimal losses (if any) in soil moisture beneath the foundation and shallow

TABLE 1A.2a Depth of Tree Roots, Plains Area, United States*

Name	Age, years	D_2, ft (m)
Plantanus occidentalis (American sycamore)	6	7 (2.1)
Juglans nigra (black walnut)	6	5 (1.5)
Quercus rubra (red oak)	6	5 (1.5)
Carya ovata (shag bark hickory)	6	5 (1.5)
Fraxinus americana (ash)	6	5 (1.5)
Populus deltoides (poplar or cottonwood)	6	6 (1.8)
Robinia pseudoacacia (black locust)	Unknown	24–27 (7.3–8.2)

*After Ted Koslowski [6].

TABLE 1A.2b Depth of Tree Roots, London, England (PI above 40)*

Name	Age	D_1 m (ft)†	H (height), m (ft)
High water demand			
Elm	Mature	3.25 (10.6)	18–24 (59–79)
Oak	Mature	3.25 (10.6)	16–24 (52–79)
Willow	Mature	3.25 (10.6)	16–24 (52–79)
Moderate water demand			
Ash	Mature	2.2 (7.2)	23 (75)
Cedar	Mature	2.0 (6.6)	20 (65.6)
Pine	Mature	2.0 (6.6)	20 (65.6)
Plum	Mature	2.0 (6.6)	10 (32.8)
Sycamore	Mature	2.2 (7.2)	22 (72)
Low water demand			
Holly	Mature	1.55 (4.9)	12 (39.4)
Mulberry	Mature	1.45 (4.7)	9 (29.5)

*After National House-Building Council, United Kingdom [7].
†Interpolation of *maximum* depth of root influence on foundation design at $D = 2$ m, per Ref. 7.

