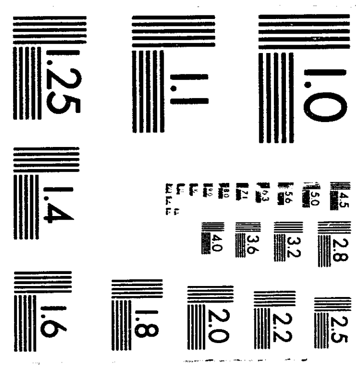

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A METHOD FOR AQUIFER AND PIEZOMETRIC SURFACE MAPPING WITH A CONE PENETROMETER

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ABSTRACT

The electronic cone penetrometer (ECPT) is increasingly being used for environmental characterization of hazardous waste sites, especially to delineate subsurface lithology and to obtain samples of groundwater. A potentially powerful use of the ECPT is the mapping of subsurface hydrostratigraphic features and aquifer piezometric surface(s) by using measurements of pore pressure. Most published studies on the use of the ECPT have been limited to shallow sand-clay sequences and indicate only limited success in hydrogeologic characterization. In this paper, we discuss a method for delineating the depth and thicknesses of unsaturated and saturated zones on the basis of the nature and rate of pore pressure dissipation. We have used this method to depths of 110 ft at several sites underlaid by clay-sand or weathered shale-limestone sequences. The equilibrium pore pressures in the saturated zone should ideally indicate the depth of the water table or aquifer piezometric surface; however, our data indicate that an apparent equilibrium value for pore pressures may be obtained that may be lower or higher than the true value, depending on the composition and grain size of the material in the aquifer, the depth of the dissipation test within the saturated zone, and the history of use of the porous filter in the cone penetrometer assembly. Consequently, the data on dissipation must be carefully calibrated and tested with measurements in a monitoring well before the data are used to determine piezometric surfaces.

INTRODUCTION

Characterization of subsurface hydrogeology is one of the major objectives of remedial investigations at hazardous waste sites with contamination of soil or groundwater (or both). This characterization includes hydrostratigraphic mapping (the depth to the water table or the first saturated zone, vertical changes in permeability within the unsaturated and saturated zones, thicknesses of aquifers and aquitards, etc.), estimation of horizontal and vertical hydraulic gradients, and the hydraulic properties of the contaminated aquifer. Conventional approaches to hydrogeologic characterization are based on the drilling of soil borings and monitoring wells, water level measurements, and hydrologic testing. These methods are environmentally intrusive and expensive and provide hydraulic parameters that are averaged on a relatively large scale.

Increasingly, electronic cone penetrometers (ECPTs) are being used for rapid hydrogeologic characterization. A review of published work indicates that the use of the ECPT in environmental investigations has been limited generally to depths of a few tens of feet in sand-clay horizons and has focused primarily on lithologic classification and collection of groundwater samples (1-3). In this paper, we discuss the use of ECPT

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data on pore pressure for rapid hydrogeologic characterization by determining (a) the depths and thicknesses of aquifers and aquitards and (b) the elevation of the water table or piezometric surface. We have conducted hydrogeologic characterization using the ECPT to depths of 110 ft in a variety of geologic settings.

COLLECTION AND INTERPRETATION OF ECPT DATA

Electronic cone penetrometers consist of a cone at the end of 1-m sections of steel rods that are pushed into the ground by using hydraulic rams (4). In its basic configuration, the cone is fitted with strain gauges and a pressure transducer. The strain gauges measure the tip resistance and sleeve friction during penetration. A pressure transducer is located just behind the tip to record pore fluid pressures through a porous filter. Measurements of tip resistance, sleeve friction, and pore pressures are recorded continuously as the cone is being advanced.

Tip resistance and sleeve friction together measure the geotechnical properties (strength, compaction, cohesiveness, etc.) of the material being penetrated. As the cone is pushed through a cohesive clay horizon, the cone forms a cavity with relatively little caving-in of the walls. Consequently, both the tip resistance and sleeve friction are relatively low. In low sandy horizons with a low degree of compaction, the uncohesive material generally is difficult to push aside and is likely to keep caving in on the cone, resulting in higher tip resistance and possibly higher sleeve friction. Because of the disturbance of the material around the cone during penetration, in situ pore pressures are altered. Significantly high pore pressures are developed in cohesive materials with lower permeability, such as clays, because of consolidation around the cone (5). Pore pressures may also increase initially in sand layers with higher permeability, but the buildup is relatively less compared with the clay layers. Soil and lithologic classifications that are based on tip resistance, sleeve friction, and instantaneous pore pressures have been proposed (4,6-8).

