Multivariate integration of CPTu/SMR and hydraulic conductivity measurements for the definition of hydrofacies in unconsolidated sediments

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ABSTRACT
This paper reports on a study designed to complement conventional direct measurements of hydraulic properties with indirect, but continuous, downhole geophysical measurements. Data from cone penetrometer (CPTu) soundings combined with a soil moisture resistivity (SMR) probe were correlated to high-resolution hydraulic conductivity measurements in 16 long-screened observation wells. A multivariate statistical analysis of the data enables hydrofacies to be defined even at locations where only indirect data are available. Due to their low cost and ease of implementation, additional CPTu/SMR soundings can be made to further improve the 3D characterisation of hydraulic conductivity in heterogeneous deposits.

RÉSUMÉ
Ce papier présente une approche de caractérisation hydrogéologique basée sur la définition de relations statistiques *in situ* entre des mesures directes et indirectes des propriétés hydrauliques. Des essais de pénétration au cône (CPTu) combiné à une sonde mesurant teneur en eau et résistivité électrique (SMR) ont été corrélés avec des mesures haute résolution de conductivité hydrauliques à 16 puits d'observation. L'intégration statistique multivariable des différentes mesures montre bien le potentiel de la caractérisation indirecte. Puisque les sondages CPTu/SMR sont relativement peu coûteux et facile à réaliser, l'ajout de tels sondages permettra une meilleure définition de l'hétérogénéité de la conductivité hydraulique.

1 INTRODUCTION

A major control on groundwater flow and contaminant transport through an aquifer is the spatial distribution of its hydraulic properties. Numerical models may now support large amounts of information, but input data are often derived from only a few boreholes and geophysical logs. This scarcity of information about the spatial distribution of aquifer properties can introduce considerable uncertainty into groundwater flow and transport problems. Although some degree of uncertainty may be handled within a geostatistical framework (e.g. Poeter and McKenna 1995), this approach cannot serve as a substitute to field characterisation when reliable predictions are needed.

Another problem often faced with aquifer characterisation is the choice of relevant methods employed to recognise features of interest (e.g. channels) and the cost related to their application in the field and subsequent analysis. Unfortunately, conventional field methods can rarely provide the needed level of detail and accuracy (lack of data and resolution). For example, pumping tests provide only average hydraulic conductivity values and there are rarely sufficient wells at a site to adequately characterise the spatial distribution of hydraulic properties. Thus there is a clear need to develop site characterisation methodology that enables mapping of the spatial distribution of hydraulic properties in a time and cost effective manner.

There are two general approaches related to aquifer characterisation: (1) direct and (2) indirect. The first approach involves direct measurement of the hydraulic properties of interest. In unconsolidated sediments, numerous techniques have been developed to characterise small scale variations in hydraulic conductivity. For example, Zemansky and McElwee (2005) and Ross and McElwee (2007) report on multi-level slug tests conducted at discrete intervals within fully screened wells with a dual-packer assembly. Flowmeters traditionally used to evaluate transmissivity of fractures intersecting open boreholes have also proven to be useful at delineating vertical profiles of hydraulic conductivity in unconsolidated sediments (e.g. Morin 2006). These methods are effective at characterising vertical profiles but their lateral resolution depends on the number of accessible wells.

Other methods have been available to estimate hydraulic conductivity directly by incorporating an extension of conventional hydraulic tests within direct-push equipment. These methods include constant-drawdown pumping test (e.g. Cho et al. 2000), slug test (e.g. McCall et al. 2002) and permeameter test (e.g. Lowry et al. 1999). With these methods, the screen used for the hydraulic tests is exposed to the sediments by a dual-tube design. In this procedure, nested rods (tubes) are simultaneously advanced to a predetermined test interval. The inner rod is then removed and a screen is inserted into the formation. Once testing is completed, the screen is retrieved, the inner rod reinserted, and the system is advanced to the next interval. Even though these methods do not require the installation of observation wells to obtain a direct estimate of hydraulic conductivity, they may be expensive to apply in practice because the direct-push rig needs to stay in place during all of the operations. This is particularly true for direct-push pumping and slug testing methods when continuous profiles of hydraulic conductivity are needed.

