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USE OF PIEZOMETRIC CONE PENETRATION TESTING WITH ELECTRICAL CONDUCTIVITY MEASUREMENTS (CPTU-EC) FOR THE DETECTION OF HYDROCARBON CONTAMINATION IN SATURATED GRANULAR SOILS

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ABSTRACT: Piezometric Cone Penetration Testing with soil Electrical Conductivity measurements (CPTU-EC) was used for the detection of hydrocarbon saturated granular soils at two airport fuel storage areas. Details of the CPTU-EC equipment and site subsurface conditions are provided. Test program phases, including laboratory testing, field insitu testing and CPTU-EC data interpretation are described. Comparisons are made between CPTU-EC and adjacent monitor well data. Limitations to the CPTU-EC method are discussed.

KEYWORDS: Piezometric Cone Penetration Test, Soil Electrical Conductivity, Free Phase Petroleum, Hydrocarbon Product Contamination, Airport Fuel Tank Farms, Computerized Data Acquisition, Continuous Soil Profiling.

INTRODUCTION

Programs to remediate groundwater accumulations of free phase petroleum hydrocarbon products, consisting primarily of aviation jet fuels, are ongoing at the fuel tank farms at John F. Kennedy (JFKIA), La Guardia, and Newark International Airports, in and around the city of New York. The Port Authority of New York and New Jersey (Port Authority) frequently requires supplemental groundwater information in addition to that acquired in monitor wells at the sites.

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STRATIGRAPHICS, a consulting company specializing in penetrometer data acquisition, was retained by Port Authority to evaluate the use of penetrometer soil electrical conductivity measurements (CPTU-EC) to delineate the accumulations of hydrocarbon products in the subsurface at the sites. STRATIGRAPHICS personnel had previously conducted similar studies on using penetrometer conductivity measurements for the detection of hydrocarbon contaminated soils and for the detection of groundwater ice crystals in Arctic permafrost soils (Reference 1).

The penetrometer technique provides various advantages during geo-environmental subsurface investigations. These advantages include a relatively non-destructive test procedure; immediate, computerized data reporting and interpretation; continuous profiling; a high degree of exploration personnel safety; and lower exploration costs and higher productivity as compared to borehole techniques.

The experimental program for evaluating the applicability of penetrometer soil electrical conductivity measurements for the detection of free phase petroleum hydrocarbon products in groundwater consisted of two phases. The first was a laboratory study using typical site soils, groundwater, and jet fuel. A series of 60 tests was performed in order to establish a range of expected field measurements. The initial laboratory study was followed by field studies at the Satellite and Bulk Fuel Farms at JFKIA.

CPTU-EC soundings were performed adjacent to monitor wells for comparisons between penetrometer and monitor well data. CPTU-EC soundings were also performed at intermediate locations for correlation to the areal distribution of hydrocarbon product accumulations. A total of 48 CPTU-EC soundings were performed during the field study (Figures 1 and 2).

SOIL ELECTRICAL CONDUCTIVITY

Soil electrical conductivity is controlled by the conductance of the system of soil particles and fluids occupying the soil pore spaces. Factors affecting soil electrical conductivity, especially for sand aquifers, include:

Mineralogy Siliceous sand grains are essentially non-conductive, so granular soil electrical conductance is dependent on the quantity and conductance of the soil pore fluid. Clay minerals have some electrical conductance due to adsorbed water and ionic charges, thus clay conductance depends on both mineralogy and pore fluid characteristics.

Pore Fluid The electrical conductance of pore fluids plays the major role in granular soil electrical conductivity. Sands saturated with conductive fluids, such as saline water or landfill leachates, have a relatively high conductivity. Sands saturated with petroleum hydrocarbon products typically have low electrical conductivity because most petroleum hydrocarbon products are poor conductors.

