Geotechnical Behavior of Overconsolidated Surficial Clay Crusts

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The overconsolidated crust of fine-grained sedimentary deposits may exert a significant influence on the performance of structures located in the near surface. The degree of influence depends on the thickness of the crust and its degree of development in comparison with the underlying deposit. The development of a crust is a result of the combined effect of chemical and physical processes acting in place. In this paper, the principal factors responsible for the development of surficial crusts and the resulting geotechnical characteristics of surficial clay crusts are described. Changes in intrinsic soil properties and the variable nature of surficial crusts produced are discussed. Examples from several sites are presented that illustrate the important consequences of crust development on the resulting geotechnical properties, and a description of the implications of the presence of a crust on design practice is given.

Most surficial fine-grained sedimentary deposits exhibit an upper stiff overconsolidated zone that represents a crust developed largely as a result of in situ modification after deposition of the original material. Correct recognition of the extent of the crust and accurate characterization of its engineering properties are of considerable practical significance to geotechnical engineers. Common design situations that may be influenced to some degree by a surficial crust include bearing capacity and settlement of shallow foundations, embankment stability, retaining wall behavior, and stability of slopes. Other problems involving foundation elements in tension, such as pullout or uplift behavior of vertical and inclined pile anchors, screw anchors, or plate anchors, actually may derive a majority of support from the crust.

In the northeast and mid-Atlantic states of the eastern United States and in southern Canada, weathered surficial crusts have been described in a number of areas, generally associated with marine clay deposits, glacial lake deposits, and flood plain deposits. This area includes the Hackensack Meadows of New Jersey, glacial Lake Warren in western New York, glacial Lake Hitchcock of western Massachusetts and Connecticut, and the Atlantic Coast areas of Portsmouth, New Hampshire; Portland, Maine; and the Boston Basin. Other significant fine-grained deposits exhibiting an upper surficial crust include glacial Lake Hudson around Albany, New York, glacial Lake Champlain, certain areas around metropolitan New York, and the Champlain Sea clays of southern Ontario and northern New York.

This paper presents a review of the principal mechanisms involved in the development of overconsolidated surficial clay crusts and discusses the impact of the various mechanisms on the geotechnical behavior of the resulting deposit. Examples of typical soil properties from several sites that contain a crust are presented.

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DEVELOPMENT OF SURFICIAL CRUSTS

Most sedimentary deposits resulting from erosion and redeposition of individual soil grains or grain assemblages develop a surficial weathered crust as a result of postdepositional changes or in-place weathering of the parent material. The degree of formation of a crust depends on the weathering mechanisms that operate through time following deposition of the parent material and therefore is dependent in part on the geologic age of the original deposit. Kenney (*1*) defined *weathering* as follows:

> Weathering is those processes which cause structural disintegration and decomposition of geological materials under the direct influence of the hydrosphere and atmosphere. Disintegration is physical breakdown of the structure of a material, and decomposition is chemical alteration of the constituent minerals and matrix materials.

Hence, weathering involves both physical and chemical processes.

The most common types of physical and chemical weathering mechanisms that produce weathered crusts in sedimentary clay deposits include

1. Seasonal fluctuations in the groundwater level; alternating wetting/drying cycles and translocation of materials;
2. Seasonal temperature changes; alternating freeze/thaw cycles;
3. Erosion or other removal of overburden stress or unloading;
4. Oxidation;
5. Leaching; and
6. Cementation.

These and other mechanisms act in varying degrees to alter the parent deposit and produce materials that exhibit behavior that often does not follow traditional soil mechanics theories or fit typical models of mechanically overconsolidated soil behavior (i.e., overconsolidation resulting from simple unloading).

Geochemical Weathering

The development of a surficial crust in an unaltered sedimentary deposit is largely the result of in-place weathering. Therefore, it is important to have an understanding of the complexity of weathering processes to have a better appreciation for the resulting complexity of the weathering product, that is, the crust. Weathering of diagenetic sedimentary deposits can be thought of as the chemical and physical decomposition of individual particles or particle assemblages. This decomposition may involve both disintegration and alteration of minerals and other constituents within the deposit.

This weathering occurs on two scales: (a) a macroscale in which the processes occur beneath the developed soil profile or solum and would take place without the solum; and (b) a microscale in which the processes only act on the immediate near-surface material or soil solum, often referred to as the A and B horizons by soil scientists or agronomists. Although the latter may have limited importance in geotechnical engineering, it is the former that is of most significance to geotechnical performance of the various design problems previously described. Weathering that is a continuous process occurring below the soil solum is sometimes referred to as *geochemical weathering* (*2*). The most common reactions associated with geochemical weathering include oxidation, reduction, alternating cycles of these reactions, hydration, solution, and hydrolysis. Other processes, including cation exchange and carbonation, also may operate to weather materials in place (*3*).

Oxidation

Oxidation is an important reaction that occurs in well-aerated environments where the oxygen supply is high and the biological demand for it is low. Normally, oxidation is thought of as occurring in soil zones above a permanent water level where the void space is only partly filled with water, that is, in the vadose zone. The most important reaction is the alteration of ferrous iron to ferric iron:

$$Fe^{2+} \rightarrow Fe^{3+} + e^- \qquad (1)$$

The oxidation of iron as described by this reaction disrupts the electrostatic neutrality of the crystal lattice, allowing collapse of the crystal lattice, and can promote additional weathering in the presence of oxygenated water; it allows for the formation of an oxide, Fe_2O_3, or hydrous oxides such as $Fe_2O_3 \cdot H_2O$ (goethite) and $2Fe_2O_3 \cdot 3H_2O$ (limonite). Manganese compounds within the soil are also affected by oxidation. Oxidation of pyrite is also a common reaction during weathering.

Reduction

Reduction occurs in the portion of a soil profile that is saturated or near saturated, such as below the water table, where oxygen supply is low and biological oxygen demand is high. In this case the iron is reduced to the ferrous state, which is highly mobile and can be lost from the system if there is sufficient groundwater movement. If the ferrous iron is retained in the system, it may move into fissures or channels within the sediment and be oxidized or remain in the soil matrix and react to form sulfides and other compounds. If the deposit remains in a reducing environment and a state of saturation or near saturation throughout its geologic history, and it is not subjected to alterations produced by oxidation, the sediment is often referred to as "unoxidized."

Oxidation-Reduction

In zones of transition between a fully aerated environment and a fully saturated environment, groundwater generally fluctuates as a result of seasonal fluctuations in precipitation. In these transition zones, alternating cycles of oxidation and reduction will occur depending on the biological oxygen demand and the availability of oxygen.

Hydration

Hydration is the surface adsorption or association of water molecules or hydroxyl groups with minerals. Hydration usually occurs at the surface or edge of mineral grains. An example is the formation of gypsum crystals:

$$CaSO_4 \text{ (anhydrite)} + H_2O \rightarrow CaSO_4 + 2H_2O \text{ (gypsum)} \qquad (2)$$

Solution

Solution involves the dissolving of simple salt compounds such as carbonates and chlorides that may be present as mineral grains in some soils. An example is the dissolving of calcium carbonate in calcareous deposits:

$$CaCO_3 + 2H^+ \rightarrow H_2CO_3 + Ca^{2+} \qquad (3)$$

One result of solution reactions can be the leaching of minerals from the system if there is sufficient groundwater movement or the precipitation and redeposition of minerals into segregated zones. The leaching of carbonates and other minerals is a common result of solution activity. The degree of leaching depends on groundwater chemistry and fluctuations, infiltration, time, and initial mineral composition.