The second general approach involves using indirect geophysical measurements that are related by a semi-empirical or *in situ* relationship to geologic facies or hydraulic properties. For example, Archie's law relates the porosity of a formation to its formation factor, defined as the ratio of bulk resistivity to fluid resistivity. This approach has the potential to be effective at characterising spatial variability of the hydrogeological properties of aquifers as geophysical measurements allow very high sampling.

Traditionally, when working with cone penetrometer testing (CPT) systems, geological facies are defined following the Robertson (1990) or the Fellenius and Eslami (2000) charts that correlate sleeve and tip stress to sediment textures. Geotechnical engineers have also developed empirical relationships for predicting hydraulic conductivity from mechanical properties obtained by CPT (Farrar 1996). However, the resulting data only yield order-of-magnitude estimates of hydraulic conductivity.

In unconsolidated sediments, the measurement of electrical properties with direct-push equipment is relatively recent. For example, Sellwood et al. (2005) use electrical conductivity logs to locate zones of interest to perform slug test with the dual-tube direct-push method. Some attempts have been also made to use electrical conductivity to predict hydraulic conductivity (Schulmeister et al. 2003). However, as will be shown in this paper, the use of a single parameter to deduce geological facies or hydrofacies is not sufficient and an integrated approach that combines several geophysical (indirect) parameters is more effective.

The overall site characterisation methodology proposed herein necessitates first the installation and the development of observation wells where direct and indirect measurements may be taken to establish *in situ* relationships. At this stage, extensive indirect characterisation (e.g. CPTu/SMR soundings) takes place near these wells. Finally, hydraulic properties are attributed to the new soundings from established *in situ* relationships and interpolated at the study area scale in order to get the spatial distribution of the hydraulic properties. In this paper, we investigate the potential of a multivariate approach to establish *in situ* statistical relationships between geophysical properties (mechanical and electrical) and high-resolution hydraulic conductivity measurements to characterise unconsolidated aquifers.

2 METHODOLOGY

The study area is located 40 km south of Quebec City, Canada, and encompasses an area of about 12 km^2. The superficial material is comprised of littoral sediments that were deposited and reworked during the presence of the Champlain Sea (Bolduc 2003). The sediments are mainly fine to medium sand but range from coarse sand to clay-silt (Figure 1). Average thickness of the sediments is around 10 m. Existing borehole logs indicate that coarser sediments were deposited in the middle and again at the top of the unconfined aquifer. Farther from the center of the study area and deeper into the aquifer, average sediment particle size generally decreases.

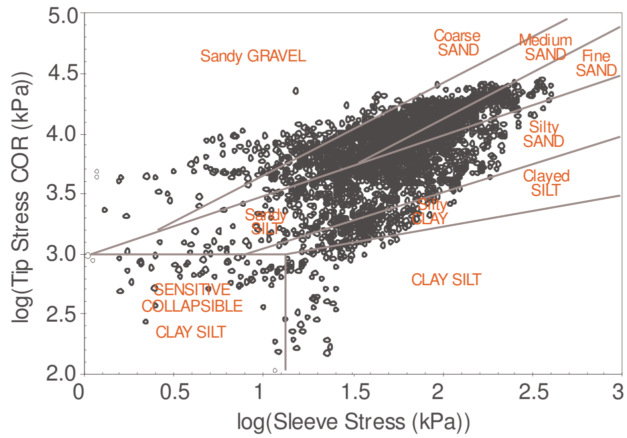


Figure 1 - Fellenius and Eslami (2000) CPT profiling chart showing the log of the tip stress (kPa) versus the log of the sleeve stress (kPa).