The high instantaneous pore pressures generated during cone penetration dissipate or decay over time to a lower value as the materials reach equilibrium. The change in pore pressure with time at a given depth can be recorded by temporarily stopping penetration of the cone. The dissipation time required to reach equilibrium depends on the hydrologic and mechanical properties (permeability, compaction, and strength) of the materials. Conceptually, the pore-pressure decay time may be lower in the saturated zone because the presence of water will facilitate the process of equilibration. In addition, the equilibrium pore pressure after dissipation of instantaneous pressures in the saturated zone would indicate the water table or piezometric surface of an aquifer at a given depth. Thus, pore-pressure dissipation curves at various depths may be used to map the subsurface hydro-stratigraphic features and the water table or piezometric surface. Several empirical and theoretical relationships have been proposed to estimate the geotechnical and hydraulic properties of materials by using the pore pressure data (6,9); however, the ideal behavior of materials required for the application of these methods generally is not observed in the field; and, therefore, these estimations are not attempted in this paper.

Hydrostratigraphic Mapping

The use of ECPT data from the York, Nebraska, and Navarre, Kansas, sites for mapping subsurface hydrostratigraphic features is described subsequently. The York, Nebraska, site is underlaid by a sequence of clay-sand-silt layers. The Navarre, Kansas, site is underlaid by weathered and relatively fresh, interbedded shale-limestone sequences.

York, Nebraska, Site

The lithologic log from a soil boring drilled with continuous core sampling at York, Nebraska, and the ECPT penetration log obtained about 15 ft away from the soil boring are shown in Figure 1. Unsaturated loess, clay, and silty-clay layers occur to a depth of 46 ft, followed by alternating sand and clay layers up to 52 ft. Unsaturated medium sand and gravel occur from 52 ft to the water table at 70 ft. The saturated zone consists of medium sand with a dominantly silt layer from 83 to 87 ft.