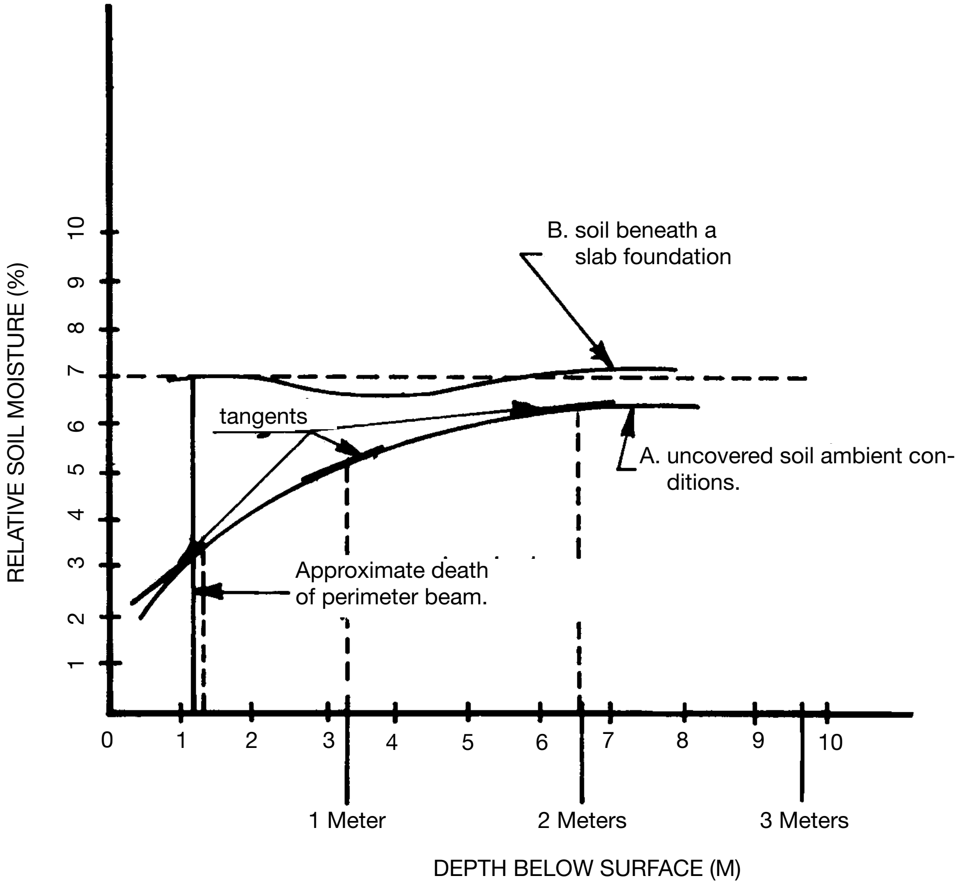


FIGURE 1A.7 Typical loss of soil moisture versus depth during a prolonged drying cycle. The tangent lines indicate the dramatic change in comparative soil moisture versus depth. (*From Davis and Tucker, Ref. 2.*)

losses outside the perimeter (Fig. 1A.7). Curve B presents moisture values taken from soil beneath the foundation. These data suggest slightly higher moisture levels than those plotted in curve A but also reflect a generally uniform buildup. The data in Fig. 1A.7 show that, while soil moisture varies to a depth of perhaps 7 ft (2.14 cm), over 85% of total soil moisture change occurred within the top 3 ft or so. Data published by McKeen and Johnson [12] reflect the same general conclusion. Their data reflect a relationship between the depth of the active zone, which varies with both suction (or capillary) pressure, and the number of cycles of wetting and drying that occur within the year. Nonetheless, between 80 and 90 percent of the total soil moisture variation occurred within the top 1.5 m (4.5 ft). Komornik presents data on an Israeli soil that show similar results [13]. The depth of moisture change extended to 11½ ft (3.5 m), but approximately 71% of the total change occurred within the top 3.2 ft (1 m). Sowa presented data that suggest an active depth of 0.3 to 1.0 m (1 to 3.2 ft) for a Canadian soil [14]. These observations, again, would seem to support the foregoing conclusions and opinions. A source for similar information can be found in “Building Near Trees” [7].

This document presents data compatible with those previously cited. Again the only question involves the issue of whether the tree height H is the important dimension describing root behavior or whether the canopy width W is the true concern, as apparently believed by most botanists.

Other authorities who agree with the statements concerning shallow feeder roots are John Haller [15], Neil Sperry [16], and Gerald Hall [17]. Haller states that the majority of feeder roots are found within 1 to 1½ ft (30 to 45 cm) of the surface. He explains that ". . . it is here that the soil is the richest and aeration the simplest." Both air and nutrition (water) are required by the healthy tree. Sperry and Hall concur. Deeper root systems are present but their primary function is to provide stability to the tree. In fact, the tap roots have the principal relationship to the tree height. This correlation is exploited by Bonsai growers who dwarf trees by shortening the tap root.

Many geotechnical engineers do not seem to share these views expressed by botanists. Dr. Poor seems to feel that the radial extent of a tree's root pattern is greater (H to $1.5H$) and the depth of moisture loss to transpiration is deeper [8]. Part of the apparent basis for his beliefs are presented in Fig. 1A.7 and in Sec. 1A.8.1 as item 11. These data as interpreted by the author seem to provide a limit on root radius of $0.5W$ (canopy width) and transpiration effective depth due to shallow feeder roots of less than 2.0 ft (61 cm) [11]. These values are of primary concern to foundation stability.

The overall maximum depth of effective soil moisture loss (active zone) appears to be in the range of about 1 to 4 m (3.2 to 12.8 ft), depending on the proximity of trees and geographic location [8,9,12–14,18]. Transpiration losses at depths below 2 m (6.6 ft), may not materially influence foundation stability [18]. These conclusions are also supported by the author's experience from 1963 to the present. The root systems for plants and shrubs would be similar to that shown in Fig. 1A.6, except on a much smaller scale. The interaction of tree root behavior and foundation failure is considered in following sections, especially 7A, 7B, 7C, and 9A.

1A.8.1 Summary: Soil moisture behavior

1. Roots per se provide a benefit to soil (and foundation) stability since their presence increases the soil's resistance to shear [19,23]. Also, the plant canopy (shade) reduces evaporation and, overall, may conserve soil moisture.