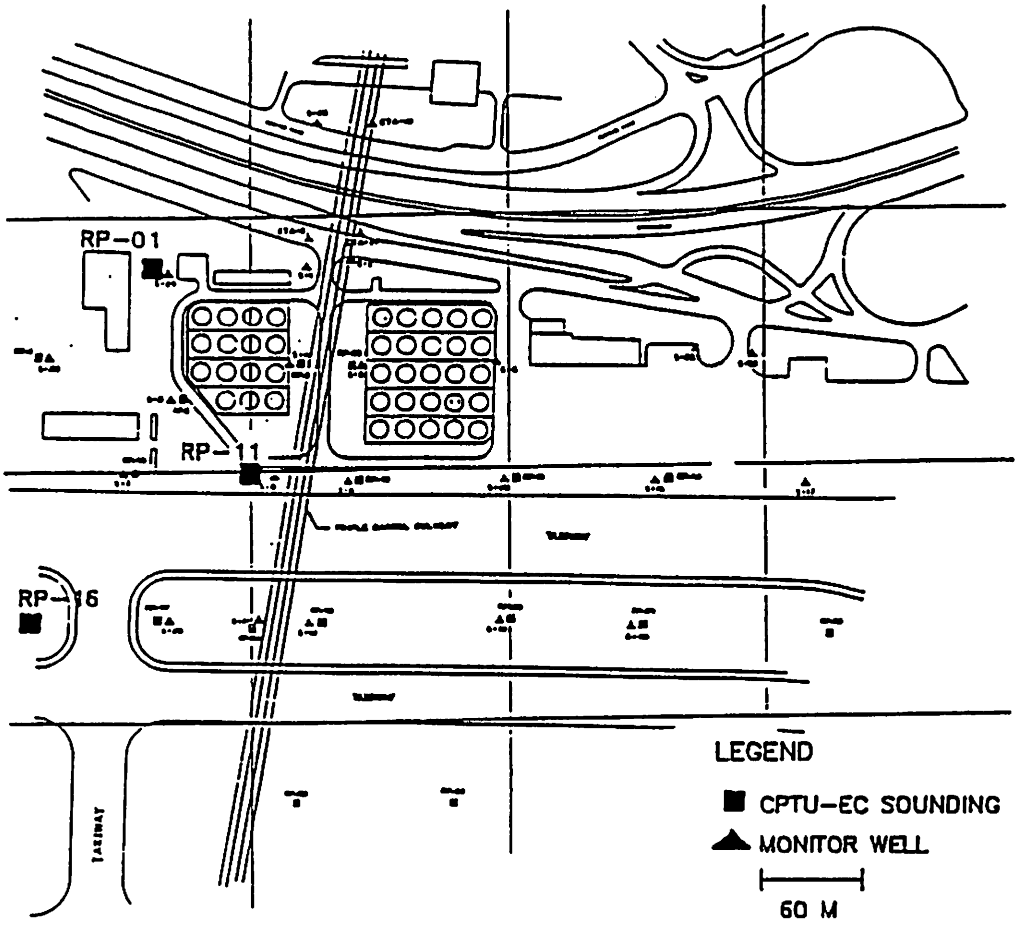

FIGURE 1 – SATELLITE FUEL FARM LOCATION PLAN

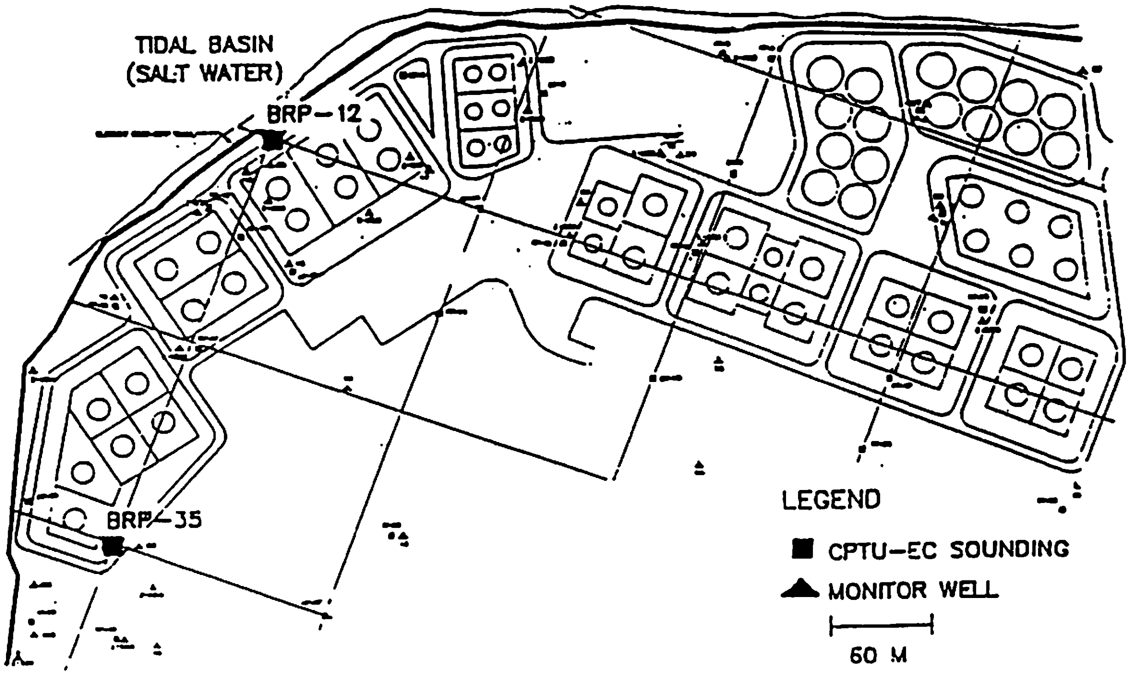

FIGURE 2 – BULK FUEL FARM LOCATION PLAN

Saturation The degree of soil saturation has a pronounced effect on soil electrical conductivity. Conductivity increases with increases in water saturation. Partially saturated sands have low electrical conductivity.

Porosity Soil porosity has an affect on soil electrical conductivity (Reference 2). Less pore fluid is required to fully saturate the pore space of a low porosity (dense) soil, resulting in lower soil electrical conductivity.

LABORATORY PROGRAM

The laboratory program to determine the effects of free phase petroleum hydrocarbon contamination on granular soil electrical conductivity included a total of 60 tests. Samples of soils from JFKIA site excavations, brackish (salty) groundwater from site monitor wells, and samples of jet fuel were used to provide a range of variables that might be encountered during field testing. Soil samples were compacted to different densities to determine the sensitivity of test results to porosity changes.