Hydrolysis

Hydrolysis normally refers to the attack of hydrogen on the crystal structure of certain minerals. The result is often a replacement of the basic ion composition by the hydrogen. An example of hydrolysis is the attack of hydrogen on the interlayer potassium of micas to produce illite (by partial K removal) or vermiculite (by full K removal). Hydrolysis is an important process that can result in partial or complete modification of weatherable primary minerals and the production of mixed layer minerals by cation replacement.

Cementation

Cementation may play a role in the behavior of surficial crusts, but its influence often may be overshadowed by more dominant processes. Cementation bonds in soils can develop by translocation of various cementing agents that then precipitate between particles or particle assemblages. Among the more common cementing agents are carbonates (calcium and magnesium), iron oxides, silica, and amorphous compounds. It is sometimes difficult to identify cementing agents in soil samples; however, there are well-documented studies of the influence of cementation on soil behavior such as stress history, compressibility, and shear strength (*4,5*). The presence of carbonates as a form of cementation may have a significant influence on geotechnical properties, for example, as illustrated by Burghignoli et al. (*6*).

In general, the combined activity of these and other geochemical weathering processes can be considered in a simplistic model that is often used to illustrate the pedochemical changes that take place to produce the soil solum. Because these processes operate at varying rates depending on ground temperature, topography, hydrology, initial soil mineralogy and composition, and groundwater chemistry, many resulting profiles are possible containing a wide number of end products.

A diagram illustrating the combined action of these processes is shown in Figure 1. All of the reactions discussed can be categorized as additions, transformations, transfers, or removals. Unfortunately, the effect of some developmental mechanisms such as leaching of carbonates or oxidation on specific geotechnical behavior have not been studied in any detail or systematic manner and therefore are unknown or poorly understood.

Physical Weathering

Physical processes that modify massive sedimentary fine-grained deposits can act in varying degrees of intensity and for varying durations to create postdepositional modifications of the deposit, which can be just as dramatic as those caused by chemical processes. The most important physical weathering processes include groundwater fluctuations, desiccation, frost action (or freeze-thaw cycles), and unloading. Other physical processes, including drained creep and organic activity of plants and animals, can also influence crust formation.

Groundwater Fluctuations

Significant changes in groundwater levels can occur in shallow depths leading to substantial changes in effective stresses. The actual magnitude and frequency of fluctuations depend on a number of factors, including site topography, regional hydrogeology, local hydrogeology, surface drainage characteristics, rainfall and other seasonal precipitation, and surface characteristics that may control runoff and infiltration. The development of overconsolidation at the surface of a soft clay by changing groundwater levels has been described by Parry (*7*), who noted that within the crust the effective stresses are caused by not only the weight of the soil but also by negative pore water stresses induced by desiccation.

An example of typical groundwater fluctuations in a clay crust is shown in Figure 2, which presents piezometer observations taken over several years at a number of elevations at the National Geotechnical Experimentation Site (NGES) at the University of Massachusetts-Amherst (UMass). The zone of active modern groundwater fluctuations is within the upper 4 to 5 m. Within this zone it can be seen that groundwater fluctuations are generally seasonal and coincide with seasonal variations in precipitation, but they are also influenced by single rainfall events that can affect daily groundwater levels in the near surface. For example, variations are greatest in the shallowest piezometer at a depth of 1.52 m, which

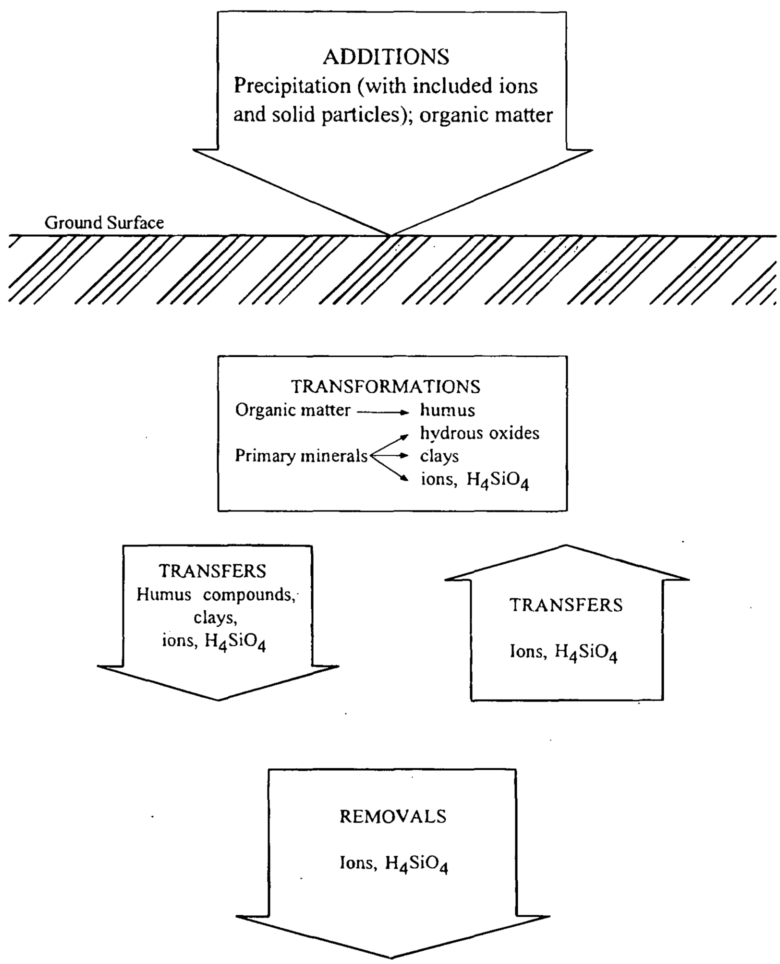

FIGURE 1 Flowchart of major geochemical processes in crust formation.