2. Tree roots tend to remove soil moisture; hence the net result, if any, is foundation settlement. Settlement is normally slow in developing, limited in overall scope, and can be arrested (or reversed) by a comprehensive maintenance program. (Refer to Sec. 7A.) Chen [20] states, "The end result of shrinkage around or beneath a covered area seldom causes structural damage and therefore is not an important item to be considered by soil engineers." Other noted authors might disagree, at least to some extent. Mike Crilly, of the Building Research Establishment, London (and others within that organization [22]) presents data shown in Fig. 1A.8 [21]. These data were collected by using rods embedded in the ground. Group 1 data, away from trees, suggest negligible soil movement at depths below the surface. (The surface loss was likely due to grass and evaporation. Refer also to item 9, below.) Group 2 data show vertical movement potential at the surface of 100 mm (4 in) and about 60 mm (2.4 in) at 1 m (3.3 ft), but below 2 m (6.6 ft) the movement is on the order of less than 15 mm (0.6 in). The data bring to mind two questions: (1) what would the moisture (and vertical movement) profiles look like if the data were taken from foundation slabs designed with perimeter beams and (2) would the conventional foundation design preclude damage? Others have suggested that surface soil movement can be related to the movement of slab foundations, although it is not always clear how the correlation might be made [2,8,22]. For example, would tests using 1 m^2 (10.89 ft^2) pads poured on the ground surface relate to tests using larger pads, i.e., 400 m^2 (4356 ft^2), or conventional foundations?

3. While some degree of settlement is noted in most light foundations on expansive soils, that specific problem by itself is seldom sufficiently serious to demand repair. In fact, according to a random sampling of over 25,000 repairs performed (principally within the Dallas–Fort Worth area) over a period in excess of 30 years, the incidence of settlement versus upheaval (as the preponderant

