MORPHOLOGY AND PEDOLOGIC CLASSIFICATION OF SWELLING SOILS

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Swelling soils occur in nature in a predictable manner. The pedologist identifies, classifies, and characterizes these unique soils and delineates their occurrence on the landscape. The concept of Vertisols, for example, is that of a soil that is unstable because of a high content of expanding lattice clay. The morphology is marked by intersecting slickensides, parallelepiped structural aggregates, and horizons that are thin and poorly expressed near microhighs but that are thick and well expressed in microlows only a few feet (meters) away. Where not destroyed by man, these soils have gilgai relief. Soils having swelling potential but lacking the other features of Vertisols are classified in vertic subgroups of other soil orders. By definition, these soils have more than 35 percent clay within a designated control section and a coefficient of linear extensibility of 0.09 or more or a potential linear extensibility of 2.4 in. (6 cm) or more. Vertisols and soils in vertic subgroups of other orders have the common property of instability because of swelling. They have a high plasticity index and a high liquid limit. They are characterized by a high content of expanding lattice clays, particularly montmorillonite. The micromorphology of swelling soils reveals a fabric of oriented clay particles along short-range shear planes.

•SOIL classification, whether developed by soil engineers or soil scientists, has the primary objective of grouping soils that have similar properties. As a result, all soils in a group exhibit similar behavior. This permits us to solve many kinds of simple soil problems and also to guide the testing program if the difficulty and importance of the problem dictate further investigation. Soil classification guides scientists or engineers by making available the results of field experience. Like soils should have similar behavior patterns, and this allows us to transfer experiences from one soil area to another like soil area.

Many kinds of soil classification systems have been developed, some to aid in the solution of specific problems. For example, in flow problems a soil engineer uses classes of permeability. The U.S. Army Corps of Engineers uses a frost susceptibility classification in which, on the basis of particle size, soils are classed according to similar frost behavior. The U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers use the Unified Soil Classification System (USCS) for all engineering problems. The AASHTO system provides a ready grouping of soil material for solving problems dealing with highway construction. Most of these systems, however, are based on laboratory analysis.

Pedologists have developed a system of soil classification based on the natural soil unit, using, in addition to measurable properties, in situ morphological features to define class limits. This system (16), adopted for general use by the National Cooperative Soil Survey in 1965, is multicategorical and has various levels, ranging from 10 orders at the most general level to more than 10,000 units at the more precise series level. In this system, predictions are made for in situ soil behavior and are used to solve both engineering and agronomic problems.

In this system, classification is based on six categories: the order, the suborder, the great group, the subgroup, the family, and the series. The 10 soil orders, which represent the kind and relative strength of the natural soil forming process, are as follows:

1. Entisols are young mineral soils that do not have genetically related horizons;
2. Inceptisols are young mineral soils that have weakly developed soil horizons;
3. Aridisols are generally dry soils when not frozen or irrigated that have started to form definite soil horizons;
4. Alfisols have a clay-enriched B horizon that is high in base saturation;
5. Ultisols have a clay-enriched B horizon that is low in base saturation;
6. Mollosols have a dark-colored surface layer, are high in base saturation, and are grassland soils;
7. Vertisols have a high clay content and shrink and swell excessively;
8. Oxisols are strongly weathered soils of tropical regions;
9. Spodosols have subsurface horizon of accumulated organic matter usually with iron or aluminum; and
10. Histosols are organic soils.

Suborders reflect either the presence of or lack of waterlogging or soil differences produced through the effect of climate or vegetation. Great groups are based on the kinds and sequence of major soil horizons and other compositional or morphological features. Subgroups represent the central or typic segment of the group or have properties of the group and one or more properties of another group. Families are based on properties important to the growth of plants or to the behavior of soils used for engineering. The soil series is the lowest category and includes soils that have profiles almost alike and a limited range in soil properties so that the expected behavior is the same. Most soil maps are made at the series level.

Five moisture regimes are defined in terms of the groundwater level and the presence or absence of water held at a tension of less than 15 bars (1500 kPa) as follows:

1. In the aquic moisture regime, the soil is saturated and the groundwater is on or close to the surface for significant parts of the year;
2. In the aridic or torric moisture regime, the soil is dry in all parts more than half of the time that soil temperature is warm enough to grow plants;
3. In the udic moisture regime, the soil is not dry in any part for as long as 90 days (cumulative), and the water moves through the soil at some time in most years;
4. In the ustic moisture regime, the soil is dry part of the time, but moisture is present at a time when conditions are suitable for plant growth; and
5. In the xeric moisture regime, the soil is dry in all parts for at least 45 consecutive days during the warm season.