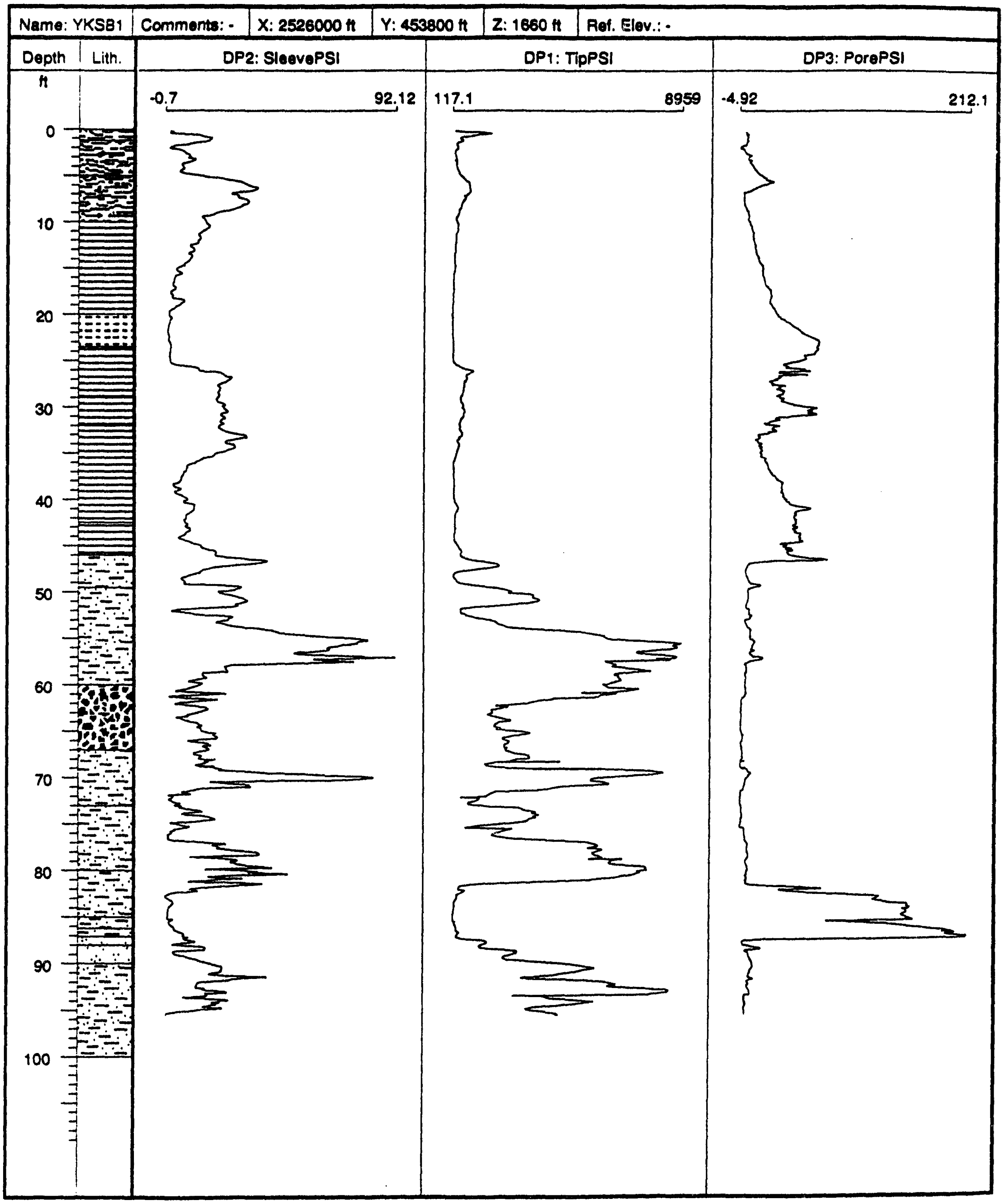

Figure 1. Lithologic and cone penetration logs from York, Nebraska.

Variations in tip stress, sleeve friction, and instantaneous pore pressures in the ECPT penetration log are well correlated with lithologic changes observed in the soil boring. Tip stress and sleeve friction are low in clay and silt layers, compared with the sand and gravel layers. Instantaneous pore pressures were high in the unsaturated or saturated loess-clay-silt layers, indicating significant compaction of low-permeability materials. Within the sand-gravel layers, instantaneous pore pressures were negative or near zero, both in the saturated and unsaturated zones. Ideally, the instantaneous pore pressure in the relatively high-permeability sand and gravel layers should be zero at the water table and should increase with depth as the hydrostatic pressure increases. Because such ideal changes in the instantaneous pore pressure readings were not observed, dissipation of pore pressures was recorded at several depth intervals to estimate the depth and thickness of the saturated zone.

Dissipation of pore pressures in the unsaturated zone was significantly different from that in the saturated zone. Typical dissipation curves in these zones are shown in Figures 2-4. Initial pore pressures in unsaturated clay layers (60-120 psi) remained high or increased further for about 5 min (Figure 2). After this time, the dissipation rate varied and time t_{50}, defined as the time for a 50 percent decline in pore pressure from the initial reading, generally was in excess of 10 min or was not reached at all. The rate of pore pressure decline after t_{50}, if reached, ranged from 2 to 60 psi/min. Buildup of pore pressures in the unsaturated sand layers was much less than that in the clay layers, but the dissipation behavior was the same (Figure 2). The pore pressures either did not decline for more than 100 min or declined quickly but fluctuated significantly at near-zero values without reaching an apparent steady state.

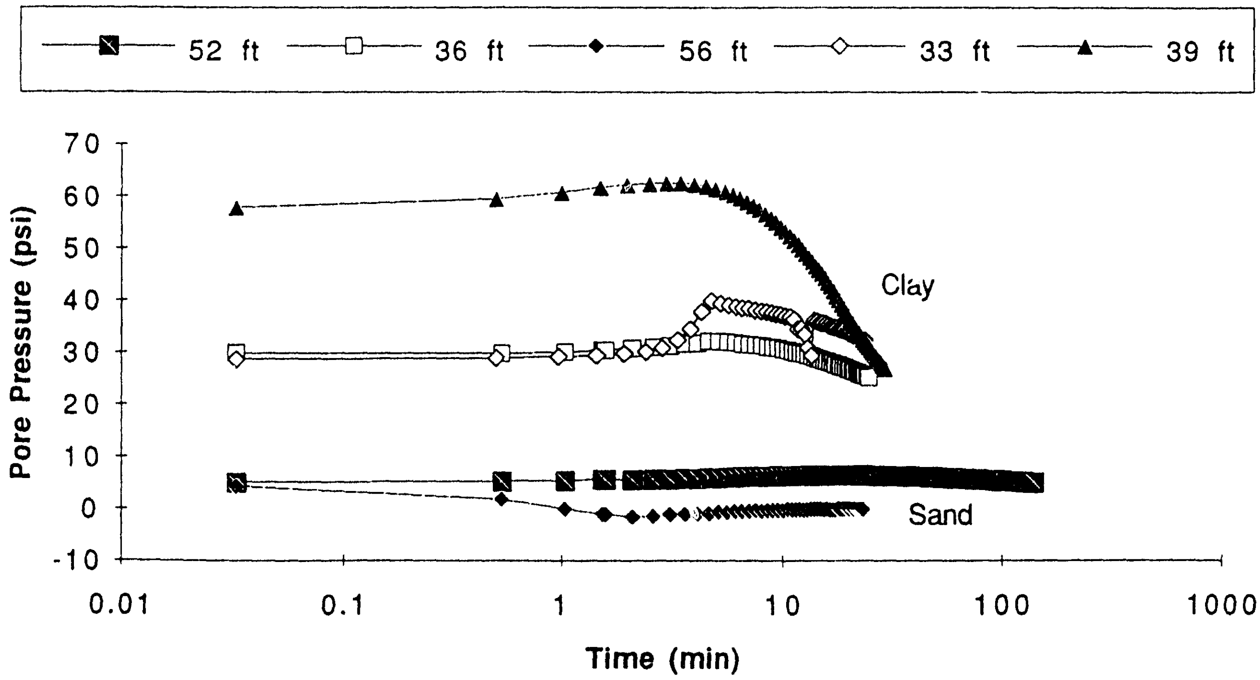

Figure 2. Pore pressure dissipation curves in unsaturated clay and sand layers at York, Nebraska.