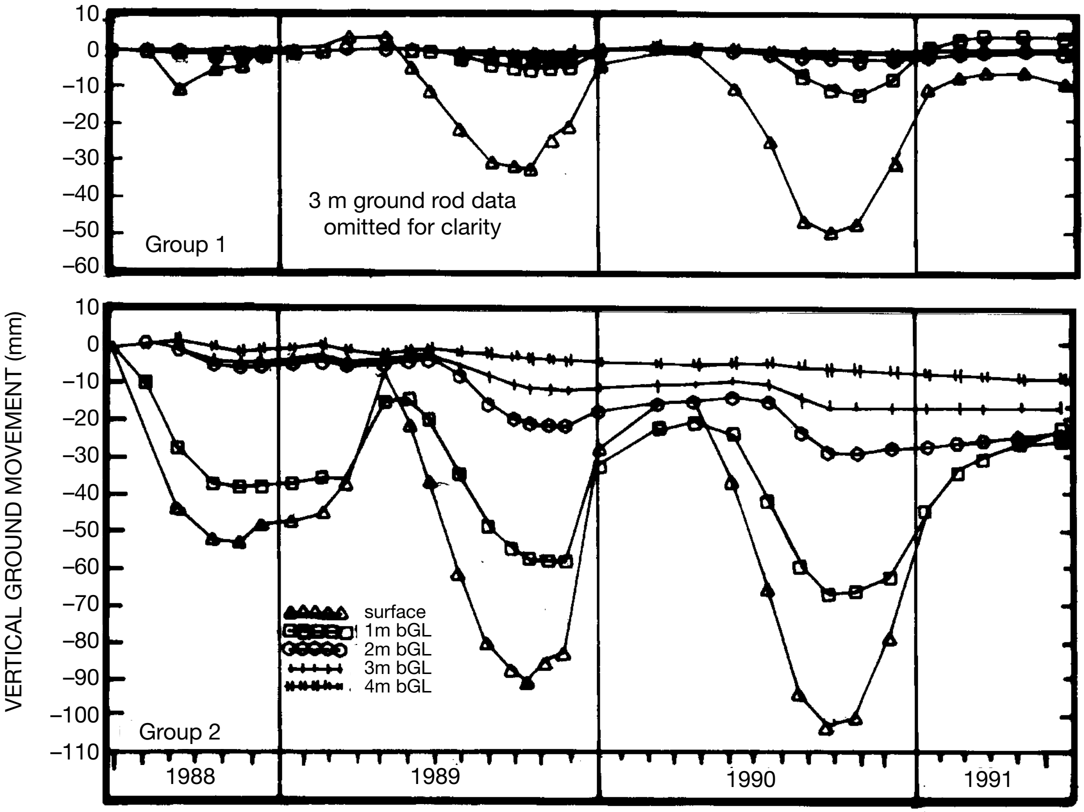


FIGURE 1A.8 Results obtained from ground movement rods: remote from trees (Group 1); and near trees (Group 2).

cause for repair) was about 1.0 to 2.3 (30 to 70%). [Three out of four foundations repaired were of slab construction (as opposed to pier-and-beam) and over 94% of the foundations were of steel-reinforced concrete construction.] Most of the repairs catalogued as "settlement" involved instances of: (1) shimming of interior pier caps (pier-and-beam foundation), (2) underpinning (raising) slab foundation wherein proper mudjacking was not included in the initial repairs and subsequent mudjacking of the interior slab was required, or (3) foundations constructed on uncompacted fill. Delete these from the settlement statistics and the incidence of settlement repairs is reduced to something like 3%.

4. Texas' shallow soils generally exist at moisture levels between the SL and PL with, as a rule, the moisture contents somewhat closer to PL.* In deeper soils, the *W*% is something higher, between the PL and LL. (For comparative purposes, the C_W rating ≈ 20.)

5. All soil *shrinkage* ceases when *W*% approaches the SL (by definition) and does not commence until the moisture content is decreased below the LL. *Soil swell* in expansive soils effectively ceases at *W*% content above or near the PL. (Refer to Chap. 6.) Thus, moisture changes at levels much below the LL or much above the SL do not affect expansive soil volume (or foundation movement) to any appreciable extent.

*The Atterberg limits (LL, PI, PL, SL, *W*%) are discussed in detail in Sec. 2A.

6. Expansive soil particles tend to shrink at moisture *reductions* between something below the LL and the SL. Refer to Fig. 1A.8 [23]. Those existing at a *W*% between the SL and PL tend to swell upon access to water. Refer to Figs. 7B.2 and 1A.8. [*Nonexpansive* (or noncohesive) soils are prone to shrink when water is removed from them at or near saturation (or LL). Particle consolidation largely accounts for this volumetric decrease rather than particle shrinkage.]

7. The data depicted in Fig. 1A.9 (McKenn, Ref. 24) suggest a basic relationship between soil volume change and *W*% expressed as pF [pF is the logarithm to base 10 of the pressure in centimeters of water (1 pF = 1 kPa, 2 pF = 10 kPa, 3 pF = 100 kPa, etc.)]. The range of volume change versus pF decreases between the field capacity (2.2 pF) and shrinkage limit (5.5 pF). For more practical concerns, a plant's removal of water (transpiration) is probably limited even further, to that level between field capacity (2.2 pF) and the point of wilt (4.2 to 4.5 pF). Note that the field capacity represents a *W*% less than the LL and the point of plant wilt is well above the SL. Similar conclusions have been published by F. H. Chen [20].

Evapotranspiration, on the other hand, would transcend a wider scope. The combined effect of soil moisture withdrawal could reflect soil volume changes between the field capacity and SL—a wider range than that likely for transpiration alone.

A soil can gain or lose moisture, within specific limits, without a corresponding change in volume [20,23,24].

8. There is definitely a relationship between shrinkage and swell in an expansive soil. A soil that swells will shrink (and vice versa) upon changes in available moisture. However, assume a given specimen where an increase of 4% moisture produces a swell of *X*%. Will removal of 4% moisture cause the soil to shrink *X*%? Not likely [20].