The mean annual temperature at a depth of 20 in. (50 cm) is used to define the soil temperature regimes as given in Table 1.

The objective of this paper is to relate that part of this soil taxonomy system that deals with properties and behavior of expansive soils to engineering experiences and uses. The two major groups of soils in the United States that exhibit instability in the form of a high shrink-swell potential are the Vertisols and those integrated with Vertisols by their assignment to vertic subgroups. There are at least 24 million acres (9.7 million hm^2) of Vertisols in Texas, Oklahoma, Mississippi, and Alabama (2) and smaller acreages in several other parts of the country.

NATURE OF EXPANSIVE SOILS

There is much known about the nature and behavior of expansive soils as a result of elaborate tests in both the soil mechanics and soil science laboratories. Clay content (1, 6, 12, 15), organic matter content (3), cation-exchange capacity (6, 7), kind of adsorbed cations (1, 3), charge density (12), amount and kind of clay minerals (1, 12), and bulk density (5, 12) have been shown to affect soil swelling. However, there is a general lack of recognition concerning the in situ testing of expansive clay soils, and there is a need for predicting a soil's behavior in its natural state. Gromko (8) recognized this deficiency and concluded, on the basis of studies on the process of in situ

Table 1. Soil temperature regimes.

Regime	Temperature (deg F)	Location
Pergelic	<32	Permafrost areas
Cryic or frigid	>32 <47	Northern latitudes, high elevations in mountains
Mesic	>47 <59	Mid-latitudes
Thermic	>59 <72	Southern latitudes
Hyperthermic	>72	Subtropics
Isothermic or isomesic	<90	Tropics

Note: 1 F = 1.8 (C) + 32.

Figure 1. Microlows contain water in area of gilgai microrelief common to Vertisols in Texas.

Figure 2. Microhighs occupy lighter colored areas in this area of gilgai microrelief.

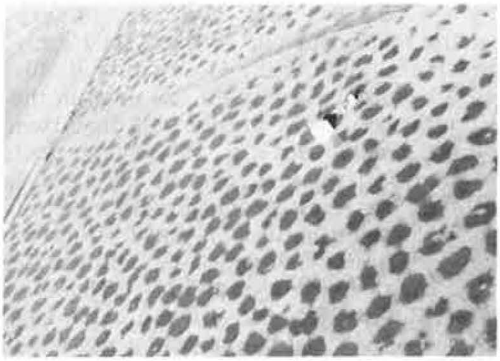
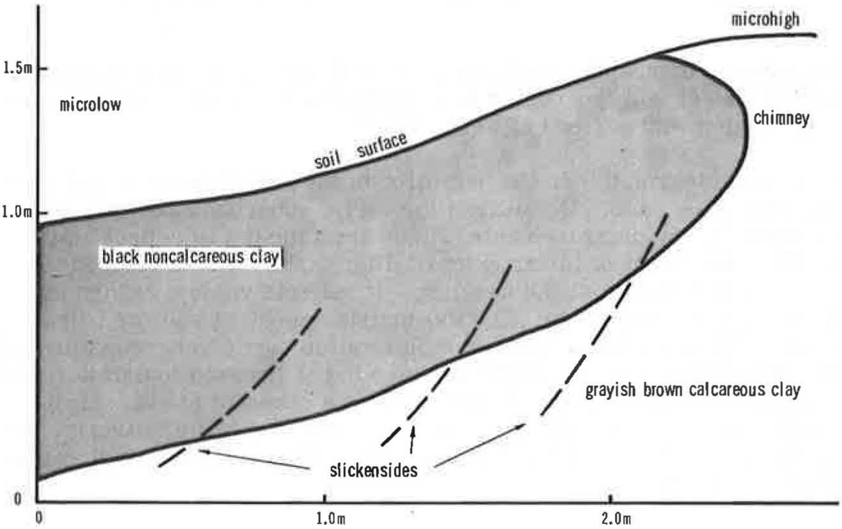


Figure 3. Typical morphology of Houston Black soil series.



heave, that predictions of behavior can be made by integrating several tests with climatic data. The tests he proposed are free swell index, Atterberg limits, colloid content, and one-dimensional consolidation tests. He modified these tests with climatic information. Soils having critical test values are most susceptible to expansion in those areas having lengthy drought periods followed by periods wet enough to saturate the soil.