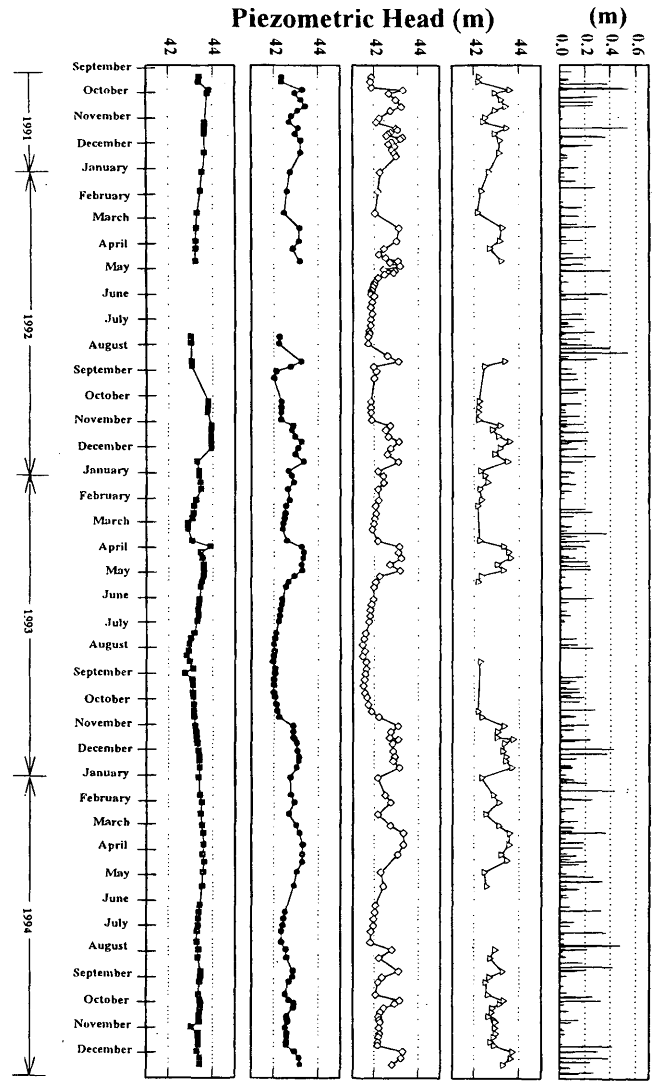

FIGURE 2 Groundwater fluctuations at NGES UMass-Amherst.

actually goes dry in the summer months. Below the active groundwater zone, it can be seen that the amplitude and frequency of groundwater fluctuations are less affected by single events and even show less pronounced influence for seasonal variations in precipitation. The maximum observed fluctuation in static groundwater level over a 3-year period has been about 2.5 m.

What are the consequences of fluctuations in the static groundwater level to the development of a surface crust? Consider a site in which the groundwater table fluctuates from the ground surface to a depth of 3 m. If the total unit weight of the soil is taken as 1.9 Mg/m^3 and a constant preconsolidation stress (σ'_p) of 143 kPa is assumed throughout the profile, the stress history fluctuates within the upper 10 m as shown in Figure 3 simply from the change in groundwater position. As can be seen, the impact on the overconsolidation ratio ($OCR = \sigma'_p/\sigma'_{vo}$, where σ'_{vo} equals the in situ vertical effective stress) within the upper 5 m is dramatic with the *OCR* at a depth of 1.5 m varying from about 5 to 10. Below a depth of about 5 m, where the soil is normally consolidated, the magnitude of difference between the stress history at the two different times is probably within the measurement error of the laboratory determination of the preconsolidation stress.

This simplistic example illustrates the importance of having reliable measurements of in situ pore-water pressures throughout a site profile to evaluate soil behavior. For example, if correlations are being developed between laboratory tests and in situ tests, it is imperative to have pore pressure measurements at the time the in situ tests are performed to determine effective stress accurately.

Desiccation

The surface of a sedimentary deposit is susceptible to drying out as a result of contact and exposure to the atmosphere. In the zone immediately beneath the surface, water is lost by evaporation at different times of the year as a result of climatic changes. This reduction in water content can result in strong capillary action, resulting in the development of negative pore-water pressures, which in turn results in an increase in effective stress. This in effect can produce a preconsolidation effect in the soil; the development of high lateral stresses may also produce fracturing or fissuring of the soil. The significance of negative pore-water pressures or matric soil suction in the zone of capillary saturation and in the vadose zone has been presented in detail by Fredlund and Rahardjo (*8*).

Over time, and with multiple cycles of wetting and drying, an extensive fracture pattern can develop. Infilling of the open fissures with washed material can help produce coatings on the face of fracture surfaces and can also help reduce crack closure during wetting. In soils composed of expansive clay minerals, the cyclic wetting and drying may produce slickensided surfaces as a result of development of passive failure planes from expansion. Desiccation by surface drying may also produce an increase in soil unit weight resulting from a reduction in void ratio from the consolidating effect of an increase in effective stress. The water content in this part of the crust may be near or below the plastic limit.

The thickness of the desiccated zone of a crust depends on climatic conditions and the seasonal fluctuations in the groundwater table. Even below the desiccated crust, other weathering processes produce an altered zone that is still considered, along with the drying crust, as part of the crust. The lower extent of the crust in most clay deposits is generally taken as the depth at which the undrained shear strength exhibits a minimum value.

Desiccation may also be produced by vegetation, especially large trees, which can also produce fissuring of clays. Large reductions in water content can occur in the upper few meters of soil as a result of root penetration and water removal by trees. This reduction in water content can produce consolidation of the soil leading to enhanced settlements of shallow foundations. A number of cases of this type have been reported previously (*9,10*). When trees are removed, the groundwater level may recover (*11*), producing a reduction in effective stress. A general rule of thumb regarding the influence of trees appears to be that the root penetration of trees is approximately equal to the height of the tree. The zone of influence of water removal by large trees may extend as much as 20 m beyond the base of the tree.

Frost

Seasonal fluctuations in the maximum depth of frost penetration can produce results in the soil similar to desiccation. Frost action is

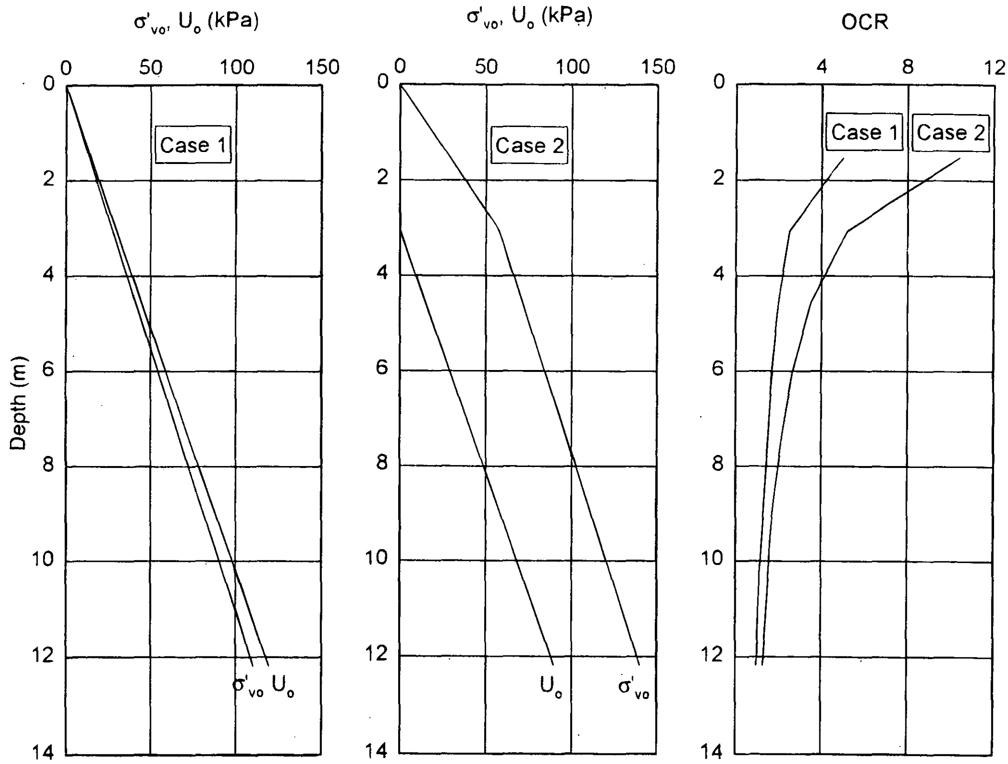

FIGURE 3 Changes in stress history resulting from groundwater fluctuations.

obviously more important in northern latitudes but can still produce modifying surficial effects in other areas from occasional climatic changes. For example, Ladd (*12*) described the formation of an overconsolidated freeze-thaw crust in marine deposits at James Bay in northern Quebec, Canada.