Chen's report, outlining a series of tests using a Denver remolded clay shale, indicates that only at the point of critical dry density does shrinkage equal swell [20]. Figure 1.10 depicts test data showing the shrink and swell resulting from controlled initial moisture contents. In these tests, the dry density was kept reasonably constant (107.0 ± 0.6 lb/ft^3) and the initial moisture content was

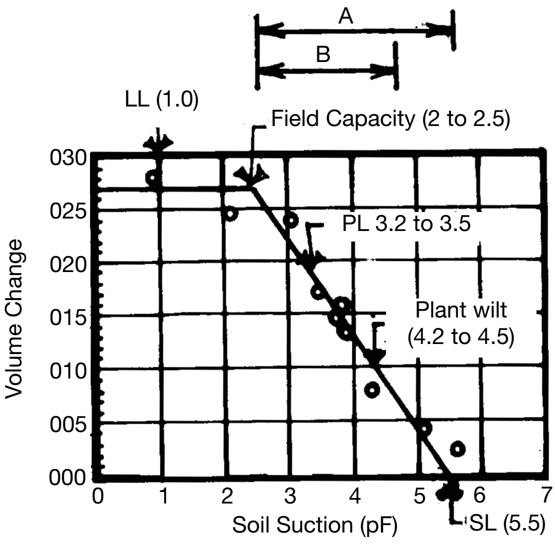


FIGURE 1A.9 Range of relative volume change. A: evaporation and transpiration; B: transpiration.

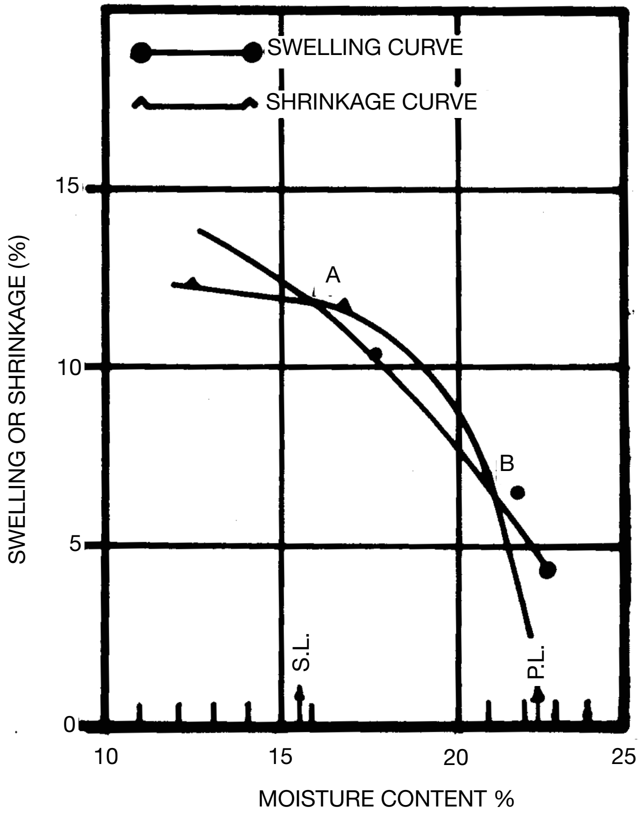


FIGURE 1A.10 Effects of moisture content on swelling and shrinkage.

varied from slightly below the shrinkage limit (15.5% versus 15.1%) to slightly below the plastic limit (22.4% versus 22.3%). The samples were placed under a surcharge pressure of 1 lb/in^2 (7 kPa) and allowed to swell in distilled water. After two or three days the specimens were removed from the water, weighed, and allowed to dry. Once air-dried to initial weight, each specimen was again weighed and the density and moisture content determined. From these data, the percent shrinkage or swell was determined.

As expected, the swell potential decreases as the initial moisture (in situ) increases, approaching zero as the moisture contents nears saturation. Also, shrinkage ceases both at the moisture content referred to as the shrinkage limit (SL) and at or near saturation. Shrinkage is equal to swell at points *A* and *B*. Between the points *A* and *B* shrinkage potential is greater than swelling. Outside this range, the reverse is true.