2.1 Observation Well Installation and Development

The locations of 16 observation wells were selected based on a preliminary conceptual model. These sites were chosen to be representative of the expected hydrofacies encountered in the study area. The observation wells were installed with a direct-push rig (Geotech 605D) at the same location (same hole) where the prior CPTu/SMR soundings were obtained (see Section 2.2). A 76-mm OD metal casing equipped with an expendable point was first pushed into the ground to the desired depth. Then a 52-mm ID (60 mm OD) fully-screened PVC well was inserted inside the metal casing before this outer casing was withdrawn. Slots in the PVC screen were 0.024 mm (10/10000 inch) wide, in accordance with the average particle-size distribution of the sediments. With this type of installation procedure, the sediments are held in direct contact with the screen, there is minimal disturbance to the surrounding aquifer, and gravel packing is avoided. Tests conducted in gravel-packed wells have indicated that flowmeter measurements may yield misleading results because the annulus of high permeability around the well screen can allow flow to bypass the meter (Boman et al. 1997).

In addition to proper well installation, it is critical that observation wells be developed thoroughly in order to obtain accurate information regarding hydraulic properties (Butler, 1998). For example, an undeveloped well can under-estimate hydraulic conductivity because of the presence of fine sediments that clog the screen or the formation. Consequently, an aggressive development approach is necessary to correct the disturbance that occurs during the installation process.

In this study, considerable attention was paid to well development and the hydraulic conductivity values estimated from field tests should be representative of the true aquifer values in the vicinity of the wells. Several pumping-surging configurations were tested to insure adequate well development. A well was considered well developed when its global hydraulic conductivity was no longer affected by development operations. The pumping-surging operations were performed with an inertial pump equipped with a foot valve and a surge block having a diameter slightly less than the inside diameter of the well. The well development configurations tested were: (1) with the foot valve at the bottom of the well only; (2) at three intervals (bottom-middle-top) and; (3) at 0.5 m intervals. For each configuration, the well was developed until no turbidity was observed in the discharged water. Before and after each configuration, slug tests were conducted over the fully-screened interval. The pneumatic method was used for test initiation. This method involves placing an airtight wellhead apparatus on top of the well and pressurizing the air column in the sealed well casing. A slug test is initiated by a very rapid depressurization of the air column using a release valve. Changes in water level were measured using a pressure transducer. From the different configurations it appears that pumping-surging development at 0.5 m is the most effective way to insure adequate well development (Figure 2).

Table 1 - Technical specifications, measurement resolution and measurement scale (support) for the CPTu/SMR probes and the electromagnetic (EM) flowmeter.

Parameter	Range	Resolution (cm)	Support (cm)
CPTu/SMR			
Tip stress	0-9 kN	2.6 +/- 3.6	point
Sleeve stress	0-9 kN	2.6 +/- 3.6	point
Resistivity	1-10000 ohm-m	2.6 +/- 3.6	9
Water content	0-100%	2.6 +/- 3.6	3
EM flowmeter			
Hydraulic conductivity	0.5-25 LPM	15	15

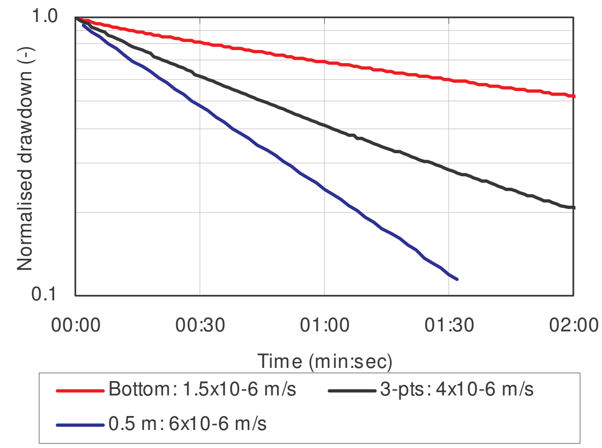


Figure 2 - Observed normalised drawdown as a function of time at observation well P6-362P for different pumping-surging well development configurations. Hydraulic conductivity is proportional to the slope of the time-drawdown curve. Note that for the 0.5-m configuration over-pumping did not change the slope of the time-drawdown curve (not shown).

2.2 Indirect and Direct Characterisation at Observation Wells

2.2.1 CPTu/SMR soundings (indirect)

Direct-push soundings were carried out with a cone penetrometer testing system including pore pressure measurement (CPTu) combined with a soil moisture and resistivity (SMR) probe. The CPTu/SMR soundings were conducted using a Geotech 605-D rig that is crawler-mounted for best all-terrain capability. The depth of penetration is measured using a depth encoder mounted on the push frame.

