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EXPERIENCE WITH THE DP CONDUCTIVITY CONE

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ABSTRACT: Recent advances in cone penetration technology has led to the ability to measure an increasing number of in situ soil properties. The electrical conductivity of a soil can now be measured by the conductivity cone which enables an assessment of groundwater quality. This paper presents basic theory relevant to the electrical conductivity of saturated soils, describes calibration of the conductivity cone developed by D J Douglas & Partners Pty Ltd (DP) and presents results from a local case study demonstrating application of this test in an environmental investigation.

1. INTRODUCTION

A method used for monitoring groundwater quality is measuring the electrical conductivity of a soil. The electrical conductivity of the groundwater will generally increase with an increase in dissolved solids and decrease if insulating contaminants are present. These principles form the basis for the use of a conductivity cone developed for groundwater quality monitoring.

The development and application of a resistivity cone (resistivity is the inverse of conductivity) is well documented by Campanella and Weemees (1990). Fugro-McClelland used a conductivity probe in conjunction with static cone penetration testing and piezocone testing to investigate groundwater contamination at a site in the north-west of England (Tonks, Hunt and Bayne, 1993).

D J Douglas and Partners Pty Ltd (DP) has developed a conductivity cone consisting of two circumferential surface electrodes mounted in an insulated module behind a standard friction cone penetrometer. The DP conductivity cone has the capability of providing a continuous record of cone resistance, friction resistance and bulk electrical conductivity of the soil. These measurements have been used for detailed stratigraphic logging, determination of soil properties and monitoring groundwater quality.

Typical applications of the conductivity cone include:

- delineation of pollutant plumes;
- monitoring groundwater quality;
- investigation of salt water intrusion; and
- determination of corrosion potential.

Laboratory tests to verify the accuracy of the conductivity cone measurements and a case study of a contamination survey of a chemical factory site are discussed after presenting basic theory.

2. ELECTRICAL CONDUCTIVITY THEORY FOR SATURATED SOILS

Groundwater quality investigations generally require the measurement of the fluid conductivity of the pore water of a soil. The conductivity cone measures the bulk conductivity of the soil/water mixture which is less than the fluid conductivity of the pore water as the soil particles act as insulators. It is therefore necessary to consider the factors which influence the bulk conductivity of a soil so as to estimate the fluid conductivity of the pore water. Bulk soil conductivity is influenced by the following factors:

- conductivity of the pore filling solution (fluid conductivity);
- porosity of the soil;
- shape of the soil pore spaces;
- degree of saturation;
- temperature;
- type and quantity of clays present.

Archie's Law (Equation 1) relates conductivity to that of the saturating fluid and soil porosity.

$$F = \sigma_w/\sigma_b = an^{-m} \qquad [1]$$

where F is the formation factor:

σ_w is the fluid conductivity.
σ_b is the bulk conductivity.
n is soil porosity
a, m constants for a given soil.

For unconsolidated soil, a ≈ 1. The constant m is a measure of the pore tortuosity (grain shape). It is approximately 1.5 for sands and 1.8 to 3 for various clays. (Jackson et al, 1978).

Archie's formula has been recognised as an oversimplification of the relationship between bulk soil conductivity and pore fluid conductivity especially at lower fluid conductivities, or in the presence of significant quantities of clay minerals in the soil. The presence of clays adds an additional component to the bulk electrical conductivity due to the effect of surface conduction in clay minerals. This effect makes estimation of fluid conductivities from bulk conductivity measurements very difficult in clays, since the amount of surface conduction depends not only on the quantity, but also the type of clay minerals present.

Another important effect which needs to be considered when estimating the fluid conductivity is temperature dependence. The temperature dependence of the fluid conductivity results from the effect temperature has on ionic mobility. This is in the order of a 2% increase in fluid conductivity per 1°C increase. This may be significant when comparing fluid conductivities determined with the conductivity cone in the field to fluid conductivities corrected to 25°C.

3. LABORATORY INVESTIGATION

An extensive laboratory investigation was conducted into the measurement of the electrical conductivity of a soil with the DP conductivity cone. The aim of the investigation was to verify the accuracy of the conductivity cone.

A preliminary investigation was required to determine suitable calibration procedures. This consisted of measuring cone conductivities for known calibrated fluids in different sizes of vessels. This investigation showed that the calibration vessel if less than 0.5 m diameter restricted the electric field emitted by the electrodes of the conductivity cone.

Vessels larger than 0.5m gave the same cone conductivity for a solution of known conductivity, indicating negligible boundary effects.

The main laboratory investigation consisted of circulating fluids of various conductivities through a cylindrical chamber filled with "density" sand. Measurements of the bulk conductivity of the sand/water mixtures were taken with the conductivity cone and simultaneously measurements of the fluid conductivity were taken with a YSI water quality meter.