The effect of soil freezing on overconsolidation has been described in detail by Chamberlain (*13*), who found that preconsolidation stresses in plastic soils could be induced by freezing and could greatly exceed in situ prefrozen stresses because of large increases in pore-water tension during freezing. The formation of a preconsolidated frost crust has also been described by Vahaaho (*14*) as a means of stabilizing road beds in Finland. The increase in preconsolidation stress of soft, normally consolidated clays resulting from a decrease in temperature is also well documented. Alternating freeze-thaw cycles can result in the development of jointing or fissuring and may also cause water migration.

Unloading

Reduction in effective confining stress resulting from uplift, erosion, or changes in pore pressure can also produce cracks and joints within an otherwise massive deposit. Joints in surficial crusts are typically produced by elastic rebound coupled with alternating shrinking and swelling or freeze-thaw cycles. Most unloading in surface crusts is generally considered to take place as a result of the removal of overburden accompanied by physical erosion. The degree of removal may vary dramatically from a few meters to several tens of meters depending on the geologic setting. In most young sedimentary deposits, unloading may have a minor effect on the formation of crusts.

EFFECTS OF CRUST-FORMING PROCESSES

What are the overall consequences of these and other processes on the resulting extent and geotechnical behavior of a crust? Bjerrum (*15*) has shown that the thickness of a crust may range from as little as 1 to 3 m to as much as 6 to 8 m depending on landscape position (i.e., well-drained versus poorly drained topographic position) and site hydrogeology. Table 1, taken from Brenner et al. (*16*), summarizes the effect of a number of the mechanisms discussed on the geotechnical properties of marine clays.

Alteration of Deposit

The overall result of the development of a surficial crust as a result of in-place weathering is that the material in the crust often shows little resemblance to the underlying material. It should not be surprising, then, that in many cases the observed behavior, such as undrained shear strength or in situ stress state, cannot be fully explained by stress history. In these cases stress history may be considered to be the result of both chemical and physical phenomena.

The most obvious consequence of crustal development is the modification of the original geologic deposit. The extent of the development in terms of both degree of modification and depth depends on a number of factors. Processes of crustal development, both physical and chemical, require time to operate and are affected

TABLE 1 Effect of Postdepositional Processes on Geotechnical Properties of Marine Clays [from Brenner et al. (*16*)]

Process	Geotechnical property								
	Water content	Liquid limit	Plasticity index	Liquidity index	Preconsolidation pressure	Compressibility	Undrained strength		Sensitivity
							Undisturbed	Remoulded	
Desiccation	−		±	−	+	−	+		
Chemical weathering	±	+	+	−	+	−	+	+ or −[1]	− or +[1]
Leaching	±	−	−	+	−	+	−	−	+
Cementation		+	+		+	−	+	+[2]	+

\+ Increase; − Decrease; ± little or no change
[1] Depends on type of clay mineral
[2] Depends on amorphous content

locally at any given site by climate (rainfall and temperature fluctuations), vegetation, topography (degree of slope and relative landscape position), material (original mineralogic composition at time zero), and time (geologic age of the deposits).

The most obvious and significant results of the alteration or modification of the virgin deposit as a consequence of the formation of a surface crust are

1. Changes in soil color,
2. Changes in soil structure,
3. Changes in mineralogic composition,
4. Changes in intrinsic properties, and
5. Increase in soil variability.

It is because of the fundamental changes that take place on a small scale that the geotechnical behavior changes on a large scale. Table 2 presents a classification of soft clay proposed by Bjerrum (*17*) that compares weathered clays in the crust to unweathered clays on the basis of water content, Atterberg limits, shear strength, and compressibility.

Soil Color

The matrix colors of sediments sometimes have been related to the state of oxidation and the chemical status and distribution of iron. The oxides of iron have visual properties that may be determined by the distance between iron atoms. For example, hematite, Fe_2O_3, has an iron-iron distant of 2.88 Å and a red color. The hydrated iron oxides, such as goethite and limonite, tend to be lighter in color. A reduced form of iron, iron sulfide, has an iron-sulfide distance of 2.27 Å and a very light color.

Colors observed for the unoxidized matrix in which the iron occurs in the ferrous state include dark gray, dark greenish-gray, greenish-gray, green, blue, and bluish-gray. Soil color ranges for the oxidized zone of most sediments include reddish-brown, yellow-brown, and olive-brown. The change in soil color from those of the unoxidized to those of the oxidized state can occur rapidly upon exposure to air (*18*).

In the transition zone between unoxidized and oxidized zones, where groundwater fluctuates, soil colors will reflect characteristics of both an oxidizing and a reducing environment. Background base color may appear as brown, whereas distinct "blotches" of gray or blue-gray are present or as gray with distinct blotches of brown. The thickness of this mottled zone depends on the mineral composition of the soil, the degree of groundwater fluctuations, and the chemical composition of the groundwater.

Mineral Composition

In some cases, changes in mineralogic composition will also accompany weathering. An example of such alteration is shown in Figure 4, which shows carbonate profiles obtained at three sensitive marine clay (Leda) sites in northern New York. The first site, IDA, occupies a geomorphic low position in the landscape that does not allow groundwater fluctuations to go much below a depth of 0.6 m, even during extended dry periods. The site is capped by a surficial sand deposit about 1 m thick. It is suspected that this site has undergone very minimal modification since deposition, and it exhibits no significant surficial crust. The carbonate composition shown in Figure 4 shows relatively small modification near the surface relative to the underlying material. In contrast, the other two sites sit on more well-drained geomorphic positions about 1.2 km from the first site. The groundwater table fluctuates as a result of seasonal precipitation, and the lowest level historically may have been on the order of 4 to 5 m below ground surface. These sites display a substantial surficial crust that contains distinct blocky soil structure and common fissures. The degree of alteration of the carbonate mineralogy at both of these sites is pronounced down to a depth of about 3 m. Such obvious changes in composition, brought about by postdepositional changes, may help explain differences in soil behavior that may not be explained only by differences in stress history.

Scale Effects

It has long been recognized that significant scale effects can be present in fine-grained deposits that exhibit secondary structure mainly in the form of microcracks, discontinuities, fissures, joints, and other macroscale features. Weathered crusts developed in sedimentary clay deposits often display a blocky fissured soil structure, with the individual frequency of fissures or joints related to the degree of structural formation. Even laboratory shear strength tests performed on larger-than-normal specimens may be adversely affected by the frequency and orientation of fissures. Lo et al. (*19*), Garga (*20*), and others have shown clearly that the undrained shear strength of stiff fissured clays and other structurally dependent soils is related to the size of the specimen and that field tests that include a larger volume of soil, such as plate loading tests or large scale field shear box tests, generally give

TABLE 2 Classification of Soft Clays [from Bjerrum (*17*)]