Laboratory testing showed that the electrical conductivity of the JFKIA sand samples depended primarily on the amount of water filling the soil pore spaces (degree of water saturation). Soil conductivity decreased with increasing substitution of pore water by jet fuel (Figure 3). A jet fuel saturated sand sample had an electrical conductivity similar to that of a dry sand sample.

The laboratory study indicated that in order to discriminate between dry sands above the water table, and free phase petroleum hydrocarbon product saturated sands below the water table, data on soil saturation was also required. A pore water pressure transducer, used during Piezometric Cone Penetration Testing (CPTU), was added to the CPTU-EC penetrometer to determine soil saturation.

Soil stratigraphy defined by Cone Penetration Test (CPT) measurements can be used to distinguish between the effects of soil type and pore fluid chemistry on measured soil conductivities. Thus, the soil shear resistance measurements of the CPT penetrometer, the piezometric measurement of the CPTU penetrometer, and soil electrical conductivity measurements were all combined in a CPTU-EC penetrometer in order to provide sufficient data to define petroleum hydrocarbon product contamination of saturated granular soils.

PENETROMETER TECHNIQUE

CPTU-EC penetrometer testing consists of smoothly pushing a small diameter (0.044 m - 1.7 inch), instrumented probe (penetrometer) directly into the ground, while a computer data acquisition system displays and records the soil shear resistance, pore water pressure response and soil electrical conductivity during penetration (Figure 4).

