The rôle of *in situ* testing in coastal environmental monitoring

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Résumé

L'urbanisation croissante du domaine côtier et les changements de climat attendus et les effets induits, comme par exemple, l'élévation du niveau de la mer, la probabilité de l'intrusion d'eau salée, l’augmentation des orages et des tempêtes etc., et leur interaction avec la population humaine sont susceptibles de dégrader l'environnement de manière complexe. Afin d'avoir un plan efficace de lutte et de réduction du risque, il faut élaborer un plan de surveillance adéquat qui soit possible et économique. L’utilisation des technologies de pénétration au cône (CPT) offre de telles possibilités. L'essai de pénétration au cône a fait beaucoup de progrès durant les dernières quinze anneés et les interprétations des résultats obtenus qui en découlent sont basées sur des principes bien établis. L'incorporation des techniques géophysiques dans les technologies CPT ouvre une nouvelle voie pour caractériser les conditions du sous-sol dans le domaine côtier. Dans cet article, les auteurs passent en revue certaines de ces technologies pour délimiter et déterminer les caractéristiques du sol. Deux études de cas sont présentées. D’une part, on compare les performances de l’instrumentation classique d’un forage avec celles que permet le pénétromètre au cône et d’autre part, on évalue l’apport de la fluorescence induite par laser utilisant les technologies CPT pour détailler entre autres la concentration en hydrocarbures polyaromatiques (HAP) dans les sédiments de portuaires.

Abstract

The increasing urbanization of coastal areas and the impeding climate change and the related changes, e.g., in sea-level rise, probability of salt water intrusion, increase in the storm surges etc., and their interaction with the human population is likely to degrade the environment in a complicated way. In order to have any kind of effective mitigation plan, an effective monitoring plan is required which is both feasible and economical. Cone penetration technology (CPT) offers such a scheme. Cone penetration testing has made a great progress in last 15 years and the interpretations of obtained results are based on established principles. Incorporation of geophysical techniques into CPT offers a new way to characterize subsurface conditions in coastal areas. In the present paper, the authors review some of the technologies to delineate the soil conditions. Two case histories are presented, one comparing the performance of conventional monitoring well with that of cone penetrometer enabled well and the second is the CPT based laser induced fluorescence to detail the concentration of polyaromatic hydrocarbon (PAH) in harbour sediments.

1.Introduction

"The marine environment - including the oceans and seas and coastal areas - forms an integral whole that is an essential component of the global life-support system and a positive asset that presents opportunities for sustainable development" (Agenda 21, 1992).

Seen from the above statement issued by the governmental committee that the coastal environments occupy one of the most dynamic interfaces on Earth, at the boundary between land and sea, and they support some of the most diverse and productive habitats. These habitats include natural ecosystems, in addition to important managed ecosystems, economic sectors, and major urban centers. The existence of many coastal ecosystems is dependent on the land-sea connection or arises directly from it (e.g., deltas and estuaries) (IPCC, 2001). However, this system has been attacked continuously either naturally or anthropogenically. Nutrients run-off, sewage discharge, accidental or intentional spilling of petroleum are some of the examples that are continuously degrading the coastal environments. To plan, execute and monitor environmental restoration efforts / degradation, an efficient, cost effective and least time consuming technology is required. Cone Penetration Technology is one such technology to offers many advantages, as it is cost effective, provides continuous real time data, measurements are accurate. It is possible to build 3D-stratigraphy. It allows enhanced delineation of contaminants, vertical resolution being ~ 5 cm, among others. In the following paragraphs some of these changes are discussed briefly and then CPT has been described in details.

1.1.Urbanization

With the continued urbanization of the coastal areas and ever more increasing demands of the related industries, the water balance of a coastal aquifer can get affected in several ways, with serious impacts upon human water supplies and coastal ecosystems. Urbanization can also have large impacts upon ground- and surface water quality. The dynamic balance between fresh and salt-water at depth can be altered due increased pumping due to increase in demand from public-water supply, which can lead to shift in position of the interface between fresh and salt waters and possibly cause salt-water intrusion into pumping wells. Furthermore, urbanization can result in the reduction of aquifer recharge rates (and affect the interface position) by increasing the fraction of impervious surface on the landscape. These changes in the water balance not only affect the interface between salt and fresh water at depth in aquifer, but can also affect pond levels, wetland levels, stream flow, and the salinity regime of tidal creek systems.