	Classification	Water Content	Shear Strength	Compressibility
Weathered clays in upper crust	Frost treated, dried-out clays	$w_n \approx w_p$	Very stiff, fissured, with open cracks	-
	Dried-out clays	$w_n \approx w_p$	Very stiff, fissured	Low compressibility
	Weathered clays	$w_p < w_n < w_L$	Shear strength decreases with depth	Low compressibility curved e-log σ'_v curve
Unweathered clays	Young normally consolidated clays	$w_n \approx w_L$	s_u/σ'_{vo} constant with depth	$\sigma'_{vc} \approx \sigma'_{vo}$
	Aged normally consolidated clays	$w_n \approx w_p$	s_u/σ'_{vo} constant with depth	$\sigma'_{vc}/\sigma'_{vo}$ constant with depth
	Young normally consolidated quick clays	$w_L < w_n$	s_u/σ'_{vo} constant with depth	$\sigma'_{vc} \approx \sigma'_{vo}$
	Aged normally consolidated quick clays	$w_L < w_n$	s_u/σ'_{vo} constant with depth	$\sigma'_{vc}/\sigma'_{vo}$ constant with depth

w_n = water content
w_p = plastic limit
w_L = liquid limit
s_o = undrained shear strength
σ'_{vo} = in situ vertical effective stress
σ'_{vc} = preconsolidation stress

lower shear strengths than laboratory tests because of the greater probability of including macrofeatures within the test specimen.

Results from undisturbed samples and even field vane tests tend to give higher strength values because macrofeatures are not always present. In fact, the results of laboratory tests on undisturbed samples from normal size sampling tubes (e.g., 76 mm) actually may be inadvertently biased toward the high (unsafe) side because only those specimens that remain intact during preparation are tested. The remainder of the sample, which tends to fall apart, often cannot be trimmed and placed into a testing fixture and is discarded.

These scale effects may have serious implications in design relating to choosing a design shear strength value or strength profile for use in analysis. This issue was addressed by Meyerhof (*21*), who suggested that a strength reduction factor be used when the end-bearing capacity of bored and driven piles in stiff fissured clays is evaluated.

Bjerrum (*17*) and Pilot (*22*) noted that the thickness and strength of the crust may have an important role in defining the mode of failure of an embankment. The selection of the undrained shear strength profile in the weathered crust of an otherwise soft clay deposit may also have a strong influence on the stability analysis of embankments or footings as demonstrated by Sagaseta and Arroyo (*23*) and others (*24*). This consideration is important because a substantial portion of the failure surface under shallow footings or embankments may be located within the crust.

A suggestion for reducing the undrained shear strength profile obtained in the crust from the field vane has been presented by Tavenas and Leroueil (*25*). Other schemes for reducing the field vane strength in the crust have also been presented (*26*). One reason that field vane strength tests may show what appear to be unusually or abnormally high undrained shear strength values in the crust is that the test may not represent undrained loading conditions and therefore the response obtained may include a significant component of drained behavior. It has been suggested that the field vane be used to define the thickness of the crust by identifying the location of minimum strength in the profile rather than determining the absolute undrained strength.

Scale effects may also be manifested in surficial crusts and evidenced in the flow characteristics (i.e., hydraulic conductivity) of the deposit. Most surficial clay crusts have a significantly higher hydraulic conductivity than the underlying unweathered deposit. For example, results of in-place hydraulic conductivity tests presented by Lafleur et al. (*27*) indicated that the hydraulic conductivity of the brown oxidized crust of a marine clay may be two to three orders of magnitude higher than that of the underlying gray unoxidized zone. It has also been demonstrated (*28*) that

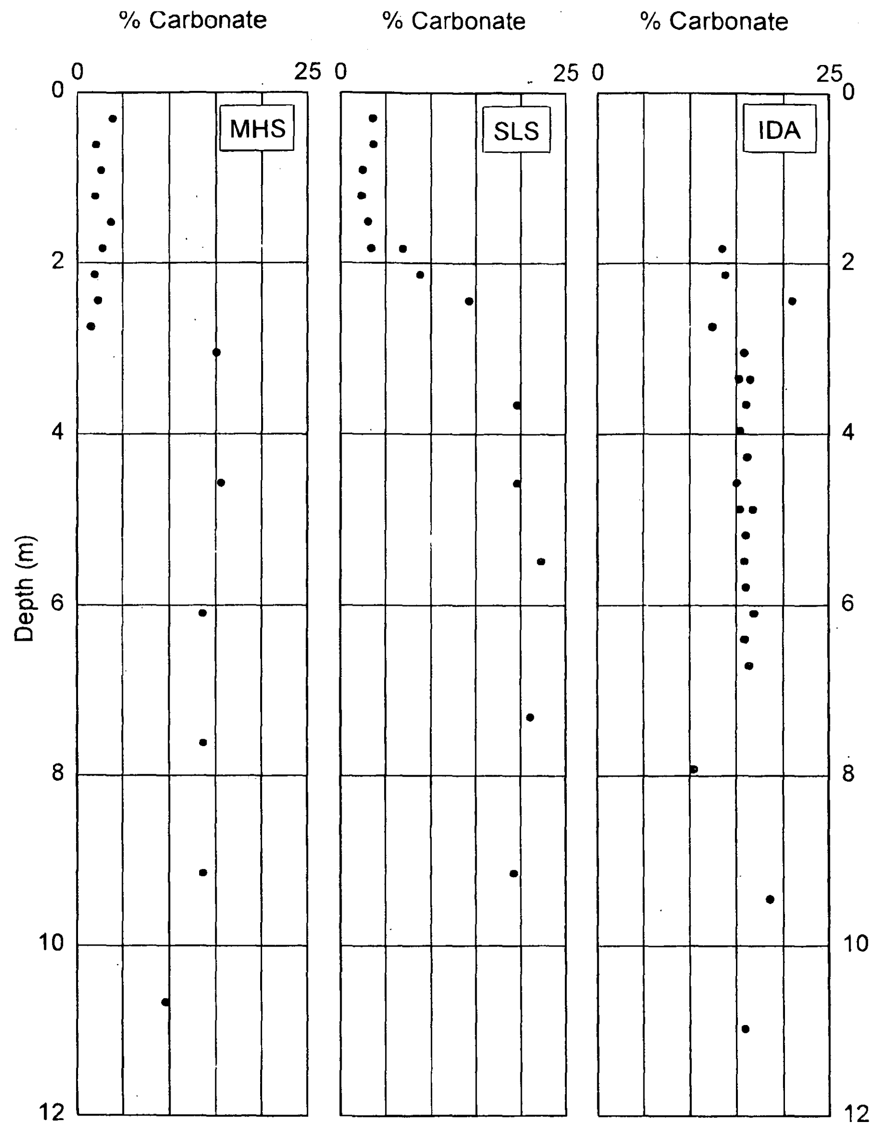

FIGURE 4 Carbonate composition at three marine clay sites.

there may be a significant scale effect when the results of laboratory and field hydraulic conductivity tests are compared with field results giving much higher values. This means that at some sites there is a high likelihood that the soil in the crust does not behave undrained during certain field-loading conditions (e.g., laterally loaded drill shafts).

Scale effects may also exert a significant influence on the results of in situ tests, such as the cone penetration and piezocone tests, which often only involve a small volume of soil. This has been illustrated by Marsland and Quarterman (*29*) and by Mayne et al. (*30*).