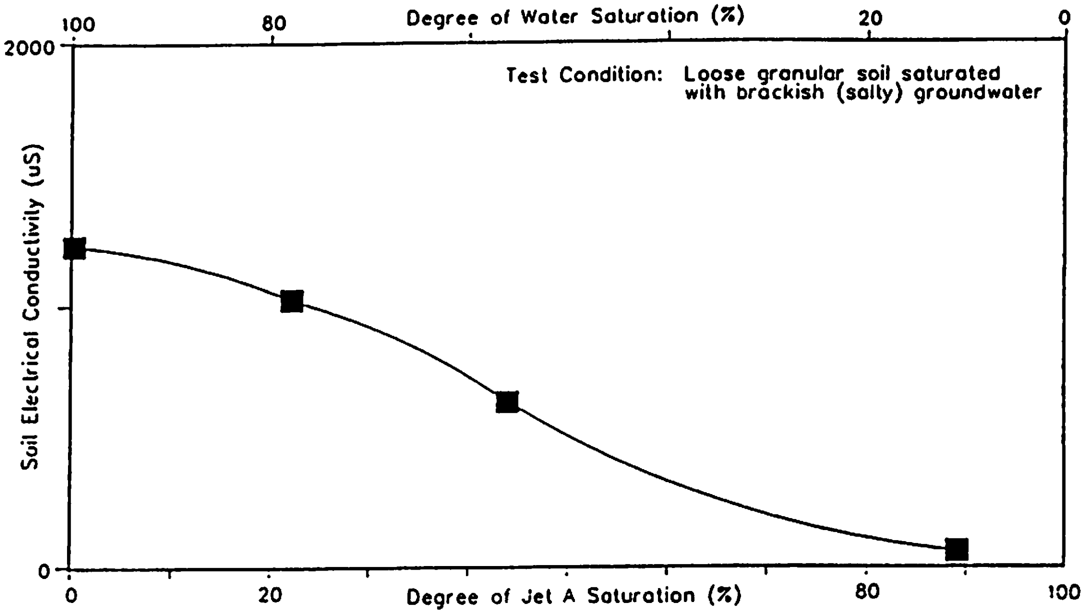

FIGURE 3 – EFFECT OF JET A PRODUCT CONTAMINATION ON GROUNDWATER SATURATED GRANULAR SOIL ELECTRICAL CONDUCTIVITY

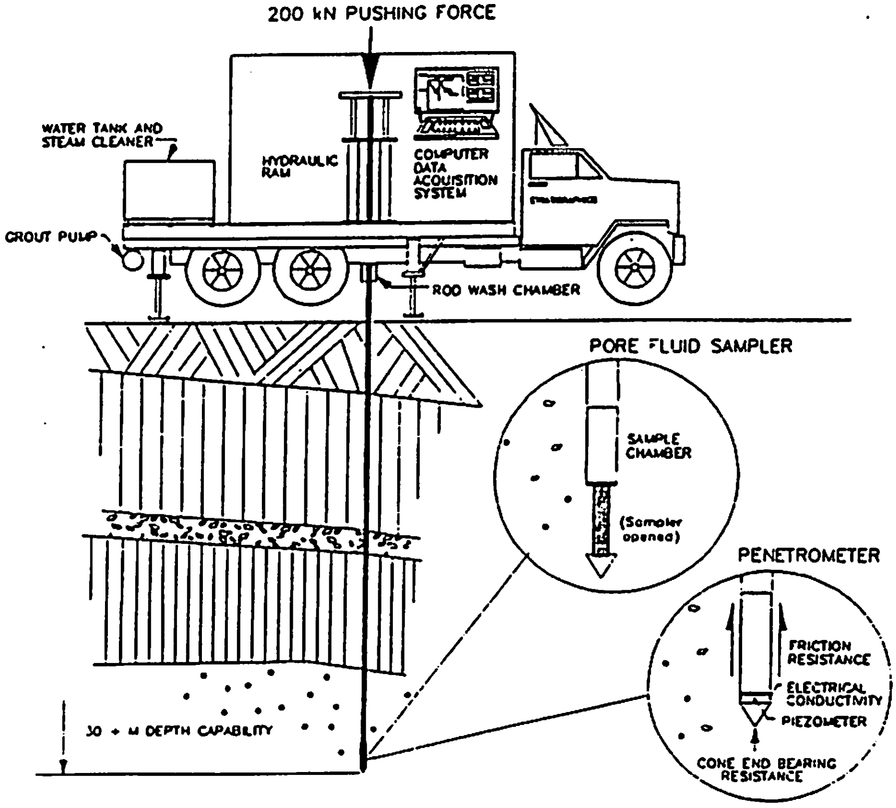

FIGURE 4 – PENETROMETER SUBSURFACE EXPLORATION SYSTEM

The penetrometer is mounted at the downhole end of a string of sounding rods. A hydraulic ram is used to smoothly push the penetrometer and rod string directly into the ground, without drilling a borehole, at a constant rate of 0.02 m/sec (4 ft per minute). Electronic signals from downhole sensors inside the penetrometer are transmitted by a cable, strung through the hollow sounding rods, to a data acquisition and display computer system at the surface.

CPTU-EC data are used to develop continuous profiles of geotechnical, hydrogeological, and gross geochemical soil conditions rapidly, accurately and economically. Penetrometer samplers can be used to obtain groundwater or soil samples for laboratory testing (Reference 3).

Site disturbance is minimized since no borehole cuttings or drilling fluids are generated during penetrometer operations. Personnel exposure to contaminated soil is significantly less than exposures during drilling and sampling. Penetrometer downhole equipment is easily decontaminated by steam cleaning during retrieval. The small open hole left in soils above the water table after penetrometer retrieval is readily grouted.

CPTU-EC PENETROMETER MEASUREMENTS

The CPTU-EC penetrometer incorporates cone resistance, friction sleeve resistance, piezometric, thermal and soil electrical conductivity sensors. The resistance of a soil to penetration is measured on the tip and along the sides of the CPTU-EC penetrometer. The soil resistance acting on the cone tip is controlled primarily by soil grain size and porosity. The cone resistance measurement has a resolution of about 0.05 to 0.10 m (2 to 4 inches). The sliding friction between the soil and the penetrometer is measured along a sleeve mounted just behind the cone tip. The friction sleeve resistance measurement has a resolution of about 0.15 m (6 inches).

A pressure transducer in the tip of the penetrometer is used to measure the soil pore water pressure response to penetration. Pore water pressure response is primarily controlled by the degree of saturation, potentiometric surface, compressibility and horizontal permeability of the penetrated soil (Reference 4). The CPTU-EC piezometric measurement has a resolution of about 0.03 m (1 inch).

The soil electrical conductivity is measured between two electrodes also mounted in the tip of the CPTU-EC penetrometer. The electrodes are insulated from the steel body of the penetrometer by plastic insulators. The soil electrical conductivity measurement has a resolution of about 0.04 m (1.5 inches). A thermistor inside the CPTU-EC penetrometer provides data on downhole equipment temperatures. These data can be used to adjust the measured soil conductivity to a corrected conductivity at a reference temperature of 25 degrees C.

CPTU-EC data are acquired as analog signals from the transducers inside the penetrometer. The analog signals are transmitted by cable strung through the sounding rod string to a computerized data acquisition system inside the penetrometer truck. The data acquisition system translates the analog signal to a digital value using a 16-bit, analog to digital (A/D) converter. The 16-bit conversion provides a digital data resolution of 1 part in 32,768.

The CPTU-EC data are logged at a 2 Hz frequency. This logging frequency provides insitu soil data at about 0.01 m (3/8 inch) depth intervals. Data appear on a high resolution, color computer monitor in real time. Real time data display allows for the immediate definition of site conditions. Data are logged on hard disk for permanent storage. A preliminary, hard copy sounding log is generated at the conclusion of each test. Recorded data are computer processed to develop interpretations of site conditions.

GENERAL CPTU-EC DATA INTERPRETATION

Correlations between penetrometer data and soil type classifications have been developed from geotechnical soil bearing capacity theory, and observational criteria from adjacent CPT soundings and drilled and sampled boreholes (Reference 5). The CPT cone resistance increases exponentially with increases in soil grain size. The CPT friction ratio (the friction sleeve resistance divided by the cone resistance) increases with increases in the fines content of a soil. A correlation scheme based on the cone resistance and friction ratio values (Figure 5) has proved most useful in interpreting soil types from CPT measurements.

Soil saturation is evaluated using the CPTU-EC piezometric data. Atmospheric (zero) water pore pressure is measured in unsaturated soils. Hydrostatic pore water pressures are measured in high permeability, granular soils below the water table. High pore water pressures are generated by penetrometer advance in saturated, fine grained soils.

CPTU-EC FIELD TESTING PROGRAM

A total of 48 CPTU-EC soundings were performed at the JFKIA Satellite and Bulk Fuel Farms. The stratigraphy at the two sites is somewhat similar. The surficial soils at both sites consist of a hydraulically placed, fine to medium sand fill, ranging in thickness from about 1.5 to 4.6 m (5 to 15 ft).