A 15 cm^2 penetrometer cone with a 60^o conical tip was used in accordance with ASTM D3441 standards (ASTM 2000). The penetrometer is advanced vertically into the soil at a constant rate of 2 cm/s, though this rate must be reduced when compact layers are encountered. Inside the probe, two load cells independently measure the vertical resistance against the conical tip and the side friction along the sleeve. A pressure transducer in the cone is also used to measure the pore water pressure as the probe is pushed into the ground. Pore pressure is an indicator of the presence of clay and was used to correct tip stress data.

The SMR probe is composed of four electrodes that are connected directly behind the penetrometer (Shinn et al. 1998). The inner two rings are used to measure soil permittivity. The soil moisture probe operates at 100 MHz, thereby reducing the effects of soil type on the measurement. The instrument measures shifts in the high frequency signal as it passes through the soil that may be related to soil moisture content. Spacing between the two inner rings is 3 cm. The resistivity measurement employs the outer two rings of the SMR probe to apply the current and to measure the voltage drop (Pole-Pole configuration). The outer electrodes are spaced 9 cm apart. The probe operates at a frequency of 1000 Hz to avoid soil polarization effects (Table 1).

2.2.2 Electromagnetic Borehole Flowmeter (direct)

Borehole flowmeters are downhole tools that measure vertical axial flow in an observation well. Profiles of axial flow during pumping conditions can help determine hydraulic conductivity profiles (e.g. Hess 1986). An electromagnetic (EM) flowmeter was chosen for these tests because of its low detection limit and large dynamic range of operation (Table 1). During testing, the perturbation created by the fluid passing across a magnetic field generated inside the probe is proportional to the average velocity of the water. In this study, an EM flowmeter was used to measure the flow profiles during pumping at 15-cm intervals to estimate the hydraulic conductivity following the analysis method provided by Molz et al. (1989). Pumping operations were performed with a centrifugal pump at a pumping rate between 4-19 LPM in order to minimise groundwater drawdown and to get maximum sensitivity. Pumping rate and hydraulic head were also continuously measured to ensure stable conditions through the entire operation and were later used in the data analysis.

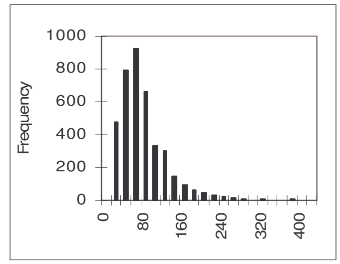
2.3 Resampling and Upscaling

Many statistical techniques require data to be equally spaced (collocated). However, this is not the case with CPTu/SMR soundings where measurements are taken at a regular time interval but at a rate of penetration that is not necessarily constant. Therefore CPTu/SMR data need to be interpolated on a regularly spaced grid from values measured at irregular intervals. To accomplish this, we used a trapezoidal integration, a technique that considers all observations within an interval to estimate a single point. With this technique, all observations on the irregular grid are first joined together by a straight line. Then the value at the estimated point on the regular grid is calculated by summing the area under the original curve over the desired interval length (Davis 1973). CPTu/SMR measurements were then resampled on a regular grid of 3 cm, a resolution close to the original grid and convenient to deal with a variety of measurement scales.

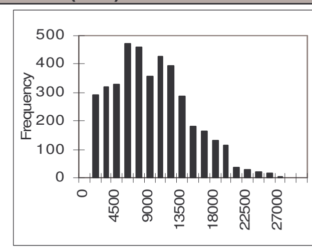
As shown in Table 1, the measurement scales (supports) for the different parameters are not identical. For example, tip stress is a point response while electrical resistivity is measured over a length of 9 cm. To be properly compared, the variations in supports need to be taken into account (Isaaks and Srivastava 1989). Hence, the parameters with the smaller support were upscaled with a moving average to the scale of the parameter with the larger support. For example, at each point of the CPTu/SMR grid, the three tip stress measurements were averaged in order to fall within the 9 cm support of the resistivity.