Gromko's approach conforms well to that used by many pedologists. Actual movement in an undisturbed soil in Israel was measured by Yaalon and Kalmar (17). They measured, in a Vertisol with a clay content of more than 65 percent and dominated by montmorillonite, an annual amplitude of vertical soil movement at the soil surface of 2 in. (5 cm). The volume changes in an undisturbed soil are smaller than those measured in the laboratory. Only the incremental wetting during rainfall resulted in sufficient moisture absorption to cause volume change. The daily change during the dry season was minimal, 0.01 in. (0.3 mm), and was related to temperature changes. Yaalon and Kalmar (17) observed a rather constant rate of shrinkage during the main dry season. Swelling, however, is very marked and immediate after a deep soil wetting that occurs after the first rain. Hamilton (10) obtained maximal seasonal movements of 2.75 in. (7 cm) in undisturbed clayey soils in western Canada.

Soil moisture regimes, as used in the soil taxonomy (16), are more definitive than climatic data of the in situ soil condition. For example, all soils in an arid climate are not necessarily dry. They may be dry, moist, or saturated, depending on their position in the landscape. In any given landscape that has uniform climate, adjacent soils may have different moisture regimes. Soils in low areas may receive runoff waters in addition to rain that falls on them. However, there is a close relation between soil moisture regimes and climate. Soils with aridic or torric moisture regimes are normally in arid climates. These soils are dry in all parts more than half of the time. Soils with ustic soil moisture regimes normally occur in areas intermediate between the arid and humid zones and have moisture regimes intermediate between udic and aridic regimes. The xeric moisture regime is typified in Mediterranean climates where winters are moist and cool and summers are warm and dry. These soils have a wetting period followed by a marked dry period.

Soils that are notoriously expansive in situ have the following climatic characteristics:

1. Very high evaporation or evapotranspiration rates during some time of the year,
2. Sufficient rainfall to wet soil thoroughly to a depth of at least 30 in. (76 cm), and
3. Periods of dry weather and periods of wet weather.

This information has been integrated with the definition of the soil classes in soil taxonomy that deal with expansive soils. Definitions for vertic subgroups are based on coefficient of linear extensibility measurements (9) but are adjusted to reflect soil moisture regimes. The coefficient of linear extensibility (COLE) was developed to identify those soils with a high potential for swelling. It reflects volume change experienced by a soil sample between ⅓-bar (33-kPa) moisture content and oven-dry content. For example, a COLE value of 0.09 is definitive for vertic subgroups for soils in the eastern United States with udic and aquic regimes but is lowered to 0.05 for soils of the deserts with aridic regimes. Vertisols also reflect a climatic effect. Most of the the Vertisols have xeric, ustic, and aridic moisture regimes, but some in thermic or warmer soil temperature regimes [where mean annual soil temperature is higher than 72 F (22 C)] have a udic moisture regime.

Morphology

Vertisols, by their definitions, have two distinct but interrelated features: the surface configuration and a unique pattern of soil horizons that underlie the surface features. Gilgai, the term used to identify the surface microrelief, is an Australian aboriginal word meaning small water hole (14) and is described as a microrelief consisting either of a succession of enclosed microbasins and microknolls in nearly level areas (Figures 1 and 2) or of microvalleys and parallel microridges that run up and down the hill in hilly areas. The height of the microridges commonly ranges from a few inches (centimeters) to about 3.3 ft (1 m). Paton (14) places those that are elongated in one direction in the linear class, and those that have no consistent preferred orientation in the nuram class. Nuram is an Australian aboriginal word meaning pockmarked. The microlows are polygonal and have microhighs surrounding them along the perimeter.

Recent fieldwork has revealed that this microrelief in the Vertisols is more complicated than a series of microhighs and microlows. The form has been characterized both in a vertical section and in a horizontal section or plan. Amplitude and wavelength are used to identify some of these features. Amplitude is determined by measuring the vertical distance between the crest of the high and the bottom of the low. Wavelength is determined by measuring the horizontal distance between the same points. Three basic types have been identified: (a) highs and lows equally developed, (b) highs of much greater extent than lows, and (c) lows of much greater extent than highs. The Houston Black series, typical of Vertisols of central Texas, is characterized by type a; that is, highs equal lows in development and have a wavelength of 6 ft (1.8 m) and an amplitude that averages 20 in. (50.8 cm).