9. Heave of surface soils occurs mostly within rather confined limits, as noted above (SL to proximity PL). It would seem that removal of surface vegetation in a $C_W \approx 20$ climate would encourage soil desiccation as opposed to net *W*% gain (assuming reasonable drainage). If expansive soils are properly drained, it would seem likely that *W*% variations largely would occur at relatively shallow depths. In climates such as London's [30 in (76 cm) annual rain distributed over about 152 days)], the in situ *W*% in absence of transpiration (lack of evaporation) should, in fact, increase.

However, once again, this effect on soil *movement* begins to cease as the *W*% approaches or somewhat exceeds the PL. It would seem that *W*% in London, for example, would be consistently higher that in the United States. London's rainfall (though roughly equivalent to Dallas–Fort Worth's annual rainfall of 30 in) is distributed rather evenly over 152 days as opposed to the 15 days that account for 80% of the Dallas–Fort Worth precipitation. The considerably more moderate temperature ranges would combine with the extended rain to logically produce both higher and generally more stable *W*%. [The annual average temperature in the Dallas–Fort Worth area is about 65°F (18°C), whereas that for London is about 52°F (11°C). The relative temperature *ranges* are 15° to 105°F (–9° to 40°C) for Dallas–Fort Worth and 38° to 78°F (3° to 25°C) for London.]

10. Vegetation (transpiration) removes soil moisture mostly at very shallow depths [15–17]. The U.S. horticulture community invariably recommends that trees be watered and fed at or near the drip line (extend of canopy). Further, most agree that nutritional roots are classically quite shallow—within 12 to 24 in (30 to 60 cm). The reasons given include: (1) root development favors loosely compacted soil, (2) roots like oxygen, (3) roots like water, (4) roots like sunlight (to some extent), and (5) roots exert only that energy necessary for survival. Under particularly adverse conditions (such as a prolonged draught) feeder roots may develop at deeper depths. Still it is generally agreed that 90% of the tree's moisture needs are taken from 12 to 24 in (30 to 60 cm).

11. It has been well established by many research projects that foundation stability is not influenced by soil behavior below the soil active zone (SAZ). In Dallas, the preponderance (87%) of that influence on foundation stability is limited to about 3 ft (1 m), although the SAZ may extend to depths in excess of 7 ft (2.13 m). [8,11] Other geographical locations report different depths for the active zone. For example: (1) for a Canadian soil, Sowa [14] indicates the depth of the soil active zone to be 1 to 3 ft (0.3 to 1 m); (2) for an Israeli soil, Komornik [13] reports an active soil zone as deep as 11.5 ft (3.5 m) but approximately 71% of the total moisture variation occurrs within the top 3.2 ft (1 m); (3) Holland and Lawrence report data on an Australian soil where soil moisture equilibrium depth is less than 4 ft (1.25 m) [9].

12. Other factors of concern include such issues as: (1) overburden tends to suppress soil expansion; doubling the effective overburden pressure (1000 to 2000 lb/ft^2) can reduce swell by about one-third (F. H. Chen) [20]; (2) the surcharge load on the soil diminishes with depth (for strip footings the effect of load is in the range of only 10% at a depth of twice the width); and (3) low soil permeabilities severely inhibit soil moisture movement, particularly in a vertical direction [expansive (sedimentary) soils in general have much higher lateral than vertical permeability].

13. Without a doubt, the age and proximity of the tree (and the depth of the perimeter beam) are very important factors that affect the amount of water a tree might remove from the foundation-bearing soil. Certainly, younger trees tend to remove moisture at a faster and greater relative rate. Also, trees tend to require much more water during growth periods. Without the leaves or during dormancy, a tree might require as little as 1% of the growth amount of moisture. The influence of transpiration or foundation stability should thus be relative to season. It would seem wise in most cases not to plant new trees in close proximity to the foundation. Nonetheless, concrete evidence available to the author seems to suggest that the impact of vegetation on the stability of foundation is grossly overstated. Any *proof* to the contrary would be welcome.