Table 2 - Descriptive statistics and frequency distribution of CPTu/SMR soundings parameters and hydraulic conductivity.

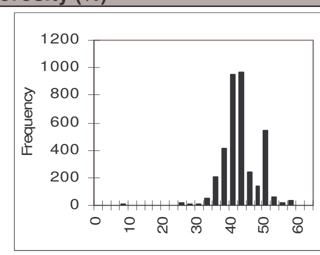
Sleeve stress (kPa)	
Mean	65.3
Median	52.4
Mode	0.5
St. dev.	49.2
Kurstosis	6.21
Asymetry	1.94
Range	404.1
Minimum	0.03
Maximum	404.1
Number	3918



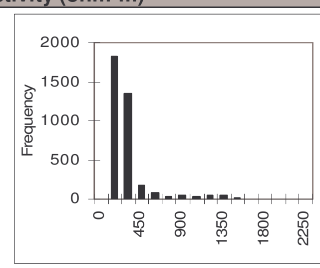
Tip stress (kPa)	
Mean	8633
Median	8094
Mode	4722
St. dev.	5216
Kurstosis	-0.09
Asymetry	0.55
Range	28100
Minimum	8
Maximum	28108
Number	4035



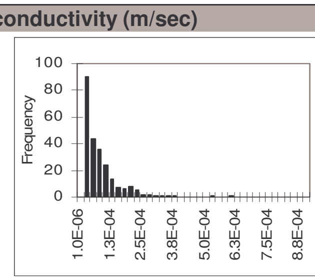
Porosity (%)	
Mean	41.0
Median	40.3
Mode	41.0
St. dev.	5.4
Kurstosis	5.21
Asymetry	-0.63
Range	51.5
Minimum	5.3
Maximum	56.7
Number	3692



Resistivity (ohm-m)	
Mean	213.5
Median	150.1
Mode	36.9
St. dev.	234.7
Kurstosis	15.52
Asymetry	3.50
Range	3054.3
Minimum	30.6
Maximum	3085.0
Number	3656



Hydraulic conductivity (m/sec)	
Mean	6.7E-05
Median	4.1E-05
Mode	1.6E-04
St. dev.	8.0E-05
Kurstosis	11.60
Asymetry	2.80
Range	5.8E-04
Minimum	2.4E-06
Maximum	5.8E-04
Number	243



Furthermore, in order to compare CPTu/SMR soundings and hydraulic conductivities that have different supports and resolutions, the support of the CPTu/SMR measurements was first upscaled to the support of the hydraulic conductivity measurements (15 cm). Then a linear interpolation was used to upscale the resolution of the CPTu/SMR measurements (3 cm) to the grid of the hydraulic conductivity (15 cm).

3 RESULTS AND DISCUSSION

Typical profiles of CPTu/SMR soundings and hydraulic conductivity measurements are shown in Figure 3, Table 2 displays the descriptive statistics and the frequency distributions of the different parameters. These measurements represent the saturated zone only and the statistics are generated from the original data before resampling and upscaling. Only the resistivity data have been corrected for temperature at 25 ^{o}C following Wraith and Or (1999).