In the saturated sand layers, initial pore pressures were either slightly higher or lower than the equilibrium value that was based on the measured water level in the soil boring (Figure 3). This observation indicates that cone penetration resulted in both consolidation and dilation of materials. Observed dilation around the cone is in contrast to the basic assumption in theoretical studies used to obtain hydraulic parameters from pore pressure data, i.e., that cone penetration results in consolidation of materials. When excess initial pressures were developed, t_{50} was less than 5 min (Figure 3). The rate of decline in pore pressure after t_{50} also was much lower than that in the unsaturated zone and ranged from 0.1 to 0.5 psi/min. A nearly steady state was reached within about 10 min.

Pore pressure dissipation in the low-permeability silt-clay layer within the saturated zone was similar to that in the saturated sand layers, although the rate of dissipation was slower (Figure 4). Initial pore pressures were very high (124 psi), but t_{50} was only 5 min. Because of the initially high pressures, the rate of pore pressure decline remained high after t_{50}, but a nearly steady state was reached within about 30 min. The dissipation behavior in the saturated silt layer was significantly different from that in the unsaturated clay-silt layers (Figures 2 and 4). Differences in the character and rate of pore pressure dissipation between the saturated sand and silt layers (Figures 3 and 4) provide evidence for changes in permeability with depth within the saturated zone. The scale at which these variations can be observed from pore pressure data (1-5 ft) is much smaller than that based on well pumping tests, which provide an average aquifer response.

Navarre, Kansas, Site

The stratigraphic section consists of unsaturated clay and weathered shale/limestone layers to a depth of 35-40 ft, underlaid by 10-20 ft of saturated, weathered calcareous shale and shaley limestone. Below this saturated zone is a claystone unit 10-18 ft thick, which is mostly dry and forms the aquitard between the overlying saturated zone and the underlying bedrock aquifer of interbedded shale and limestone.

Measurements of tip stress and sleeve friction in penetration logs were not very well correlated with lithologic changes because of the varying degree of weathering in the sequence. Instantaneous pore pressure readings also did not indicate the presence or absence of saturated zones and significant vertical changes in permeability.

Pore-pressure dissipation curves, however, were different in the unsaturated and saturated zones and were essentially similar to those described previously for the clay-silt-sand sequence at York, Nebraska. Dissipation curves were obtained at several depth intervals within the unsaturated and saturated zones. Figure 5 shows typical dissipation curves from four depth intervals. In the unsaturated zone, dissipation of excess pore pressure was very slow, and t_{50} was in excess of 10 min. In the saturated zone, dissipation was much faster, with a t_{50} of about 5 min or less. A steady-state pore pressure was reached in the saturated zone within a few minutes. Pore pressure dissipation in the claystone unit underlying the first saturated zone was much slower, similar to that in the unsaturated zone. Below the claystone layer, pore pressure dissipation in the bedrock aquifer was once again much quicker and typical of saturated zones.

The previous discussion makes it clear that instantaneous pore pressures in a cone penetration log generally do not provide a means to map the hydrostratigraphic variations. In addition, cone penetration may result in both consolidation and dilation of the materials being penetrated. Records of pore pressure dissipation are characteristic of the unsaturated and saturated zones and aquitards and can be used to delineate the depths and thicknesses of these zones. The pore-pressure dissipation rate within the saturated zone can be used to map vertical changes in permeability at a much smaller scale than may be possible from well pumping tests.