Anisotropy

Soil properties of overconsolidated clay crusts may exhibit characteristics that are directionally dependent (i.e., intrinsic anisotropy). For example, Ladd et al. (*31*) indicated that some stiff fissured clays exhibit pronounced undrained strength anisotropy. A number of studies in which samples of stiff, highly overconsolidated and often fissured clays have been trimmed in different directions have shown that shear strength under compressive loading is higher for horizontally trimmed samples than for vertically trimmed samples (*32,33*). Additionally, field investigations using the field vane test suggest that significant undrained strength anisotropy is also present in overconsolidated crusts (*34*). There is also evidence that suggests that some highly overconsolidated clays exhibit directionally dependent stress-strain behavior (*35,36*). Unfortunately, because of the difficulties in sampling, trimming, and testing natural clay crusts, there are very limited data on their anisotropic behavior.

Variability in Properties

One of the important consequences of the development processes of surficial crusts is the production of a highly variable deposit. It is expected that the properties will be more variable than those of the underlying unweathered section, and therefore more effort will be needed to define the engineering properties of the crust. Large variations in such properties as water content, shear strength, compressibility, stress history, and other compositional and structural properties can occur over relatively short distances. A few examples are presented to illustrate these variations.

Water Content and Unit Weight

Simple properties such as water content and soil unit weight often show larger variations in surficial crusts than in the underlying unaltered zone of the profile. The variation in water content obtained throughout the surficial crust and into the underlying unweathered zone at the UMass-Amherst NGES is shown in Figure 5. These data, taken from a combination of hand auger and tube samples, illustrate that large changes occur in both the lateral and vertical directions. In this case the systematic increase in water content with increasing depth helps to identify the base of the severely altered sediments as the water content approaches a relatively constant value. Some water content variations below the crust in Figure 5 represent individual silt and clay varves. Variations in unit weight of the soil at this site, obtained from individual trimmed specimens, are shown in Figure 6. Again the variation in both lateral and vertical directions of even a simple parameter is evident, and the effect of surface processes is a systematic increase in unit weight.

Water content and plasticity data obtained at two sensitive marine clay sites in northern New York are shown in Figure 7. As previously indicated, the IDA site does not exhibit a crust, whereas the MHS site exhibits a pronounced crust. These results illustrate a relatively common feature in the crust, that is, the water content is usually between the liquid and plastic limit and therefore the liquidity index is low in the crust and increases progressively into the lower unaltered zone.

Preconsolidation Stress

Variations in stress history at a given elevation within a clay crust is expected and may be considered the result of the combined effects of the chemical and physical weathering processes. Apart from the obvious problems of sampling disturbance that may

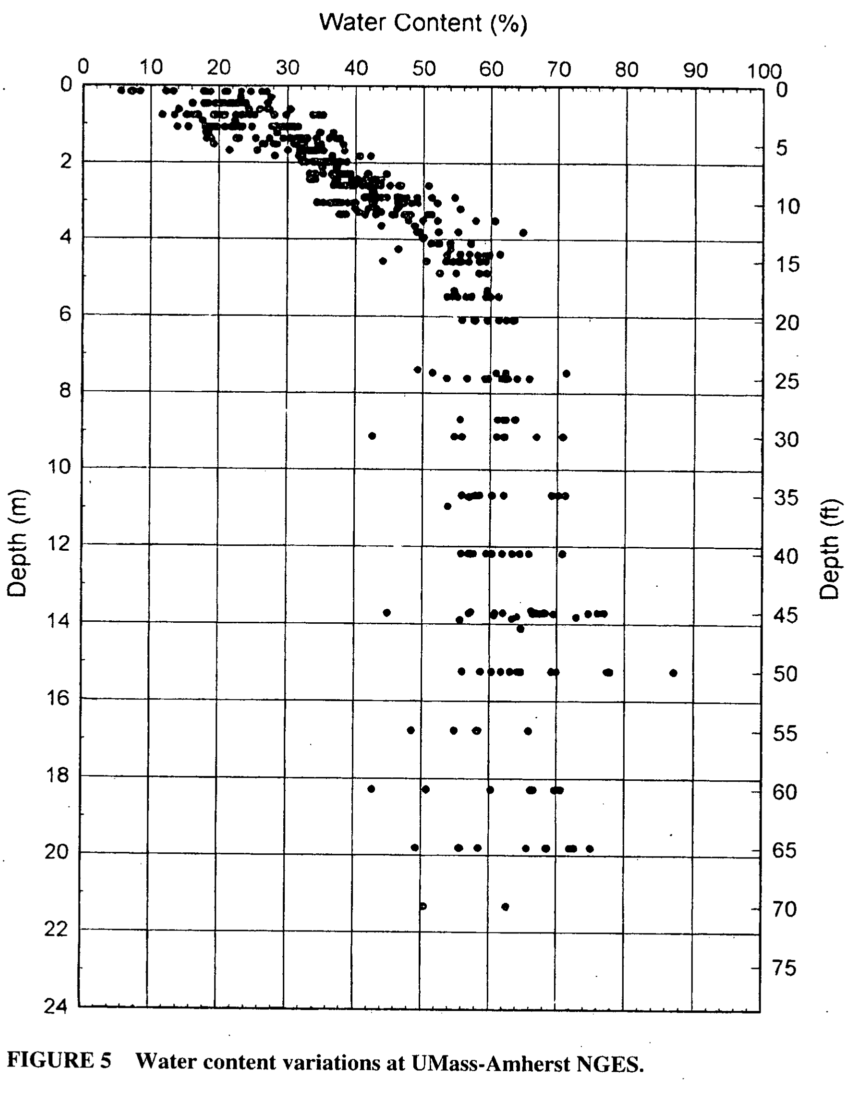

FIGURE 5 Water content variations at UMass-Amherst NGES.