1.2.Climate change

Climatic change is global phenomenon with distinctly local aspects that can affect hydrologic systems across a range of time scales. Lins and Slack (1999) examined data from national United States Geological Survey (USGS) stream gaging network of 395 stations with more than 50 years of record on unregulated streams, and documented climatically induced variations in stream discharge in the US during the 20th century. They showed that the streamflows, in general, in the conterminous US are increasing, but are exhibiting fewer extremes. Masterson and Barlow (1996) have shown that drought-induced ground-water declines over an extended period (5 years) can have larger impact on the position of interface between salt and fresh waters at the base of coastal aquifer; the position of the aquifer (in the absence of pumping by humans) is directly controlled by the aquifer recharge rate, which is sharply reduced during a drought.

1.3.Sea-level rise

Sea-level change is also a global phenomenon that can be modified by local conditions in the earth's crust. According to instrumental records collected since 1920's, the relative sea level has risen at a rate about 2.5 mm.yr-1. A recent summary of sea-level rise are likely to increase to rates of 3.5 to 6.0 mm.yr-1 by the year 2100, due to projected effects of global warming and glacio-isostatic adjustment (Donnelly and Bertness, 2001). The response of any of the hydrologic system to accelerated sea-level rise will likely be an increased tendency for saltwater to intrude both the underlying aquifer at depth and the tidal streams at the surface. Flow chart, Figure 1, shows how different agents of change can have effect on the hydrologic cycle and different responses these changes can provoke in various ecosystems.

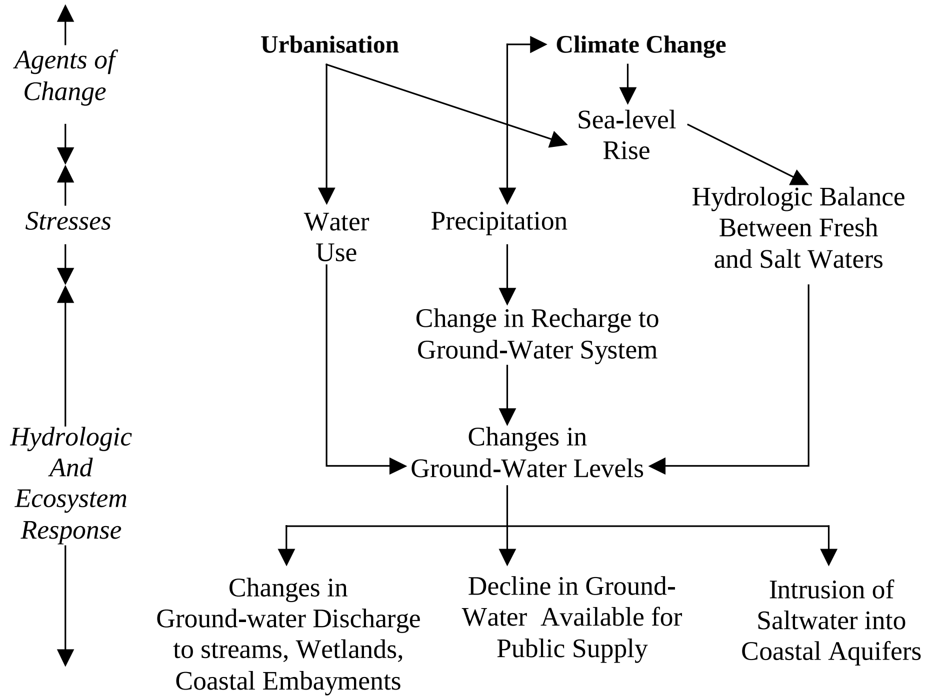

Figure 1. *Flow chart depicting agents of change can stress hydrologic system in a coastal environment resulting in different ecosystem response.*

Figure 1. *Organigramme des agents de changement pouvant soumettre contrainte le système hydrologique dans un environnement côtier induisant un réponse différent de l'écosystème.*

2.Coastal monitoring

For any effective management of terrestrial, aquatic and estuarine ecosystem, long-term monitoring of hydrologic change is important. The aim of any geoenvironmental site characterization study is to obtain very high quality information on the nature and the spatial distribution of pollutants in an efficient manner.

Any site characterization and the mitigation plan is based on the quality of data. The data is accumulated over a period of time and can come in various forms, such as topographic data, weather data, water quality, water table level, geochemical, geophysical etc. In order to have an effective mitigation plan or the site characterization plan, the subsurface data is gathered either directly through boring a well or indirectly by utilizing various geophysical techniques.