At the Satellite Fuel Farm site, this sand fill overlies a discontinuous tidal flat deposit, which consists of about 0 to 1.5 m (0 to 5 ft) of silty clay and peat. At the Bulk Fuel Farm, heterogeneous deposits of refuse and silt interlayer the hydraulic sand fill and tidal flat deposits. Underlying the tidal flat deposits at both sites is a fine to medium sand stratum in excess of 30.5 m (100 ft) thick.

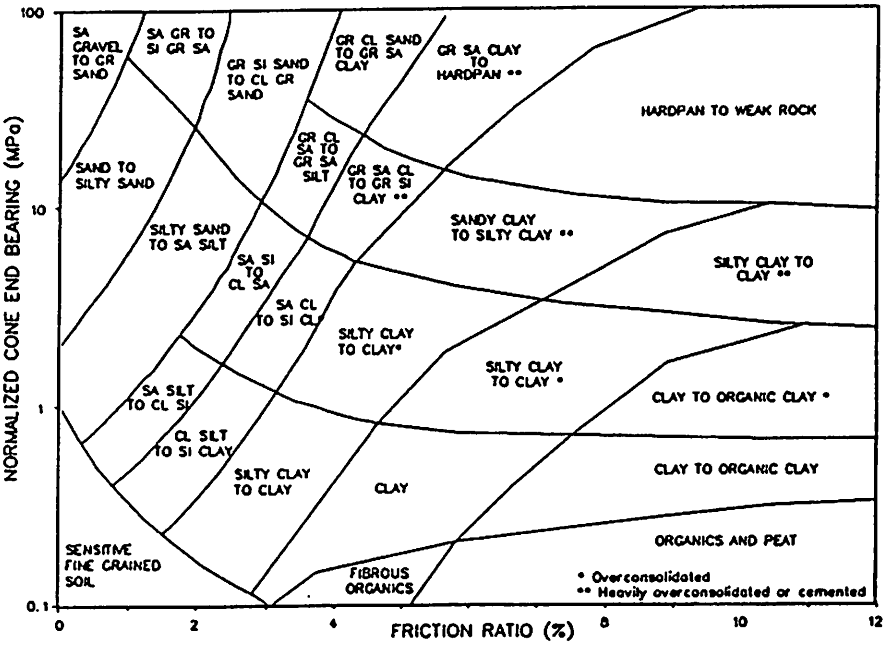

FIGURE 5 - CORRELATION CHART FOR CPT SOIL TYPES

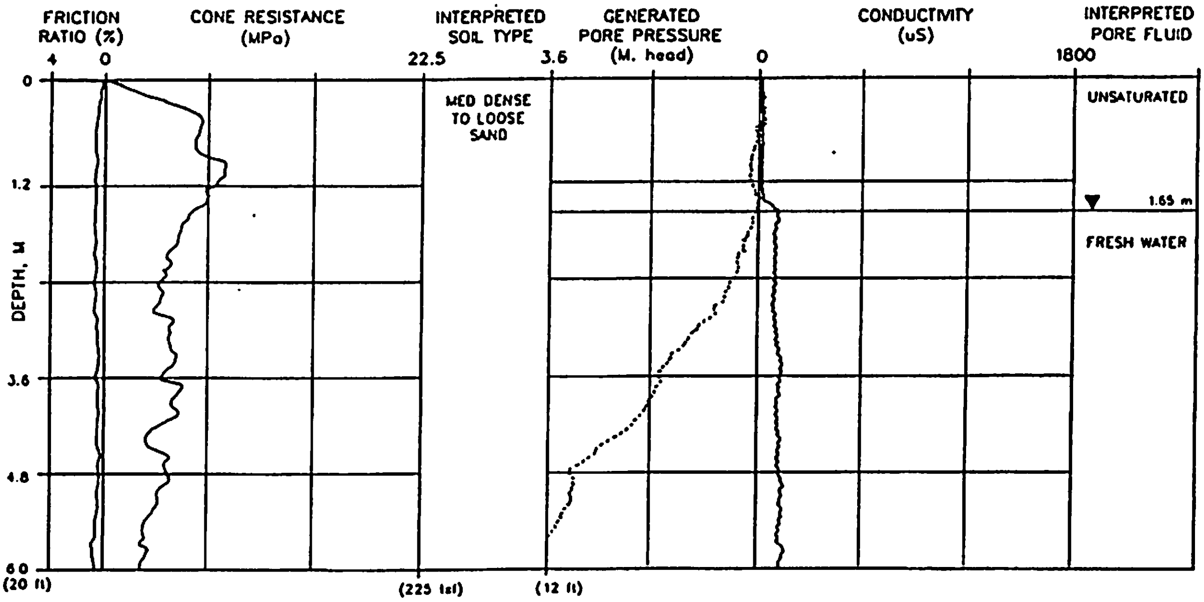

FIGURE 6 - CPTU-EC SOUNDING RP-16

The tidal flat deposits form discontinuous aquitards across the sites, resulting in both locally perched and water table aquifer groundwater conditions. At the Bulk Fuel Farm site, the groundwater has been partially contained by a slurry cut-off wall. The deeper groundwater at both sites is brackish (somewhat salty) with moderate electrical conductivity. Shallow groundwater is typically less salty and less conductive, probably reflecting a recent rainwater origin.