14. Many engineers in the United States (and probably elsewhere as well) confuse center heave with perimeter settlement. Hence, the influence of trees is often overstated. (Refer to Sects. 7A. and 9A.) Sound evidence and not wishful thinking should be the final criterion for decision making. One source for reliable data offers a history of over 25,000 actual repairs performed over 30 years. Many of these repairs were performed on structures with trees (in some cases multiple trees) located in close proximity to the foundations, sometimes as close as 1 ft (0.3 m). There is no memory of the repair company suggesting or requiring the removal of any tree, bush, or other vegetation. Yet in absence of tree removal, none of the repairs experienced a subsequent failure that could be attributed to the presence of a tree, bush, or vegetation. (These data were collected primarily from the Dallas–Fort Worth area of Texas but data points included other states from Arizona to Illinois and Oklahoma to Florida.) Does this seem to dispute the deleterious influence of trees on foundation stability? If the trees played a predominate part in causing the initial foundation failure, why did not

the same or similar problem recur? Also *many* other foundations within the same areas have a tree (or trees) in close proximity to the foundation, yet never suffer foundation distress. It does not stand to reason that trees are capable of preferentially selecting one address over another.

15. Again with reference to the study mentioned above and item 3, most of the repair causes were attributed to upheaval brought about by the accumulation of water beneath the slab foundation. (Once the source for water was removed, the foundation stabilized.) There seems to be some confusion in terminology in addressing slab heave on expansive soils. An often misused term is *natural center doming*, which allegedly describes the buildup of soil moisture due to capillary and/or osmotic transfer. Proponents believe that this phenomenon occurs in most slab-on-grade foundations, with the net result being a central high or domed area. Research does not verify this conclusion [9,11]. Also, for greater detail, refer to Sections 7A, 7B, 7C, and 8. *Center lift* is another term used in the BRAB and Post Tension Institute (PTI) books (Refs. 25, 26). This is an important design concern that relates more to upheaval than to *center doming*. (Refer to Sec. 9A.)

1A.9 CONCLUSIONS

What factors have become obvious with respect to soil moisture as it influences foundation stability?

1. Soil moisture definitely affects foundation stability, particularly if the soil contains expansive clays.
2. The soil belt is the zone that affects or influences foundation behavior the most.
3. Constant moisture is beneficial to soil (foundation) stability.
4. The water table, in itself, has little, if any, influence on soil moisture or foundation behavior, especially where expansive soils are involved.
5. Vegetation can remove substantial moisture from soil. Roots tend to find moisture. In general, transpiration occurs from relatively shallow depths.
6. Introduction of excessive (differential) amounts of water under a covered area is cumulative and threatens stability of some soils. Sources for excessive water could be subsurface aquifers (e.g., temporary perched groundwater), surface water (poor drainage), and/or domestic water (leaks or improper watering). Slab foundations located on expansive soils are most susceptible to the latter. Refer to Sects. 7A, 7B, 7C, and 9A.
7. Assuming adequate drainage, proper watering (uniformly applied) is absolutely necessary to maintain consistent soil moisture during dry periods—both summer and winter.
8. The detrimental effects on foundations from transpiration appear to be grossly overstated.

The homeowner can do little to affect either the design of an existing foundation or the overall subsurface moisture profile. From a logistical standpoint, about the only control the owner has is to maintain moisture around the foundation perimeter by both watering and drainage control and to preclude the introduction of domestic water under the foundation. Adequate watering will help prevent or arrest settlement of foundations on expansive soils brought about by soil shrinkage resulting from the loss of moisture.

From a careful study of the behavior of water in the aeration zone, it appears that the most significant factor contributing to distress from expansive soils is excessive water beneath a protected surface (foundation), which causes the soil to swell (upheaval). From field data collected in a 30 year study (1964–1994), including some 25,000 repairs, it is an undeniable fact that a wide majority of these instances of soil swell were traceable to domestic water sources as opposed to drainage deficiencies. Further, the numerical comparison of failures due to upheaval versus settlement was estimated to be in the range of about 2 to 1. Refer to Sects. 7A, 7B, 7C, and 8 for more detailed information. Also bear in mind that the data described were accumulated from studies within a C_W rating (climatic rating) of about 20 (refer to Fig. 7.B.8.3). This describes an area with annual rainfall in the range of 30 in (75 cm) and mean temperatures of about 65°F (18°C).