The decade of 1990's saw a big shift in the way a site gets characterized. The emphasis has shifted from the collection of a limited number of high quality, high cost, analytical data point that dominated site characterization in the early part of the decade resulted in a lack of broader understanding of site conditions. Moreover, these practices often required long time horizons for the compilation of sufficient data for any remedial decisions. High costs, long time frames, and limited nature of the information associated with earlier practices have led to the emergence of a number of innovative techniques designed to speed the data collection process, increase the amount of information collected, and lower the overall cost of data collection.

In the coastal environment one of the traditional way of monitoring the site has been installing the conventional monitoring wells, which is not only expensive but also generate waste which must be treated and disposed of properly.

Figure 2 below shows various phases of site characterization, originally proposed by Bouwer *et al* (1988) for waste characterization, however, it can easily be adapted for coastal monitoring programme as well.

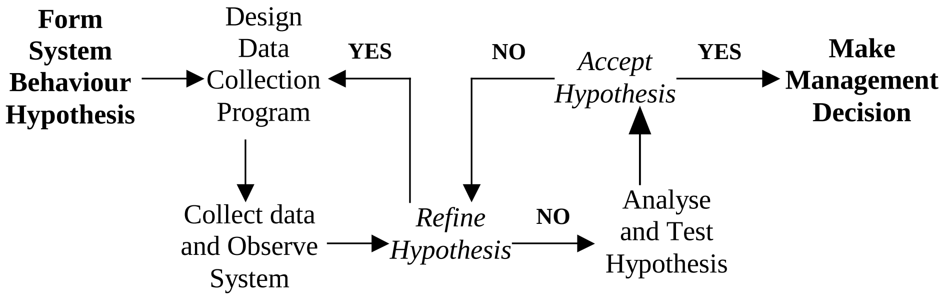

Figure 2. *Phases of site characterization (adapted from Bouwer et al., 1988)*
Figure 2. *Phases de caractérisation du site (adaptée de Bouwer et al., 1988)*

3.Push in or Cone Penetration Technology (CPT)

Cone penetration testing (CPT), which has been variously described as the push-in technology, direct penetration technology, has been effectively used in obtaining various geotechnical parameters *in situ*. Cone penetration testing is fast, economical, repeatable, and provides accurate data, which can be used in determining soil stratigraphy and geotechnical parameters. The use of cone penetration technology for geoenvironmental monitoring is an emerging field. One of the main advantages CPT offers over traditional borehole or conventional monitoring well is that no drilling waste is generated, therefore, eliminating the need for treatment and disposal of generated waste material which may be hazardous. One of the main disadvantages of this method is that no sample is retrieved; therefore, no visual inspection can be made.

Though it is possible to incorporate many different types of sensors within the body of a cone penetrometer for obtaining various geotechnical / geoenvironmental parameters. The discussion that follows hereafter deals with the comparison of soil permeability data obtained through conventional monitoring well with that of cone penetrometer enabled monitoring well and that of the detection of polyaromatic hydrocarbons (PAH) in harbour sediments, and in the following section two case histories are presented: i. the effectiveness of the cone penetrometer based laser induced fluorescence system and ii. comparison of permeability obtained by two methods discussed above.

3.1.Soil permeability

Permeability is a fundamental characteristic parameter reflecting the ease through which fluid flows through porous media. In short, the permeability affects (i) the nutrient supply and gas exchange, (ii) delivery of chemicals, (iii) rate of movement and rate of pumping, (iv) flow velocity (time) for extraction, among others. It is a parameter which is commonly sought by geotechnical engineers, coastal engineers, environmental sciences, waste management, and water resource management.

The soil permeability (or hydraulic conductivity) directly relates to the coefficient of consolidation (c_h) and the constrained modulus ($D= 1/m_v$). An electric cone with pore pressure sensor (Campanella and Robertson, 1988) or a moisture probe (Shrivastava, 1994) can be effective in gathering such data. Table 1 below lists some of the geotechnical probes that can be employed to gather such data as well as for long term monitoring programme.