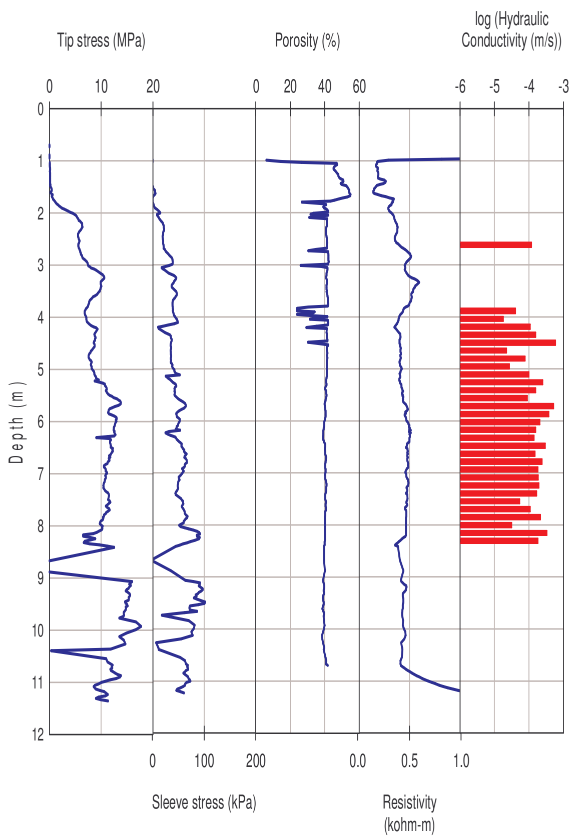


Figure 3 - Typical profiles of CPTu/SMR soundings and hydraulic conductivity measurements.

The number of measurements associated with each probe varies from 3656 to 4035, except for hydraulic conductivity where 243 intervals were tested. However, the data from CPTu/SMR soundings and EM flowmeter do not always overlap (Figure 3) and no hydraulic conductivity profiles are available at some wells. The maximum tip stress measured is 28 108 kPa; this corresponds roughly to the pressure at which the CPT cannot be physically advanced further due to the loss of anchorage. The minimum hydraulic conductivity is 2.4×10^{-6} m/s, a value that corresponds to the lower detection limit of the EM flowmeter.

The histograms displayed in Table 2 illustrate that sleeve stress, electrical resistivity and hydraulic conductivity have a log-normal distribution, whereas tip stress has a normal distribution and porosity a bi-modal distribution with a larger spike at 41% and a smaller one at 50%.

3.1 Geological Facies

To establish preliminary *in situ* relationships, all CPTu/SMR parameters are displayed on 2D and 3D scatter plots (Figures 4a, b, c and d). Also, to better understand relations between the various parameters, soil texture is identified with distinct colors based on the Fellenius and Eslami (2000) profiling chart. Hence the various textures are grouped into four classes based primarily on grain size: *sand*, *silt*, *clayey silt* and *clay*.

Scatter-plots are presented in Figures 4a, b and c of CPT/SMR mechanical and electrical measurements. Mechanical properties (tip and sleeve stress) were regrouped into a single parameter, termed *ratio,* which is defined as the ratio of the log of the tip stress to the log of the sleeve stress. No linear correlation between any parameter combinations is observed in these plots. This implies that any relationship between the different parameters may be somewhat more complex than a simple linear one.

In Figure 4d an additional dimension was added to the scatter-plot shown in Figure 4c, where the *ratio* is now presented as a function of the two electrical properties. With this expanded representation, it appears that some clusters can be distinguishable. Hence, we observe that sand is located at the base of the ratio-resistivity-porosity graph, silt regroups at an angle of 90^{o} with sand, and clayey silt is found at the top of silt. Despite some overlapping between different classes, a general trend is emerging.

3.2 Hydrofacies and hydraulic conductivity

As for the geological facies, Figures 5a, b, c and d illustrate hydraulic conductivity versus mechanical and electrical properties of sediments. In these scatter-plots (Figures 5a, b and c), some linear relationships between the parameters may be inferred. For example, hydraulic conductivity seems to be inversely correlated to the *ratio* (Figure 5a) and directly correlated to electrical resistivity (Figure 5b). However, it is when another dimension is added, as shown in Figure 5d, that multivariate clusters appear that help define particular hydrofacies. Hence three possible clusters can be differentiated: (1) permeable sand; (2) medium permeability sand; and (3) medium permeability silt.