The JFKIA Satellite and Bulk Fuel Farms have significant subsurface accumulations of aviation jet fuel, as determined in monitor wells at the two sites. For the Satellite Fuel Farm, free phase petroleum hydrocarbon product thicknesses interpreted from CPTU-EC data were compared to product thicknesses measured in nearby monitor wells. This comparison showed that the general thickness patterns were very consistent, but that the insitu CPTU-EC data indicated product thicknesses to be generally 25 to 50% less than the monitor well product thicknesses.

These results confirm the hypothesis that monitor wells generally contain a thicker accumulation of free phase petroleum hydrocarbon product than is actually present in the soil. This occurs because most products float on the capillary zone above the water table. Thus, the product fills a monitor well for the thickness of the capillary zone and for a depth below the groundwater table required to achieve buoyancy equilibrium between the product and groundwater.

An uncontaminated, water table aquifer is indicated by the CPTU-EC sounding log at the Satellite Fuel Farm Location RP-16 (Figure 6). The shallow stratigraphy consists of a homogeneous sand stratum. The piezometric measurements indicate the sand to be of medium to high permeability, and indicate a water table at a depth of 1.65 m (5.4 ft).

The soil electrical conductivity increases just above the water table, reflecting increasing soil water content. Soil conductivities are relatively low and constant below the water table, reflecting low groundwater salinity conditions. It was subsequently determined that a nearby water main was leaking, and the fresh water leakage was probably responsible for the low soil electrical conductivity measurements.

An accumulation of free phase petroleum hydrocarbon product is indicated by the CPTU-EC sounding log at the Satellite Fuel Farm Location RP-01 (Figure 7). The piezometric measurements indicate a free fluid surface at 1.83 m (6.0 ft) of depth. The very low soil conductivity between 1.83 and 2.10 m (6.0 and 6.9 ft) depths indicates a thin layer of product. Increasing soil conductivity below the product layer indicates increasing groundwater salinity and density with depth.