Tableau 1: *Différentes sondes destinées à l'instrumentation et à la reconnaissance en geotechnique.*
Table 1*: Various probes for geotechnical investigation and monitoring.*

Geotechnical sensors i. load cell for penetration resistance ii. load cell for skin friction resistance	Measures geotechnical properties, i. penetration resistance, ii. Unit skin friction resistance to determine soil types, that can aid in well construction and remediation system design.
Moisture probes	Quantifies soil moisture content and can aid in calculating hydraulic conductivity.
Pore pressure probes	Quantifies soil pore pressure for site hydraulics studies, such as direction and rate of ground water flow and provides discrete values of relative hydraulic conductivity.
Liquid / gas sampler	Extracts liquid or gas samples from subsurface for further analysis.
Small diameter well installation	Install commercial, custom designed wells using direct push technology for access to ground water.
Grouting capability	Grout is used to seal the penetration hole when a push is completed. A cement and water mixture is pumped through a tube in the penetrometer to fill the hole as the push rods are brought to the surface. This eliminates the potential movement of contaminant from one soil layer to another.

3.2.Environmental probes

Recent developments in various types of sensors, miniaturization and the robustness of the components have made it possible for these sensors to be deployed within a cone penetrometer system. Some of these sensors are listed in Table 2. In the case history section the Laser Induced Fluorescence (LIF) is described and how it is used at a contaminated site to measure the concentration of polyaromatic hydrocarbon (PAH) in a harbour sediment.

***Tableau 2**: Exemples de sondes environnementales associées à l'utilisation du CPT.*
***Table 2:** Examples of environmental probes that can be used with CPT.*

Hydrocarbon sensor system	Detects hydrocarbon contaminated soil real-time using solid state, laser induced fluorescence (LIF) technology.
Direct Sampling Ion Trap Mass Spectrometer (DS-ITMS)	Volatile organic carbons (VOCs) are collected using several Site Characterization and Analysis Penetrometer System (SCAPS) sampling probes, which extract gases from the sample matrix and transport them through an appropriate transfer line into a direct capillary restrictor interface to the ion trap. Targeted compounds may be identified based on unique peaks in the electron impact and proton transfer chemical ionization mass spectra. Sample analysis takes 2 to 3 minutes.
Thermal desorption sampler	The probe collects a soil plug into a chamber where the soil is heated. A pneumatic system transports purged VOC compounds to the surface for analysis by an ITMS, or are collected onto traps for later analysis.
Vadose sparge / ITMS sensor	Measurements are made during probe retraction. A sacrificial sleeve is used to protect the sampling port during the penetrometer push to the depth of interest, whereupon soil friction removes the sleeve when the probe is retracted. This creates a gap between the probe and the soil. A pneumatic system transports a carrier gas down through the probe where it is swept past the soil surface before the resultant vapours are drawn up to the ITMS in the truck.
Laser Induced Breakdown Spectroscopy (LIBS)	The LIBS sensor system focuses a high-powered pulsed laser onto the surface of the soil to generate diagnostic plasma. Specific wavelengths of the light in the plasma correspond to specific metal elements present in the soil. The brightness of the light at a given wavelength indicates how much of that metal is present. LIBS can detect metals in the single ppm range.
Spectral Gamma	The probe uses a NaI scintillation crystal to detect gamma radiation from radioactive waste directly in the ground. The spectral gamma results are analyzed to diagnose radionuclide identity and relative concentration.
Video Microscope System	Provides real time video images of the subsurface. 100x magnification provides soil type information and displays Dense Non-Aqueous Phase Liquids (DNAPL) contaminants.

4.Case Histories

4.1 Laser Induced Fluorescence (LIF) cone penetrometer

Laser Induced Fluorescence (LIF) can delineate the extent of subsurface Petroleum, Oils, and Lubricants (POL) contamination, as well as map subsurface stratigraphy, more accurately and less expensively than widely spaced monitoring wells and soil borings. The LIF sensor uses an ultra-violet laser to introduce fluorescence in the subsurface POL contamination. Using a fiber optic cable, the UV-laser energy is transmitted from the surface down an umbilical, through a sapphire window located on the side of the probe, and is emitted into the surrounding soil. The POL contaminants become excited and emit fluorescent energy that is carried by another finer optic cable back up to the surface where it is analyzed in real time. The process is continuous, gathering data as the probe is steadily pushed through the subsurface media (Bujewski and Rutherford, 1997; Liberman, 1998; Shrivastava and Mimura, 1996).

Figure 3 gives the results of LIF cone penetrometer in harbour sediment. Figure 3a shows the intensity of the fluorescence as obtained in the field and the Figure 3b shows the interpreted result in terms of the concentration ($\mu g.g^{-1}$) of petroleum compound in the harbour sediment. The rapidity and the ease allows the technique to be used to deduce the source of the contamination in a given stretch of harbour sediment. It can be very helpful in gaining overall understanding of general contamination patterns.