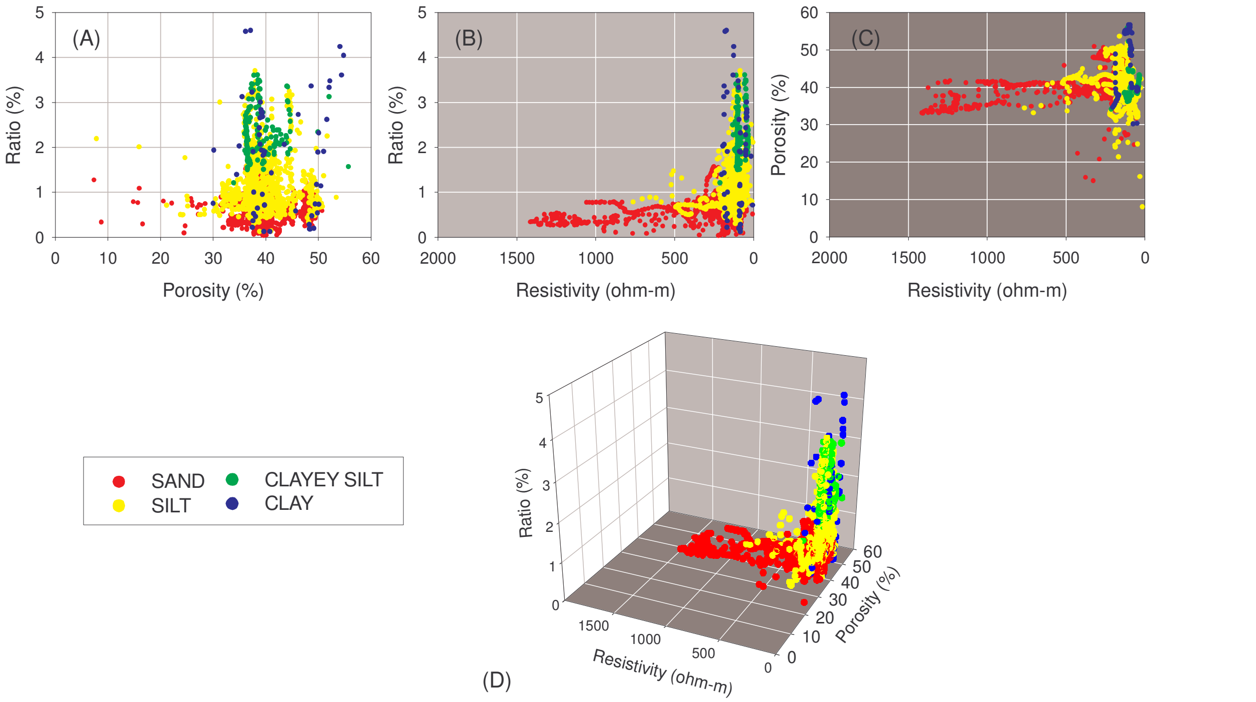


Figure 4 - (a), (b) and (c) Scatter-plots of CPTu/SMR measurements. (d) 3D graph of *ratio* (tip/sleeve) versus resistivity and porosity. The vertical resolution is 3 cm and the measurement scale is 9 cm. Sediment textures are based on the Fellenius and Eslami (2000) profiling chart (see Figure 1).