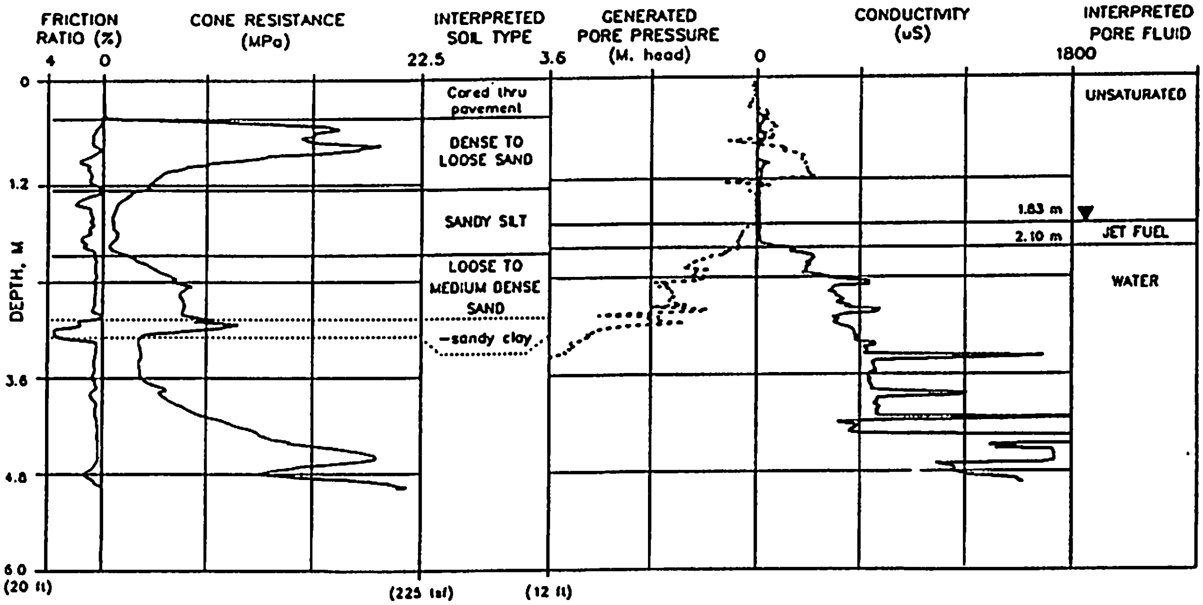

FIGURE 7 - CPTU-EC SOUNDING RP-01

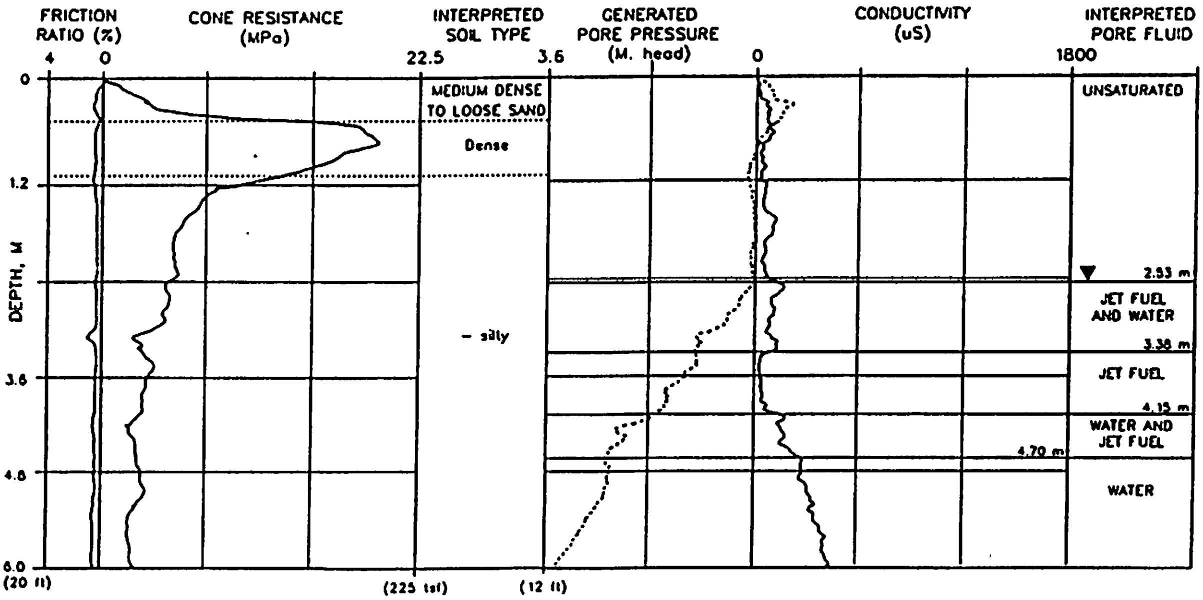

FIGURE 8 - CPTU-EC SOUNDING RP-11

Unusual results were obtained at the Satellite Fuel Farm Location RP-11 (Figure 8) next to a product recovery well. The CPTU-EC data indicate 0.85 m (2.8 ft) of a groundwater-petroleum hydrocarbon product mixture, overlying a 0.76 m (2.5 ft) thick layer of product. The product layer overlies another mixed layer, which in turn overlies groundwater.

This unexpected sequence is thought to be due to rapidly changing groundwater conditions. Record rainfalls during the autumn of 1989 are conjectured to have both raised the locally depressed water table and filled in the cone of depression created by the nearby recovery well. The former surficial product layer became inundated. Due to soil permeability effects, insufficient time had passed prior to the December, 1989 CPTU-EC study for fluid density equilibrium between product and groundwater to have been re-established .

This interpretation has been corroborated by CPTU-EC soundings combined with penetrometer groundwater sampling at other project sites with similar rapidly changing groundwater conditions. A monitor well, typically screened 1.5 m (5 ft) above and 3.0 m (10 ft) below the water table, would provide no hint of this phenomenon, because density equilibrium would occur almost instantaneously in the monitor well riser pipe.

Many of the CPTU-EC sounding logs at the Bulk Fuel Farm were not as definitive as those at the Satellite Fuel Farm. Product thickness trends from the CPTU-EC soundings did generally correspond with monitor well defined trends. However, the presence of perched groundwater and product, numerous trapped product lenses, and complex groundwater flow conditions caused by the slurry cut-off wall and the discontinuous aquitard, caused CPTU-EC data interpretation to be much more subjective than at the Satellite Fuel Farm.

Ground truthing the CPTU-EC data, acquired at 0.01 m (3/8 inch) intervals to monitor wells screened over 5 m (15 ft) lengths may not be appropriate for the complex site conditions at the Bulk Fuel Farm. The CPTU-EC sounding log at Location BRP-12 (Figure 9) illustrates some of the difficulties in interpreting data at sites with a complex hydrostratigraphy.

The CPTU-EC results were definitative in areas of the Bulk Fuel Farm where uniform conditions existed. The presence of free phase petroleum hydrocarbon product overlying a water table aquifer is indicated by the CPTU-EC sounding log at Location BRP-35 (Figure 10). Soil electrical conductivity is very low between the free fluid surface at a depth of 2.80 m (9.2 ft) and a depth of 3.29 m (10.8 ft), indicating a 0.49 m (1.6 ft) thick layer of product. A 0.15 m (0.5 ft) thick transition zone underlies the product layer and probably consists of soil saturated with both product and groundwater.