The results of the investigation indicated a linear relationship between the bulk conductivity of the saturated sand as measured by the cone, and the conductivity of the pore fluid (Figure 1).

The ratio of the fluid conductivity of the pore water to the bulk conductivity, (i.e., the formation factor defined in equation [1]) was 4.0 for loose saturated sand with a porosity of 44%. When these parameters were substituted into Archie's formula, with $a = 1$ for unconsolidated soils, m was calculated as 1.7. This compared well with the generally accepted value for sands of approximately 1.5 (Campenella and Weemes, 1990).

The fact that the test results gave good agreement with Archie's formula and generally accepted values verified that the conductivity cone was providing a reliable measure of the bulk conductivity of a soil.

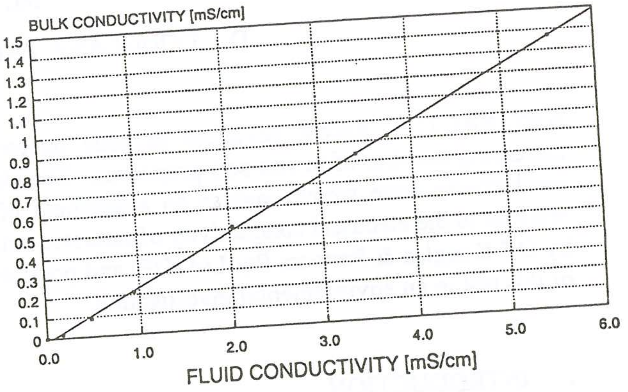

Figure 1. Relationship between the bulk conductivity and fluid conductivity of a saturated sand.

4. CASE STUDY

An investigation of a chemical factory site in a coastal region of New South Wales is described as an example of the application of the conductivity cone in groundwater ocntamination assessments.

4.1 Background

The site is occupied by a chemical factory which produces bisulphite, lead, aluminium and chromium-based chemicals. A preliminary contamination survey was conducted at the site in December 1991 during which a significant contamination plume was discovered. The source of contamination was found to be a result of liquid waste disposal in an unlined sludge pond.

Additional investigations were conducted in March 1992 and December 1993 to define the horizontal and vertical extent of the plume and to investigate the distribution of contaminants along the groundwater flow path.

Conductivity cone testing was used in conjunction with borehole drilling and groundwater sampling in all stages of the contamination survey.

4.2 Site Geology

The site is underlain by approximately 15 m of medium dense to dense sand overlying a silty clay. The clay layer forms the base of an unconfined aquifer which has a saturated thickness of about 14 m.