Water Table or Piezometric Surface Mapping

In the saturated zone, the pore pressure refers to the hydraulic head at the depth of observation. The hydraulic head caused by a column of fluid is

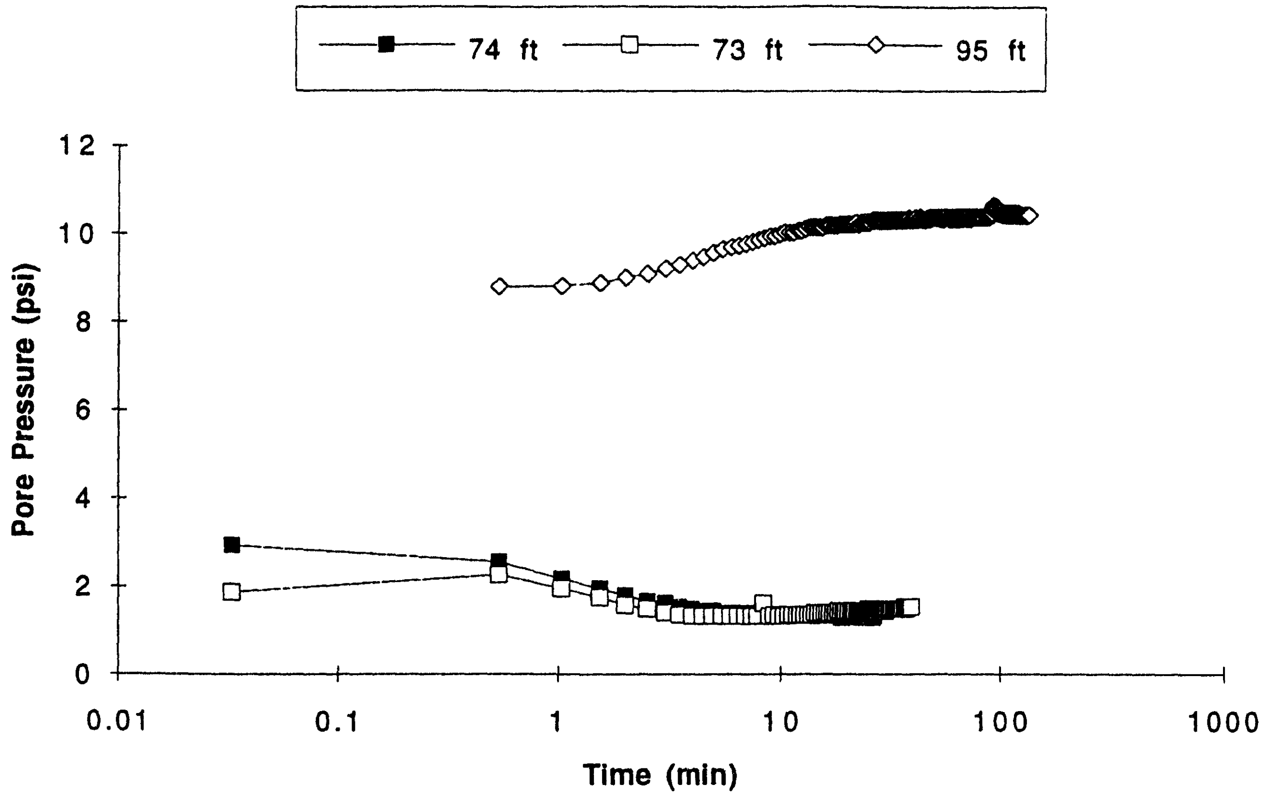

Figure 3. Pore pressure dissipation curves in saturated sand layers at York, Nebraska.