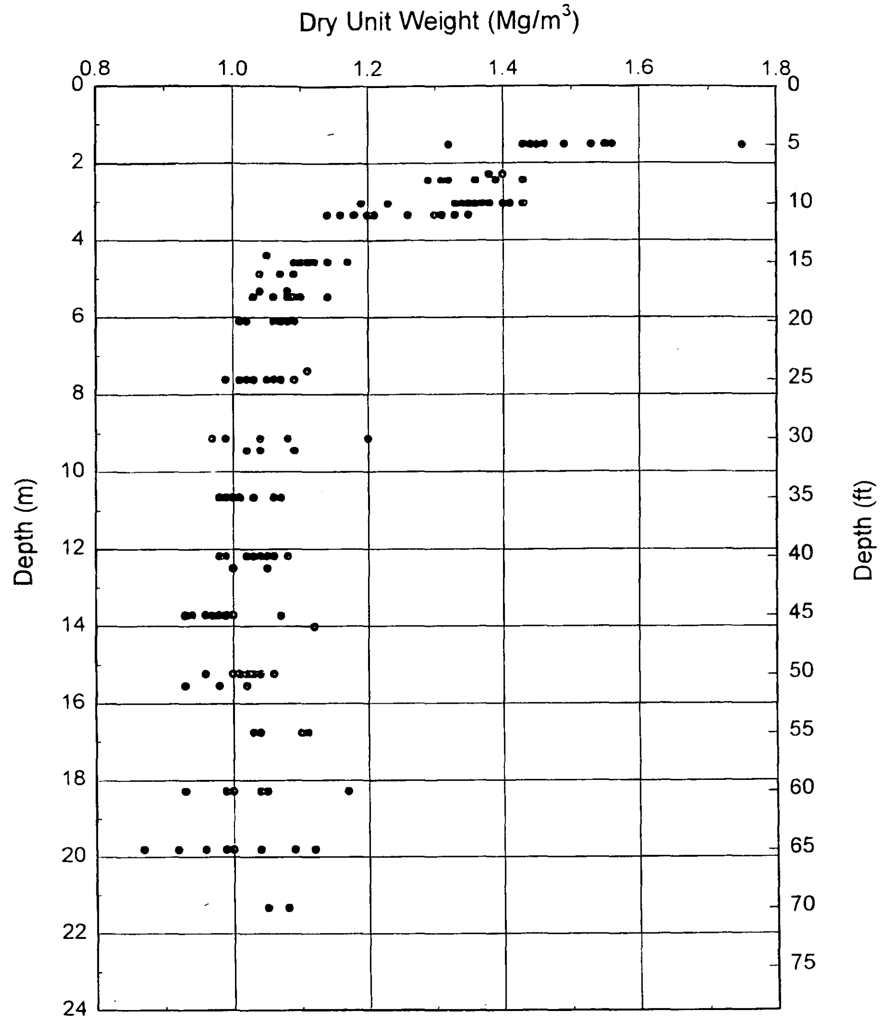

FIGURE 6 Unit weight variations at UMass-Amherst NGES.

accompany the determination of preconsolidation stress (yield stress) in the oedometer, such natural variations may be accentuated because small specimens, for example, on the order of 60 mm, are typically used in performing the test. The results of an initial series of oedometer tests performed at the UMass-Amherst NGES to evaluate stress history are shown in Figure 8. The range in interpreted preconsolidation stresses in the upper part of the profile illustrates the difficulties that can be encountered. What is the proper interpretation of the stress history profile for use in design? This variation in preconsolidation stress and its effect on settlement predictions have been recognized and discussed by Duncan et al. (*37*).

The results of Figure 8 also illustrate the difficulty in using singular values of a given property to correlate the results obtained between laboratory and in situ tests. For example, in this case, selecting which values of σ'_p should be used to develop correlations with the results of cone penetration, piezocone, dilatometer, or other in situ tests can have a significant effect on the resulting correlation. The author suspects that such natural variations are a significant source of errors encountered in the application of empirical correlations between in situ and laboratory tests for many overconsolidated clays.

In Situ Test Results

As mentioned previously, the development of a secondary soil structure from a massive deposit can affect the results of in situ tests, especially small-scale penetration tests. One expects that the variation in test results would decrease through the crust as the secondary structure diminishes with depth into the massive deposit. For example, results of prebored pressuremeter tests performed through the crust at the UMass-Amherst NGES indicate that the range of possible earth pressure coefficients that might be interpreted from the tests is very large in the crust but decreases with depth approaching the less altered zone, as shown in Figure 9. Values of $(K_o)_{min}$ and $(K_o)_{max}$ indicated in Figure 9 are obtained simply from the initial and final points on the straight-line portion of the pressuremeter test. In situ lateral stress ratios may approach limiting passive values; however, passive earth pressures in heavily overconsolidated (i.e., $OCR > 10$), near-surface soils may be much higher than previously reported, simply because a significant effective stress cohesion component has been ignored when limiting stress ratios are calculated and because stress ratios cannot be evaluated by the simple Rankine expression for cohesionless soil.

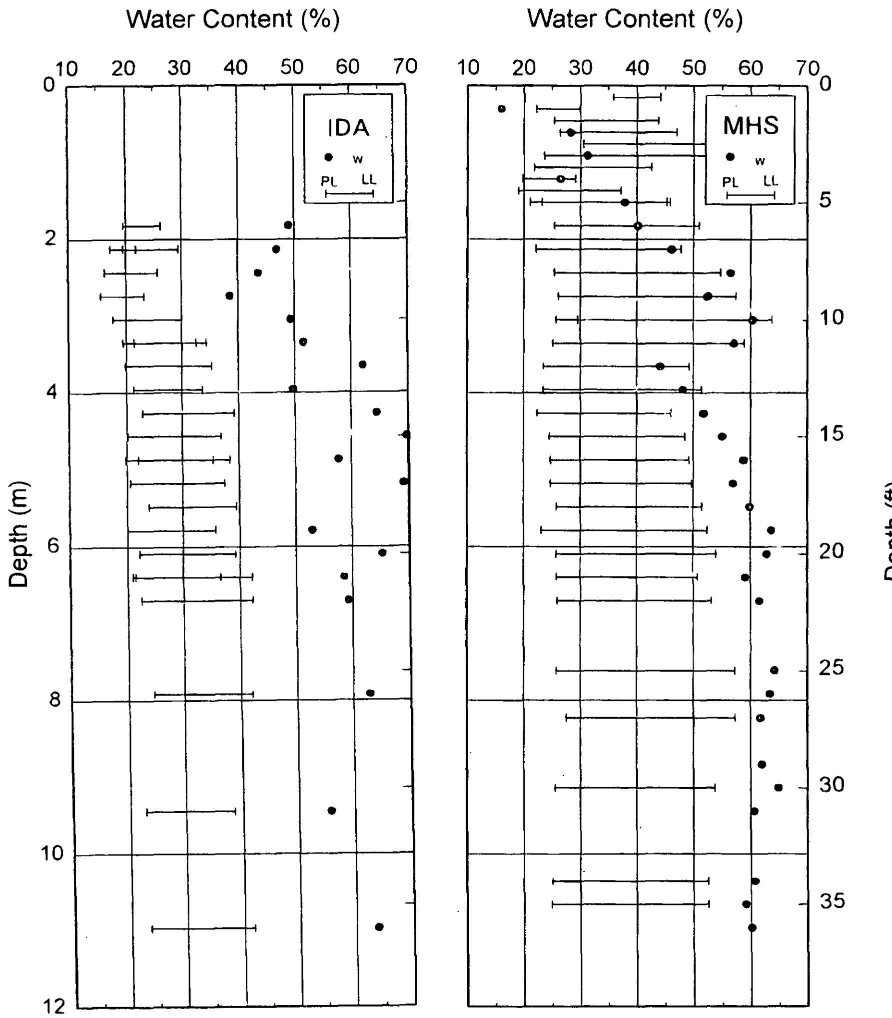

FIGURE 7 Plasticity and water content profiles in two marine clays.

The plate load test and screw plate test, which involve the response from a larger volume of soil have been applied successfully to evaluate the deformation modulus of surficial weathered clay crusts and other stiff clays by Bauer et al. (*38*) and Powell and Quarterman (*39*). Undrained shear strength values obtained from plate load tests also appear to be more applicable in clay crusts to evaluate the behavior of foundation and embankment performance.

DESIGN IMPLICATIONS

The existence of a surficial crust often is recognized and accounted for in analytical procedures for typical design problems. As previously indicated, a surficial crust may have a substantial influence on the performance of earth structures and foundations. The bearing capacity of shallow foundations in or on a surficial crust may be significantly affected by the properties of the crust. Several theories have been presented for estimating the bearing capacity of shallow foundations on a layered system (*40,41*) as well as for evaluating the contribution of a stiff crust to the settlement (*42,43*). For example, Raymond (*44*) indicated that the evaluation of properties of the crust was one of the major uncertainties in analyzing settlement of embankments on clays. The presence of a stiff crust overlying a softer material can change dramatically the distribution of vertical stress when compared with the Boussinesq pressure distribution for a uniform material. Stability of embankments also needs to consider the presence and properties of the crust (*22–25,45*). With only a few exceptions (*38,46*), there are relatively few well-documented field case histories of foundations involving surface crusts to verify the foundation performance and the use of various methods to predict performance. Engineers should take appropriate steps to acknowledge the occurrence of surficial crusts and seek reasonable solutions to design problems.