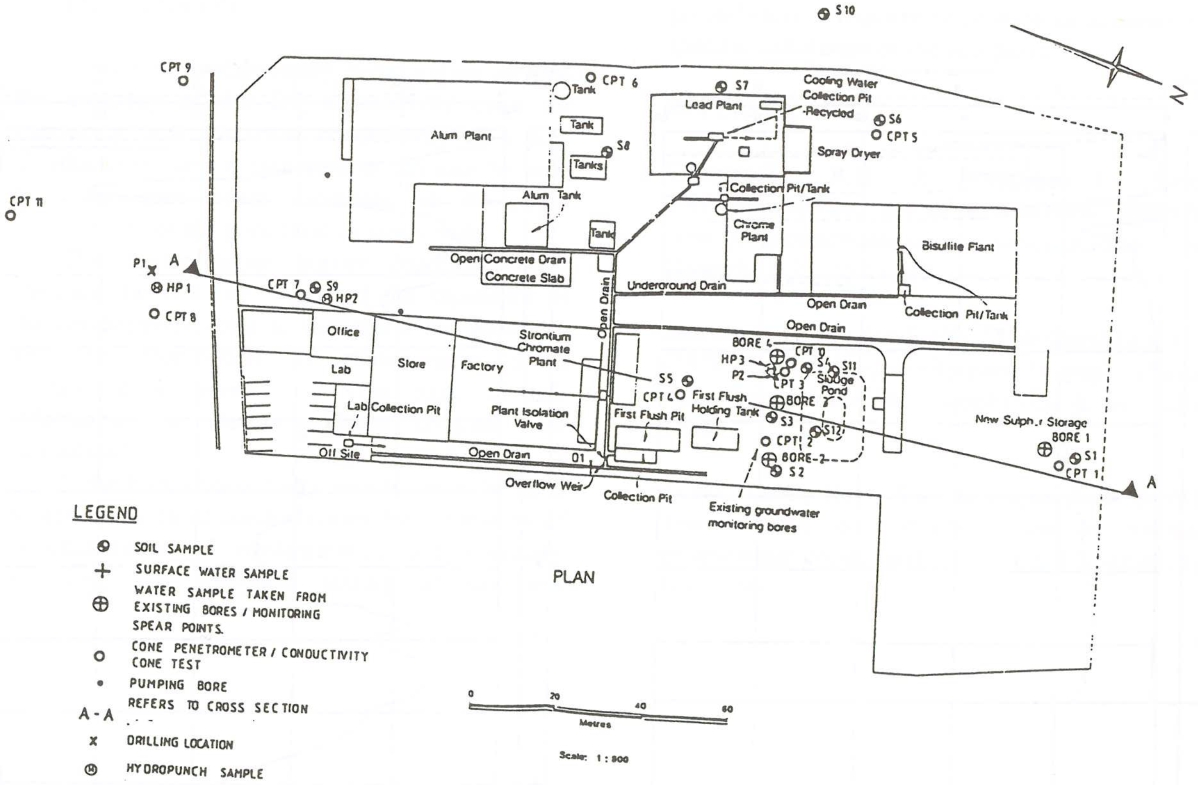

Figure 2. Site layout, contamination survey.

4.3 Fieldwork

A total of 11 conductivity cone tests were conducted using the DP conductivity cone to depths up to 15 m at locations shown in Figure 2. The testing was carried out from a 15 tonne CPT truck, which permitted penetration of the conductivity cone through very dense sand layers. Figures 3a and 3b present typical results of the conductivity cone tests, which show plots of the variation of bulk conductivity of the soil with depth.

Groundwater samples were collected using a hydropunch sampler operated from the CPT truck in addition to conventional borehole groundwater sampling techniques. The fluid conductivity and pH of the groundwater samples were measured in the field using various portable meters. Laboratory tests were also carried out for conductivity, pH and for the principal chemical constituents of interest.

4.4 Discussion of Results

The contrast of the bulk conductivities of the saturated sand for uncontaminated and contaminated groundwater was evident by comparing the conductivity cone results presented in Figures 3a and 3b.

Figure 3a presents results of the conductivity cone test CPT1 which was conducted up groundwater gradient of the sludge pond. The low bulk conductivity values (0.1 to 3 mS/cm) measured by the conductivity cone corresponded to very low concentrations of total dissolved solids (<100 mg/L) measured from the groundwater samples taken adjacent to CPT1. The results of CPT1 represent the natural or background variations of bulk conductivity of the saturated sand.

The results of the conductivity cone test conducted adjacent to the sludge pond (CPT10) are shown in Figure 3b. The bulk conductivities of the saturated sand were 20 to 40 times greater than those measured at CPT1. These high bulk conductivity values corresponded to very high concentrations of total dissolved solids (approximately 20 000 mg/L) measured by chemical analyses of groundwater samples taken adajcent to the sludge pond.

The contrast in the bulk conductivity values measured by the conductivity cone and corresponding contrast in the total dissolved solids measured in the groundwater samples provided the basis for determining the plume geometry and the dilution of contaminants. The spatial and vertical variations in the bulk conductivity of the saturated sand at the site have been illustrated by a contoured profile presented in Figure 4.

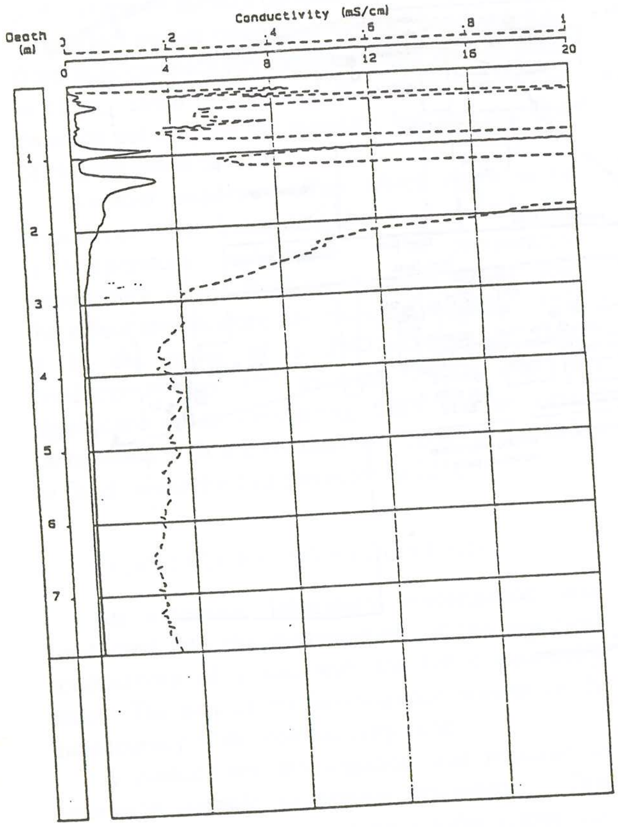

Figure 3a. Conductivity cone test results for CPT1.