The nature of the soil horizons reflects the features that occur in the natural soil surface. In other words, the soil profile underlying the microlow is markedly different from the profile under the microhigh. Typically, the microlow in the Houston Black series is characterized by a black to very dark gray colored A_1 horizon that extends to 24 in. (61 cm). This horizon changes horizontally to a much lighter color, almost grayish brown in the surface of the microhigh (Figure 3). The amplitude of the lower boundary of the dark colored A horizon ranges from about 20 in. (51 cm) to 40 in. (102 cm). The lower C horizon penetrates up into and through the overlying A_1 horizon to approach or reach the surface in the microhighs. These features have been referred to as chimneys through which the C horizon material surfaces. For this feature, Paton (14) has proposed the word mukara, which is an Australian aboriginal word meaning finger. Usually the soil surface is calcareous in the highs and noncalcareous in the lows.

The soil horizons in Houston Black soils, typical Vertisols, are not uniform and continuous horizontally throughout the unit of soil. The soil horizons are intermittent but recur at regular intervals that match the occurrence of the microhighs and microlows in the natural state. Vertisols are defined to have this recurrence in linear intervals of from 7 to 25 ft (2 to 7.6 m) (16).

This morphology is the result of the soil-forming processes that are unique in the Vertisols. The dominant soil-forming process is churning or self-swallowing, which tends to destroy the differential textural distinctions that are due to the soil-forming processes common in many other soils. The fine-textured soils shrink and form cracks that may extend downward from the soil surface to depths of 40 in. (1 m) or more during the dry period. During the first rains after the dry period, soil surface material is washed into the cracks. As the rain continues, the soil clays expand demanding more space. Some of the forces are lateral, but lateral movement is restricted by surrounding soil. The eventual thrust is upward along the pressure release chimneys; this gives rise to the microhighs. Soil material from the lower horizons is heaved up through the chimneys. Most water enters the soil through the lows, and thus these zones are normally more acid than the neighboring highs. Soil wetting is largely from the cracks migrating inward in response to capillary tension.

We have made numerous field observations that indicate that the extensive slickensides, whose occurrences have been recorded by most observers of the morphology of expansive soils, are oriented on inclined planes directed toward the top of the microhighs (Figure 4). The slickensides represent the surface of large blocks of soil that shift their relative position en masse in response to stresses that result from soil swelling.

Soils in vertic subgroups are similar to Vertisols in their unstable nature but lack the characteristic gilgai relief and accompanying subsurface characteristics. They do not have significant cracking in most years. For this reason, within subdivisions of

Figure 4. Vertisol profile showing wide cracking and common slickensides in a Vertisol; microhigh in upper right.

Table 2. Representative soils in fine and very fine families of typic and vertic subgroups.

Pedologic Classification	Mineralogy	Unified Classification
Vertisols		
Typic	Montmorillonitic	CH
Argiustolls		
Typic	Mixed	CL
Vertic	Montmorillonitic	CH
Paleustalfs		
Typic	Mixed	CL
Vertic	Montmorillonitic	CH
Paleudults		
Typic	Kaolinitic	CL
Vertic	Mixed	CH

great groups, soils are integrated with the Vertisols by their assignment to vertic subgroups (16). These soils, in higher categories of the system, are assigned to classes that most nearly reflect their dominant properties.

Properties

Soils are grouped into pedologic units on the basis of similar composition and morphologies. This pedologic concept is based on the premise that similar soil parent materials, if subjected to identical environmental conditions of climate, biological activity, topography, and time, developed identical soils.

Vertisols and soils in the vertic subgroups, the two distinct soil taxa that are dominant among those soils with swelling characteristics, have the following common properties that can be learned from the definitions of the taxa:

1. Clay mineralogy is dominated by montmorillonite or other 2:1 lattice active clays,
2. COLE values are high (16),
3. Clay content is 30 percent or more in the upper part of the soil, and
4. Unified classification is dominantly group CH.

Mineralogical data of 203 soil series from the southern United States indicate that those in vertic subgroups are evenly divided between montmorillonite and mixed mineralogy (4). Limited data indicate that those with mixed mineralogy have a relatively high proportion of montmorillonite compared to other clay minerals. None of these soils are dominated by 1:1 lattice clays. All but a few series of the Vertisols have montmorillonite as the dominant clay mineral.