REFERENCES

1. O. E. Meinzer et al., *Hydrology,* McGraw-Hill, New York, 1942.
2. R. C. Davis and R. Tucker, “Soil Moisture and Temperature Variation Beneath a Slab Barrier on Expansive Clay,” *Report No. TR-3-73,* Construction Research Center, University of Texas at Arlington, May 1973.
3. S. J. Pirson, *Soil Reservior Engineering,* McGraw-Hill, New York, 1958.
4. D. B. McWhorter and D. K. Sunada, *Ground-Water Hydrology and Hydraulics*; Water Resourses, Fort Collins, Colo, 1977.
5. H. Bouwer, R. A. G. Pyne, and J. A. Goodwich, “Recharging Ground Water,” *Civil Engineering,* June 1990.
6. T. T. Koslowski, *Water Deficits and Plant Growth,* vol. 1, Academic Press, New York, 1968.
7. “Building Near Trees,” Practice Note 3 (1985), National House-Building Council, London.
8. R. Tucker and A. Poor, “Field Study of Moisture Effects on Slab Movement,” *Journal of Geotechnical Engineering,* ASCE, vol. 104 N GT, April 1978.
9. J. E. Holland and C. E. Lawrence, “Seasonal Heave of Australian Clay Soils” and “The Behavior and Design of Housing Slabs on Expansive Clays,” *4th International Conference on Expansive Soils,* ASCE, June 16–18, 1980.
10. T. M. Petry and C. J. Armstrong, “Geotechnical Engineering Considerations for Design of Slabs on Active Clay Soils,” ACI Seminar, Dallas, February 1981.
11. R. W. Brown, *Foundation Behavior and Repair: Residential and Light Commercial,* McGraw-Hill, New York, 1992.
12. R. G. McKeen and L. D. Johnson, “Climate Controlled Soil Design—Parameters for Mat Foundations,” *Journal of Geotechnical Engineering,* vol. 116, no. 7, July 1990.
13. D. Komornik et al., “Effect of Swelling Clays on Piles,” Israel Institute of Technology, Haifa, Israel.
14. V. A. Sowa, “Influences of Construction Conditions on Heave of Slab-on-Grade Floors Constructed on Swelling Clays,” *Theory and Practice in Foundation Engineering,* 38th Canadian Geotechnical Conference, September 1985.
15. J. Haller, *Tree Care,* McMillan Publishing, New York, and Collier McMillan Publishing, London, 1986 (p. 206).
16. N. Sperry, *Complete Guide to Texas Gardening,* Taylor Publishing Co., Dallas, 1982.
17. G. Hall, “Garden Questions—How to Get a Fruitful Apple Tree,” *Dallas Times Herald,* March 24, 1989.
18. T. J. Freeman et al., “Seasonal Foundaiton Movements in London Clay,” *Ground Movements and Structures,* Fourth International Conference, University of Wales College of Cardiff, July 1991.
19. T. H. Wu et al., “Study of Soil–Root Interaction,” *Journal of Geotechnical Engineering,* vol. 114, December 1988.
20. F. H. Chen, *Foundation on Expansive Soils,* Elsevier, New York, 1988.
21. M. S. Crilly et al., “Seasonal Ground and Water Movement Onservations from an Expansive Clay Site in the UK,” *7th International Conference on Expansive Soils,* Dallas, 1992.
22. T. J. Freeman et al., *Has Your House Got Cracks?,* Institute of Civil Engineers and Building Research Establishment, London, 1994.
23. N. J. Coppin and I. G. Richards, *Use of Vegetation in Civil Engineering,* Butterworths, London, 1990.
24. R. Gordon McKeen, “A Model for Predicting Expansive Soil Behavior,” *7th International Conference on Expansive Soils,* ASCE, Dallas, 1992.
25. Federal Housing Administration, *Criterea for Selection and Design of Residential Slab on Ground Foundations,* Report No. 33, National Academy of Sciences, 1968.
26. Post Tension Institute, *Design and Construction of Post Tension Slabs-on-Grade,* 1st Edition, Phoenix, Arizona, 1980.