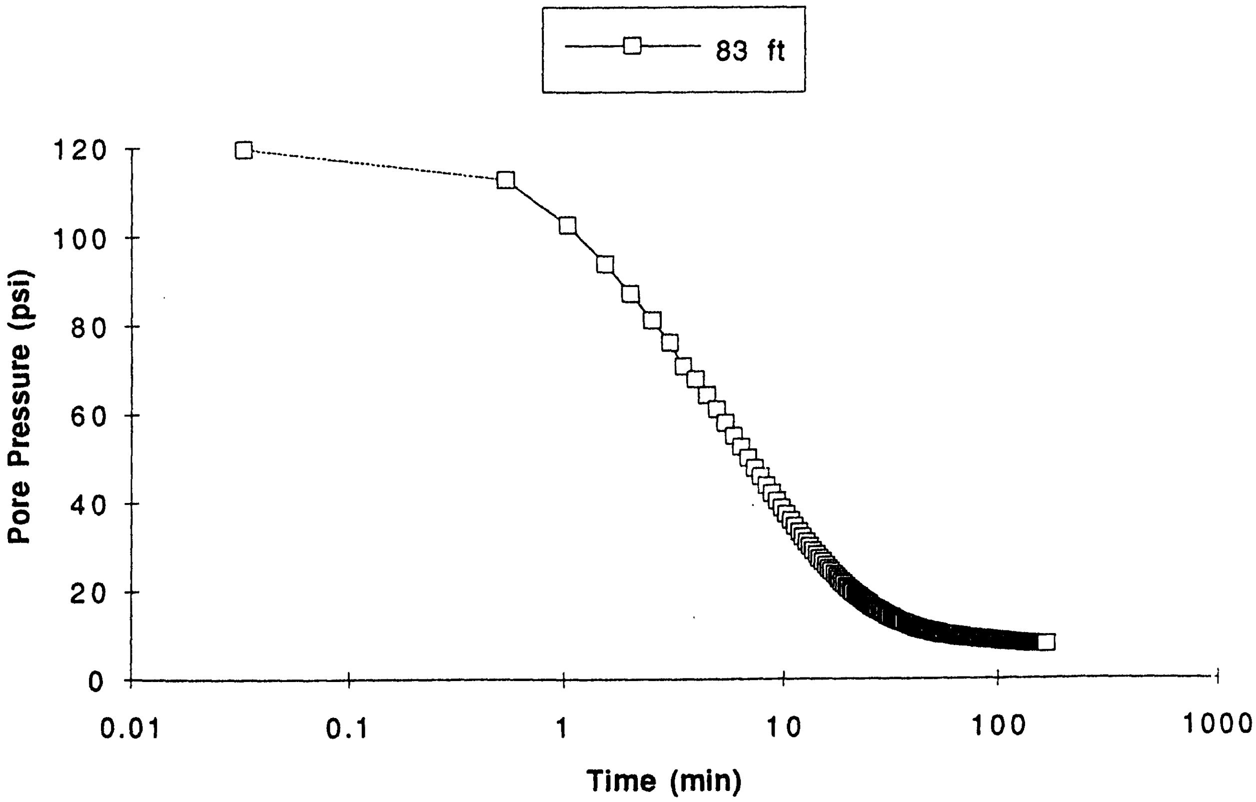

Figure 4. Pore pressure dissipation curve in a saturated silt layer at York, Nebraska.

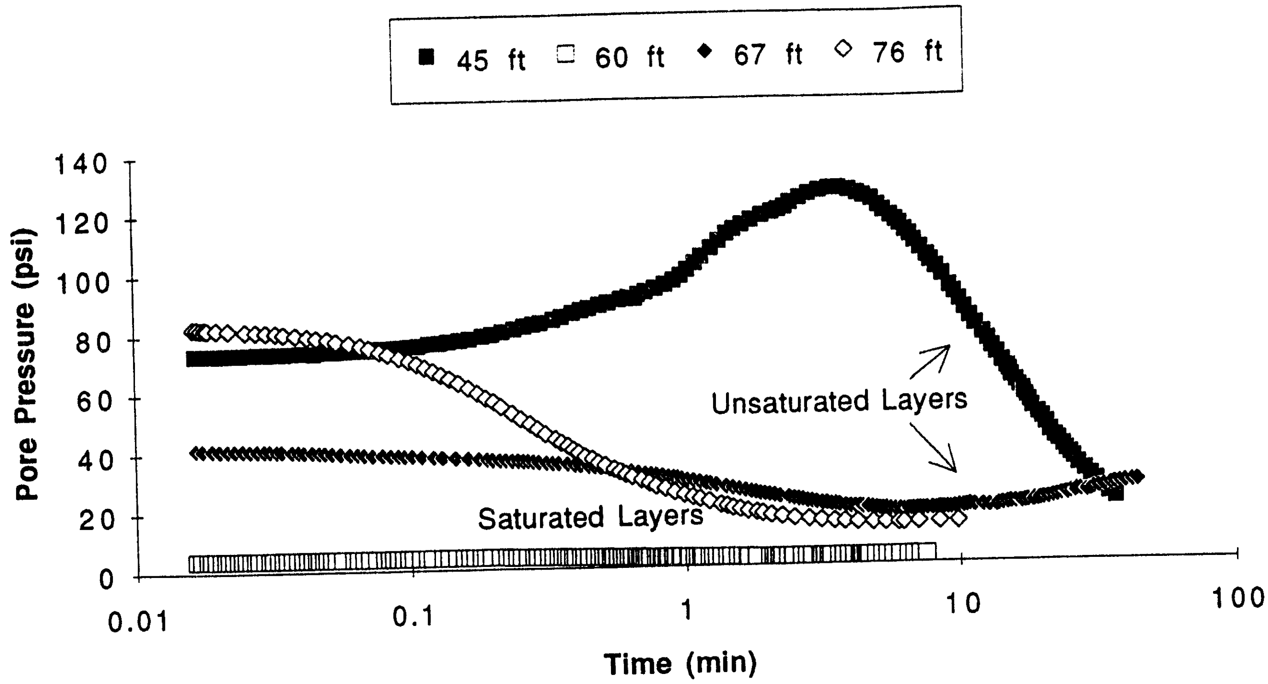

Figure 5. Pore pressure dissipation curves in unsaturated and saturated zones at Navarre, Kansas.

equal to ρ*gh*, where ρ is the fluid density, *g* is the acceleration caused by gravity, and *h* is the height of the column. Thus, for dilute waters in shallow aquifers, the pore pressure is related to the height of a water column by a factor of 2.308 (i.e., a pressure of 1 psi is exerted by a 2.308-ft water column). By subtracting the height of the water column (obtained from the equilibrium pore pressure value) from the depth of observation, one can determine the depth to the water table (or piezometric surface in confined aquifers). Additionally, if pore pressures are obtained from several depths at a single location, the magnitude of any vertical hydraulic gradient can be determined. This method for mapping water tables and vertical hydraulic gradients was tested at several sites in clay-silt-sand sequences similar to those at the York, Nebraska, site discussed previously. Results for two of the sites (Murdock and York, Nebraska) are discussed subsequently.