COLE values for Vertisols and soils in vertic subgroups range from 0.05 in arid regions to more than 0.09 in humid regions. Potential linear extensibility can be determined by multiplying the COLE times the thickness of the layer involved. Most Vertisols and soils in vertic subgroups have a potential linear extensibility of 2.4 in. (6 cm) or more.

In soils with similar clay mineralogy, clay content explains a high proportion of the variation in soil swelling. Studies of soils from the southern United States show that the clay content in representative pedons of soils in vertic subgroups exceeds 40 percent. Most of these soils qualify for group CH in the USCS. Most of the Vertisols have a clay content that exceeds 45 percent and are classified in CH. These soils have a high plasticity index and a high liquid limit. Several soils of the southern United States are given in Table 2.

Other soil properties measured by the pedologists also are highly correlated with swelling behavior. Relatively high values in such tests as moisture held at 15-bar (1500-kPa) tension and cation exchange capacity characterize the Vertisols and soils in vertic subgroups.

The micromorphology of these soils also is unique. McCormack and Wilding (13) have identified a lattisepic fabric from thin section studies of soils high in clay. They postulated that this fabric has formed as a result of stress and short-range movements of finite soil masses in response to swelling in situ. As a result of these movements, the fabric is oriented along microshear planes. Undisturbed samples of argillic and other soil horizons can be characterized by studies of the micromorphology that identify the amount and kind of soil movement that the natural soil has experienced.

CONCLUSIONS

Expansive soils are most troublesome when used as base for roads or buildings because of their behavior patterns. Jones and Holtz (11) report that heaving, cracking, and breakup of pavements, building foundations, and channel and reservoir linings in the United States cost $2 to 3 billion annually.

Expansive soils received much consideration in the development of soil taxonomy. Soil scientists are studying these soils, both in the laboratory and in the field. In addition, selected soils are being characterized by both pedologic and engineering tests. As a result, these unique soils are recognized in situ by their characteristic morphologies, and behavior predictions are based on the engineering tests that also characterize the discrete soil units. Studies have shown that a soil series or a group of soil series has consistent engineering properties, especially those related to kind and amount of clay and particle-size distribution, throughout the area of their occurrence. The science of pedology provides a comprehensive procedure for study of soils in situ. The soil is identified in place, and the composition of the material and its variation with depth are noted. Engineering behavior patterns of soils in situ may be quite different from what laboratory tests indicate they will be. Laboratory tests, such as COLE, Atterberg limits, PVC index, consolidation tests, and free swell index, however, can be used to characterize soil units recognized in soil taxonomy. Predicting soil behavior in situ requires an integration of soil test data with those soil features that are related to the environment of the soil. For example, an expansive soil not only has a sufficient quantity of swelling clays but also must experience wetting and drying periods. Soil moisture regimes and soil temperature regimes, which characterize the moisture and temperature status of soils throughout the year, are used to characterize this environment. Soils in place have a way of recording this experience in their morphologies. Deep cracks, gilgai relief, surface A soil horizons interrupted by protruding subsurface C soil horizons, and a lattisepic microfabric in the subsoil reflect the natural soil-forming processes active in expansive soils. These effects of the environmental factors are then automatically included within the classification system.

The soil survey treats the soil classification unit as a three-dimensional body. This is represented on the soil map by its aerial boundaries. The soil unit becomes a landscape unit. Prediction of behavior or performance made for the soil taxonomic unit applies to the delineated landscape unit. Thus the prediction of soil heave made for a soil series in soil taxonomy applies reasonably well to the identified mapping unit in the soil survey. The degree of reliability for predicting this behavior pattern is quite high. It is estimated that, if one digs a test pit anywhere in the delineated area, there is an 85 to 95 percent chance of revealing a soil that has the engineering properties as given for that soil series.

Stabilization techniques of swelling soils also can be made more effective by applying the knowledge of the soil environment implied by the pedologic soil unit. Prewetting and other water control measures can be devised to fit the soil drainage and the movement characteristics of the soil water. Chemical stabilization can be more effective if devised to match the soil chemistry of the pedologic unit. In addition, structures can be designed to reflect both the soil and the site conditions. This information and other data, such as an estimate of vertical heave, depth to water table, wet-dry cycles, and water contents of different soil layers, can be learned from the soil survey.

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