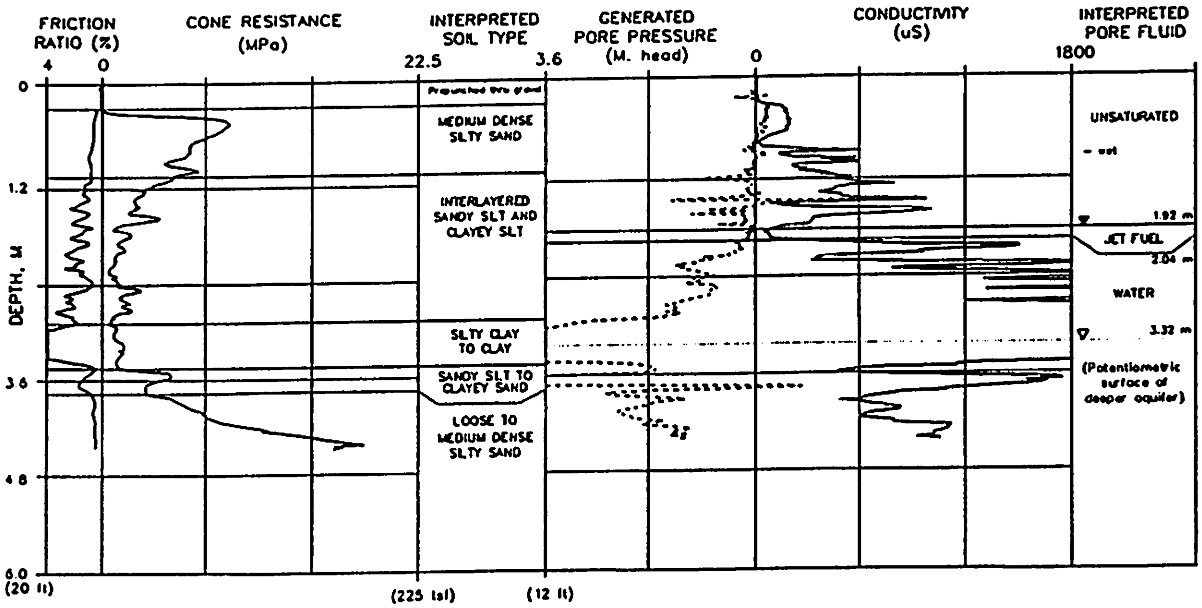

FIGURE 9 - CPTU-EC SOUNDING BRP-12

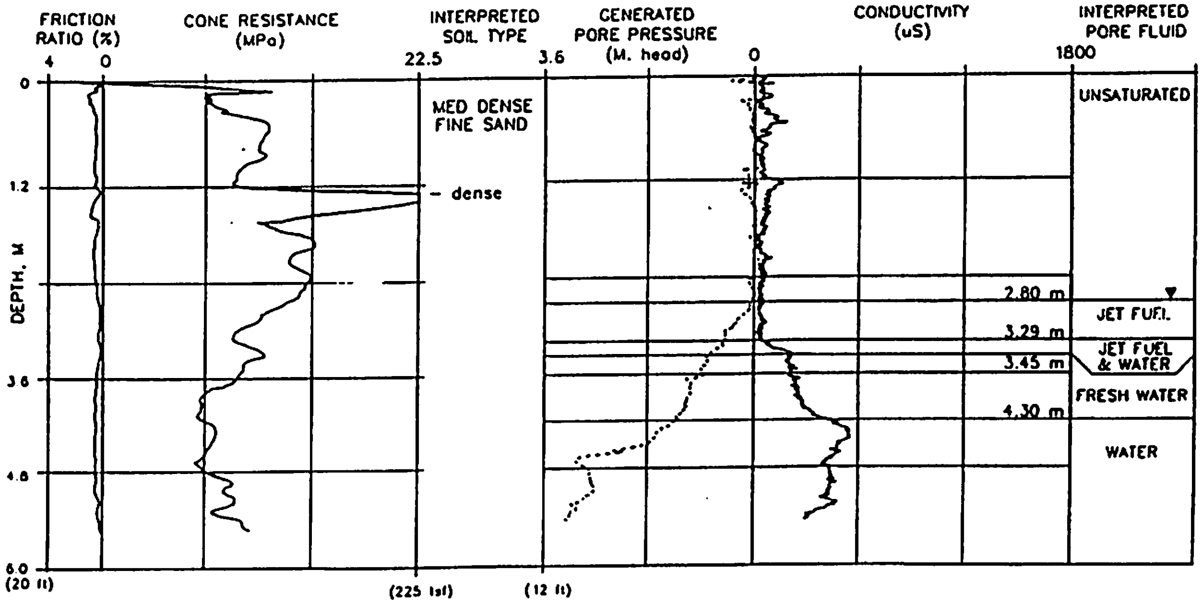

FIGURE 10 - CPTU-EC SOUNDING BRP-35

CPTU-EC COSTS AND PRODUCTIVITY

A comparison of production rates and costs for CPTU-EC and conventional monitor well surveys is as follows:

	CPTU-EC	Monitor Wells
Production Rate	8 to 12/day	1 to 2/day
Unit Cost	\$66/m (\$20/ft)	\$131/m (\$40/ft)
Cost per location, 6.1 m (20 ft) depth	\$485/ea.*	\$1066/ea.*

* includes data interpretation or inspection.

The CPTU-EC method provides a more rapid means of surveying an area, and is less than one half the cost of conventional monitor well survey methods on a per location basis.

CONCLUSIONS

The CPTU-EC penetrometer method has been shown to provide a rapid means of surveying sand aquifers for free phase petroleum hydrocarbon product contamination. In areas of more complex stratigraphy, additional testing is necessary to verify the applicability of CPTU-EC methods. Monitor wells with long screened lengths may not provide the best method of ground truthing CPTU-EC measurements at sites with complex hydrostratigraphic conditions.

Penetrometer groundwater sampling should be included in CPTU-EC field investigation programs to provide direct samples of CPTU-EC identified anomalous groundwater zones. Sensitive CPTU-EC piezometric transducers should be used to provide high accuracy in water table location.

The rapidity and the relative non-destructive nature of the CPTU-EC method especially provides advantages in areas of high priority usage or sensitivity, such as active apron areas of airport terminals, or in residential areas surrounding contamination sources. The CPTU-EC method allows for more rapid and better definition of the true thickness of free phase petroleum hydrocarbon products in groundwater, at a decreased cost. Cost savings in initial survey work should translate into better placement of permanent monitor and recovery wells, resulting in decreased overall remediation/investigation program costs.

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