Equilibrium pore pressures at Murdock were obtained in the vicinity of existing monitoring wells. Dissipation tests were performed at several depths at a given location to obtain reproducible values of equilibrium pore pressure. The dissipation curves displayed typical saturated zone behavior in which t_{50} was less than 5 min and a steady state was reached within 10-30 min. Figure 6 shows the equilibrium pore pressures measured at three depths at two locations and the expected pore pressures at each of the depths on the basis of the measured water table in an adjoining monitoring well. The equilibrium pore pressure obtained from the first depth interval at a given location was the same as that expected from the depth of the water table in the adjoining monitoring well; however, subsequent dissipation tests at deeper depth intervals within the same hole equilibrated at a pressure below that expected from the depth of the water table. This difference in multiple measurements was not due to a vertical gradient in the aquifer because water level measurements in a cluster of monitoring wells installed at different depths indicated that no significant vertical gradient was found in the aquifer. Measurements of equilibrium pore pressure at all 1depths, therefore, should plot along a straight line with a slope of 1, as shown by the "ideal curve" in Figure 6.

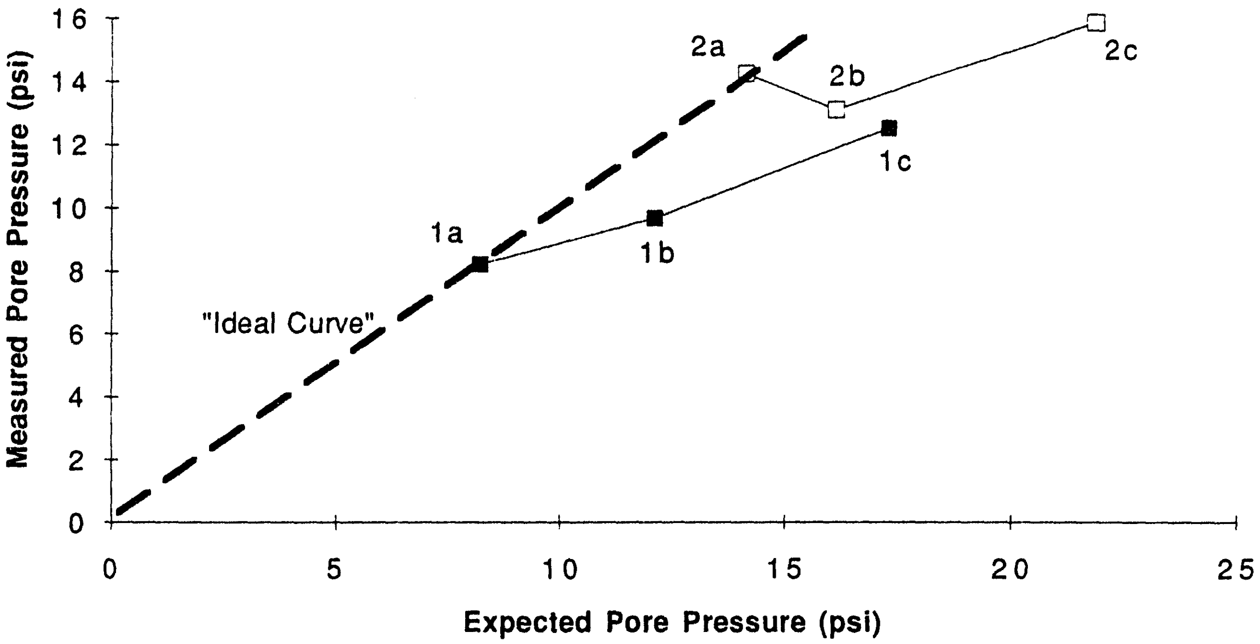

Figure 6. Measured and expected equilibrium pore pressures from two locations, 1 and 2, at Murdock, Nebraska. The depth to water table was 42 ft at location 1 and 37 ft at location 2. Dissipation was recorded at depths of 61 ft (1a), 70 ft (1b), and 82 ft (1c) at location 1, and at depths of 69 ft (2a), 74 ft (2b), and 87 ft (2c) at location 2.