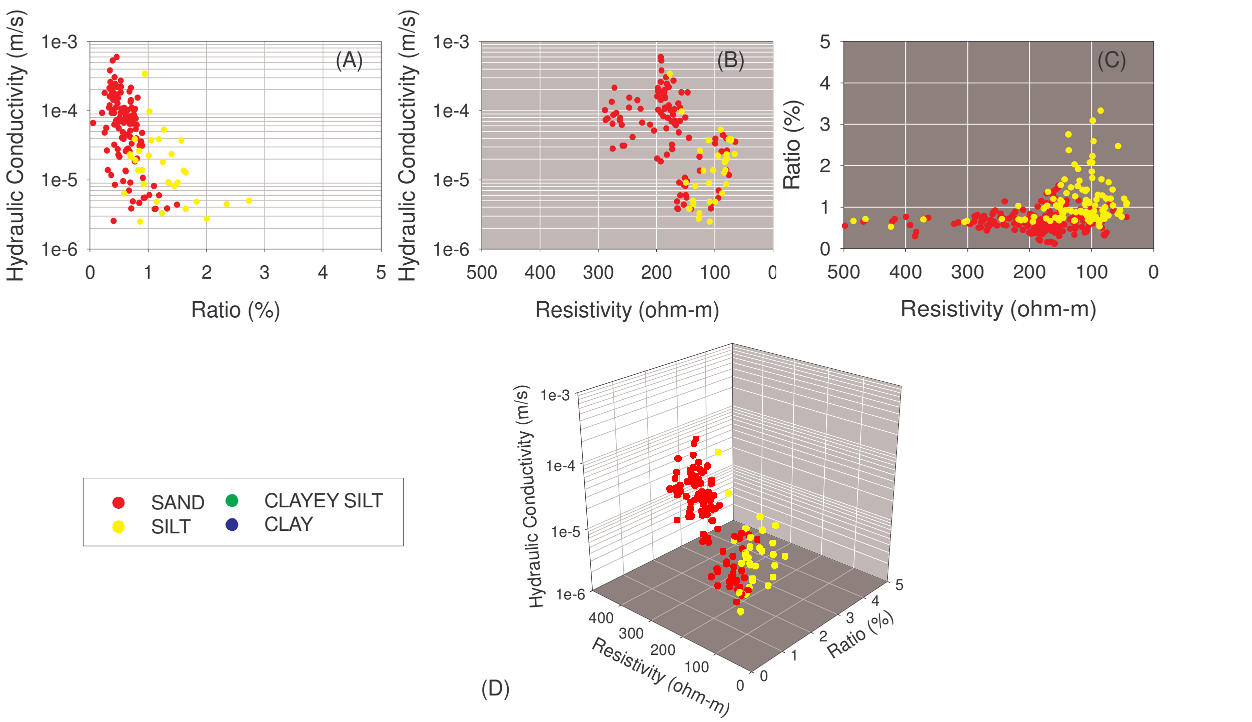


Figure 5 - (a), (b) and (c) Scatter-plots of hydraulic conductivity versus CPTu/SMR parameters. (d) 3D graph of hydraulic conductivity versus *ratio* (tip/sleeve) and resistivity. The vertical resolution is 15 cm and the measurement scale is 15 cm. Sediment textures are based on the Fellenius and Eslami (2000) profiling chart (see Figure 1).

Based on the hydraulic conductivity data, the last two clusters can be regrouped even though mechanical and electrical properties indicate different textures or origins. However, because the class-texture is based on the Fellenius and Eslami (2000) chart and that chart has not yet been validated for the St-Lambert site with sediment cores, interpretation on the origin of the sediments must be done with caution. Also, our multivariate classification may better define the different textures compared to Fellenius and Eslami chart. This could be the reason why classical two-variable chart are misclassified in our multivariate clusters.

Moreover, it appears that there is less overlapping between hydrofacies than there is between geological facies. This may provide justification for using hydrofacies directly instead of defining geological facies first and then attributing hydraulic properties to them as is traditionally done in aquifer characterisation (Ouellon et al., 2008).

4 CONCLUSION

Because geophysical and hydraulic parameters are found not to be linearly related, it appears that multivariate analyses based on the separation of homogeneous “natural” clusters is a promising way to define geological facies and hydrofacies on the basis of geophysical properties. Although the potential of this approach is demonstrated only in a qualitative manner with 2D and 3D scatter plots, a direct classification of hydrofacies and geological materials based on cluster analysis, or Bayesian approaches will be possible. These types of analyses will allow various relationships to be examined using all available dimensions (parameters), as opposed to 3D graphs where only three parameters may be analysed simultaneously. Moreover, addition of more dimensions in the analysis should further separate the barycenter of the various clusters. In the next phase of the research project, the conventional Fellenius and Eslami (2000) chart will be extended with the addition of porosity and resistivity to better distinguish geological facies at our test site.

The identification of *in situ* relationships between indirect and direct measurements at selected observation wells implies that CPTu/SMR measurements (mechanical and electrical properties) may be directly correlated to geological facies or hydrofacies. Hence, because CPTu/SMR soundings are easier and faster to acquire than direct characterisation from observation wells, the spatial distribution of the hydraulic properties will be better assessed across the study area.

This methodology will be further extended to surface and tomography geophysics (GPR and resistivity) in the future, an applied in combination with CPTu/SMR soundings to further define the spatial heterogeneity of the geological facies, hydrofacies and hydraulic conductivity.

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