SUMMARY AND CONCLUSIONS

The development of a stiff, overconsolidated weathered clay crust at the surface of fine-grained sedimentary geologic deposits is relatively common and can have some important implications for geotechnical engineering practice. As a result of the wide range in both physical and chemical crust-forming processes, a complex and highly variable soil mass may result that can be difficult to characterize accurately. The following observations are applicable to the geotechnical behavior of surficial crusts:

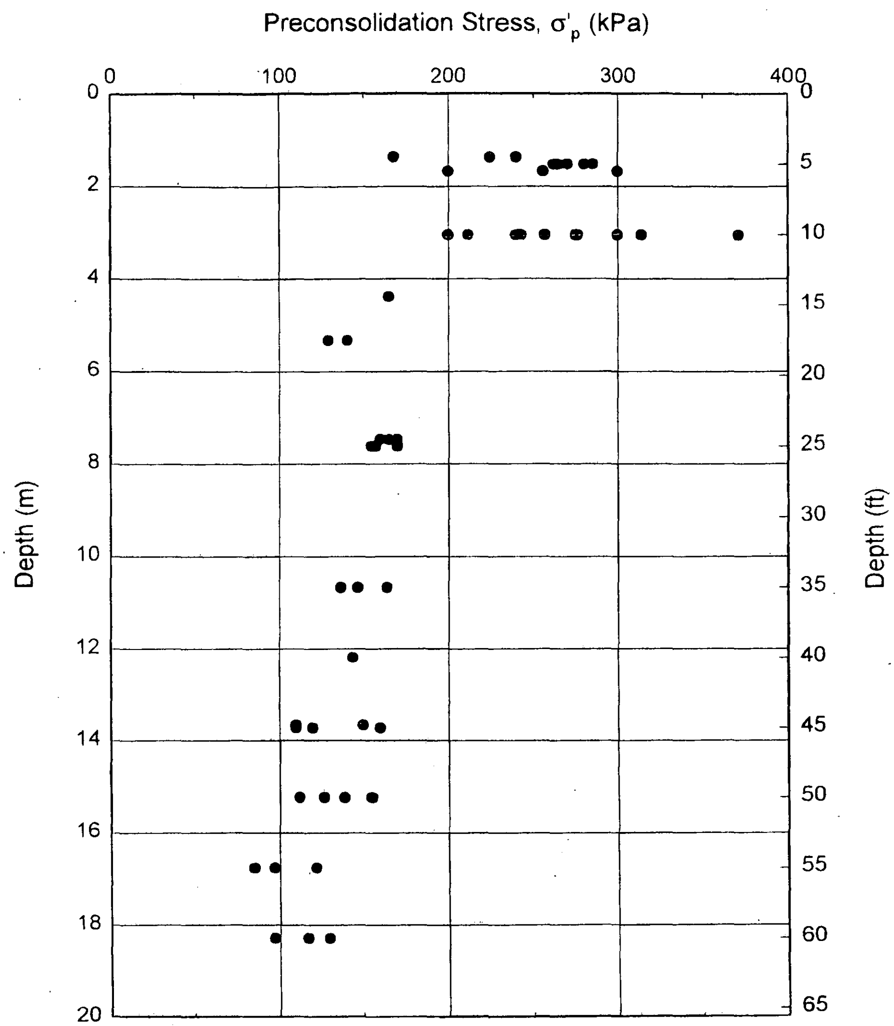

FIGURE 8 Variations in oedometric preconsolidation stress at UMass-Amherst NGES.

1. Crusts are more variable than the underlying unweathered parent deposit.

2. The extent of alteration may vary considerably over short distances and the thickness of a developed crust may be highly variable.

3. The location of the crust often coincides with the zone of maximum movement of the groundwater table, which often enhances the development of the crust. This means that large fluctuations in the magnitude and sign of pore-water pressures are common; therefore, temporal changes in soil effective stresses are common in the crust. Because the thickness of most crusts is limited to a few meters, the changes in effective stress at these shallow depths may be significant.

4. Because the water table fluctuates, the degree of soil saturation above the capillary fringe also fluctuates, and the crust often may be unsaturated.

5. Overconsolidation in the crust is often the result of processes other than simple mechanical unloading. This suggests that soil models that use normalized concepts and property relationships with stress history due to simple unloading from a normally consolidated state to predict such properties as undrained strength or coefficient of lateral stress may not be appropriate.

6. Because of the highly variable nature of the deposit, the geotechnical behavior is less predictable than that of unaltered sedimentary deposits. This means that more effort is required to characterize the properties for geotechnical designs.

7. Because of the developed structure of weathered clay crusts, soil sampling is often difficult, and the results of laboratory tests to predict structural properties such as shear strength may be unreliable and subject to significant scale effects. Therefore, like other significantly structured geologic materials such as residual soil profiles, field tests such as the plate load test or pressuremeter, which provide response of a large volume of soil, are preferred. Usually a larger number of tests is needed to accurately characterize the soil.

8. As a result of the development of secondary soil structure, the hydraulic conductivity of surficial crusts is usually controlled by secondary features such as fissures and joints and may show substantial scale effects.

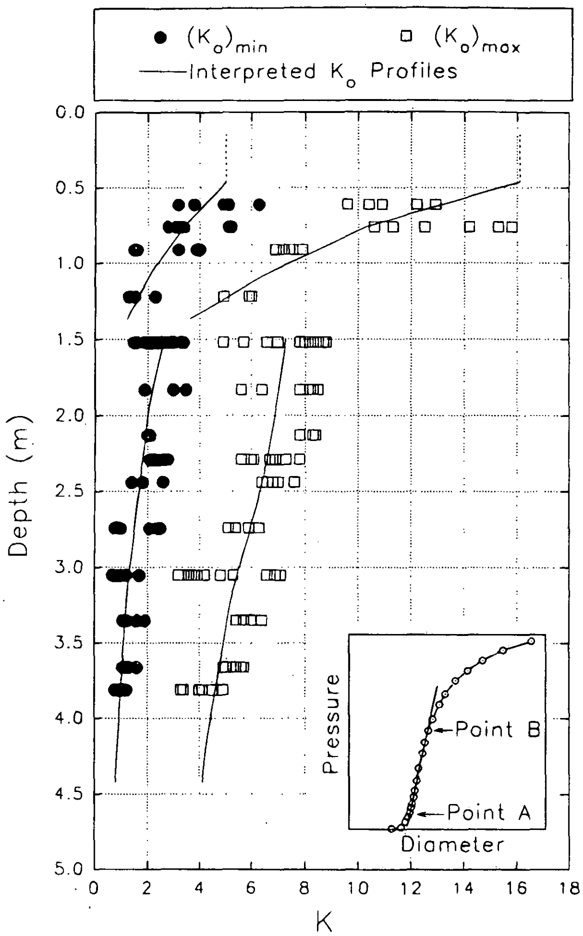

FIGURE 9 Results of interpreted in situ lateral stresses from pressuremeter tests.

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