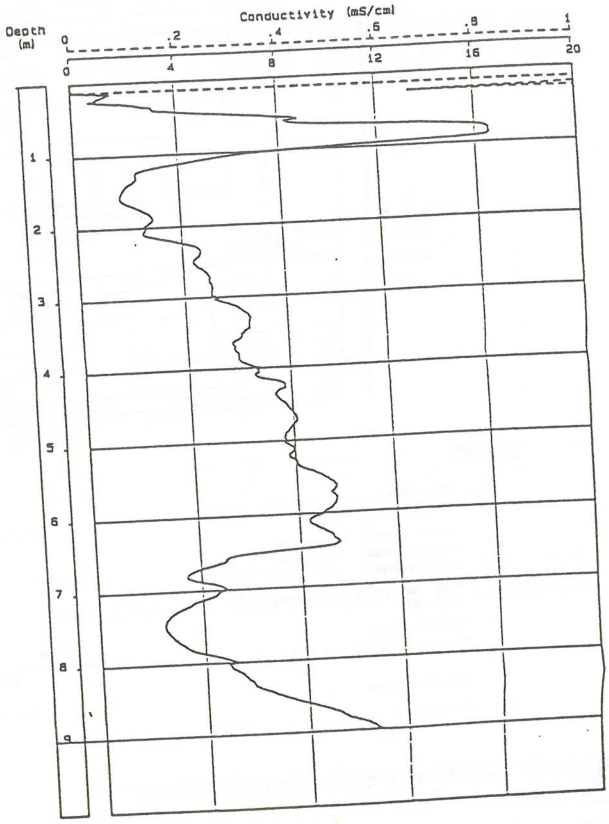

Figure 3b. Conductivity cone test results for CPT10.

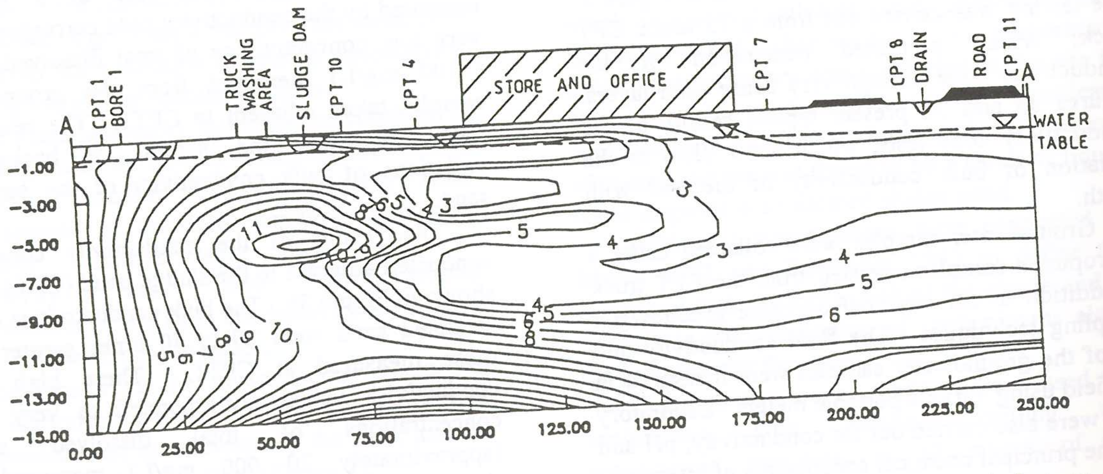

Figure 4. Bulk conductivity (mS/cm) contour profile through cross-section of chemical factory site.

The contoured profile of the bulk conductivity of the sand indicates that the maximum contamination zone occurred about 6 m below the sludge pond and extended down to the base of the aquifer. Further down gradient of the sludge pond, contaminant levels attenuated in the upper zone of the aquifer while levels remained relatively high at the base. The thin layer of contaminated groundwater spread along the base of the aquifer was contained beneath the relatively fresh groundwater of lower density above.

5. CONCLUSION

Results of the laboratory investigation verified the accuracy of the DP conductivity cone for measuring bulk electrical conductivity of a soil. Conductivity cone measurements can also be used to make first order estimates of the fluid conductivity of the pore fluid in sandy soils.

The contamination survey conducted at a chemical factory site illustrated the capability of the conductivity cone to determine the geometry and the distribution of contaminants in a contamination plume. On the basis of this information, a site remediation program was formulated.

If the bulk conductivity results are to be used to determine fluid conductivities for estimation of concentrations of contaminants, supplementary sampling and analytical testing of soil and groundwater is required to provide an accurate site specific calibration of the equipment.

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