Because the first dissipation test always produced the correct equilibrium pressure, the conclusion was that the porous filter in the cone penetrometer assembly perhaps was partially clogged, creating a pressure differential across the filter. This conclusion was tested by measuring the pressure of a 2.3-ft column of water by using the cone assembly before and after a penetration test. With a fresh filter before the test, a pressure of 1 psi was recorded, as expected; however, after a single dissipation test, the recorded pressure was much lower, ranging from 0.45 to 0.65 psi. This observation indicated that the filter should be used for only a single dissipation test.

Measurements of pore pressure dissipation with a new filter for each test were then obtained at several locations at Murdock. The water-table map constructed from these measurements was in excellent agreement with the known water levels in the area.

Measured and expected pore pressures from a single location at York, Nebraska, are shown in Figure 7. Even with a new filter, a reproducible measurement of equilibrium pore pressure could not be obtained at several depths. Additionally, the equilibrium pore pressures at several depths were greater than the expected value. This higher value was not considered to be a result of the termination of the dissipation test too early because none of the dissipation tests ended when the values were unstable and because erratic results were obtained in repeated measurements at the same depth interval. This observation indicates that, in addition to the use history of the porous filter, the depth to the water table and the composition of the aquifer materials (clay-silt-sand proportions) may impact the equilibration of pore pressures recorded in a cone penetrometer. Consequently, one must carefully evaluate the applicability of the pore-pressure dissipation technique for mapping the water table or piezometric surface at a given site. We are

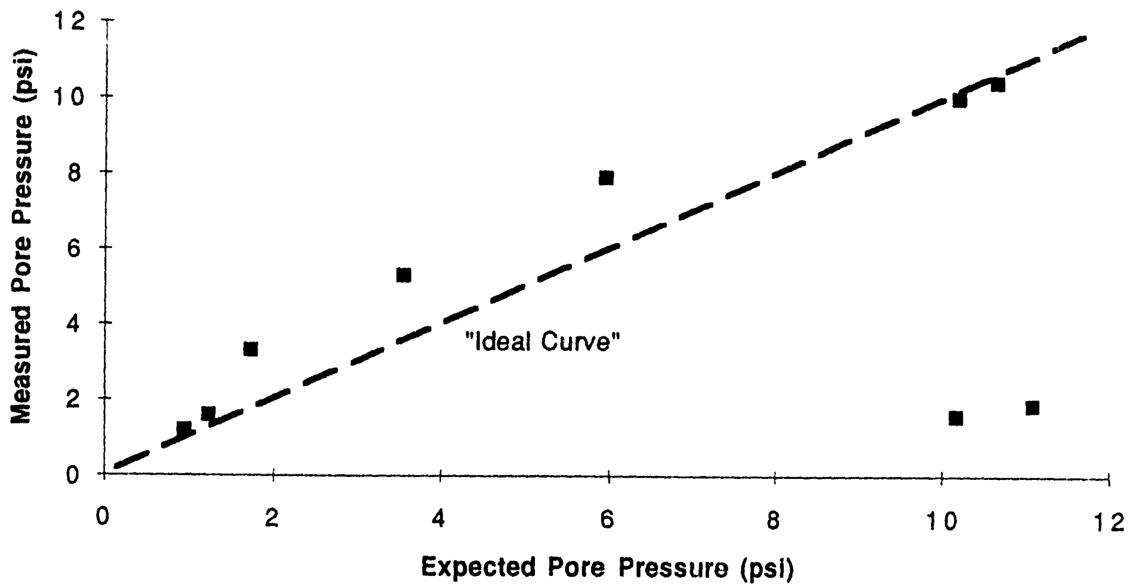

Figure 7. Measured and expected equilibrium pore pressures at multiple depths at a single location in York, Nebraska. The depth to water table was 70 ft. Dissipation was recorded at depths of 72.2, 72.9, 74.0, 78.2, 83.8, 93.5, 94.6, and 95.6 ft.

currently evaluating the specific reasons for the observed discrepancy in measuring equilibrium pore pressures to develop a reliable method for mapping water tables.

CONCLUDING REMARKS

Under ideal conditions and if excess pore pressures are not developed during penetration in the saturated zone, the instantaneous pore pressure should be zero at the water table. Below the water table, the pore pressure curve should have a slope equal to the increase in hydrostatic pressure with depth; however, such conditions are rare in actual field situations. Therefore, the use of the ECPT for hydrogeologic characterization is only limited by using traditional interpretations of the ECPT data. The method that is based on the nature and rate of pore pressure dissipation described in this paper allows the rapid determination of the depths and thicknesses of saturated and unsaturated zones and changes in permeability in the saturated zone. The ability to map the water table or piezometric surface by using equilibrium pore pressure data appears to depend on site-specific conditions and may be possible if carefully tested and calibrated against monitoring well data.

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