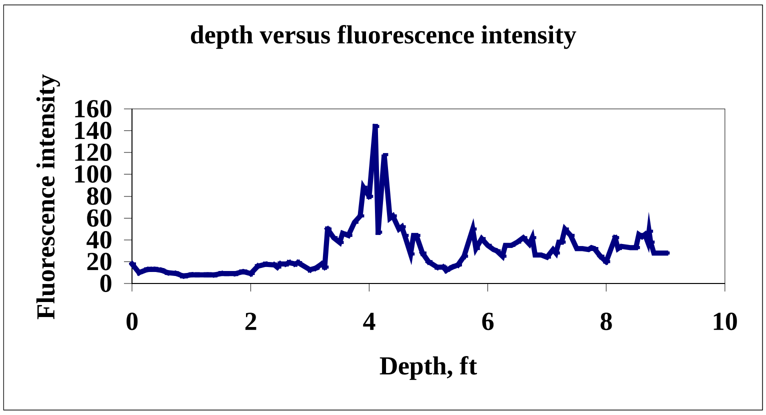

Figure 3a. *Intensity of Laser Induced Fluroscence as a function of depth in a harbour sediment.*
Figure 3a. *Intensité de la fluorescence induite par le laser en fonction de la profondeur des sédiments portuaires.*

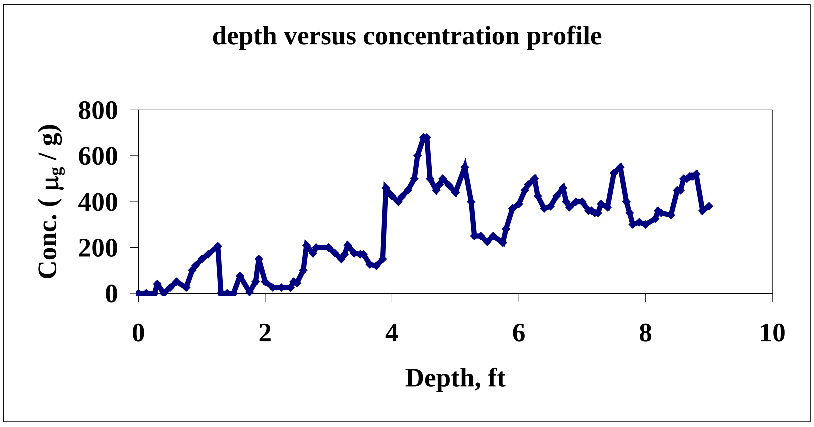

Figure 3b. *Interpreted concentration of polyaromatic hydrocarbon in a harbour sediment.*
Figure 3b. *Evaluation de la concentration d'HAP de sédiments portuaires.*

4.2 Direct push well versus conventional monitoring well

US Environmental Protection Agency (USEPA, 2002) initiated a project to evaluate the effectiveness of the monitoring well installation using cone penetration technology, to evaluate various physical as well as chemical characteristics and compare it to the monitoring wells established using conventional technique. Sites were chosen to cover a wide spectrum geological as well as their geochemical parameters. The parameters measured were ground water levels, chemical concentrations, hydraulic conductivity, and the geochemistry (natural attenuation) of the underground water. It is important to note here that the cone penetrometer based monitoring wells had no filter pack, whereas, conventional wells contained filter pack and were installed with typical drilling and completion methods.

The data generated were ground water level, hydraulic conductivity, chemical concentrations of Benzene, Toluene, Ethylbenzene, Xylene (BTEX), Methyl Tertiary Butyl

Ether (MTBE), Total Suspended Solid (TSS), and naphthalene and geochemistry of groundwater. In Figure 4, the hydraulic conductivity determined using Hvsorlev and Bower-Rice methods is shown for two different methods.

The conductivity values for conventional wells generally fall above 1:1 line suggesting that the conductivity is higher than those determined from cone penetrometer enabled well suggesting a systematic error. Henebry and Robbins (2000) studied the influence of skin effects on the hydraulic conductivity of direct-push wells without filter packs and concluded that undeveloped well had hydraulic conductivities 3.2 to 9.6 times lower than those that were developed using a minisurge block tool. It can be said that these wells in this study were not properly developed. Henebry and Robbins (2000) also concluded that properly developed direct-push wells yielded comparable results to conventional monitoring wells.

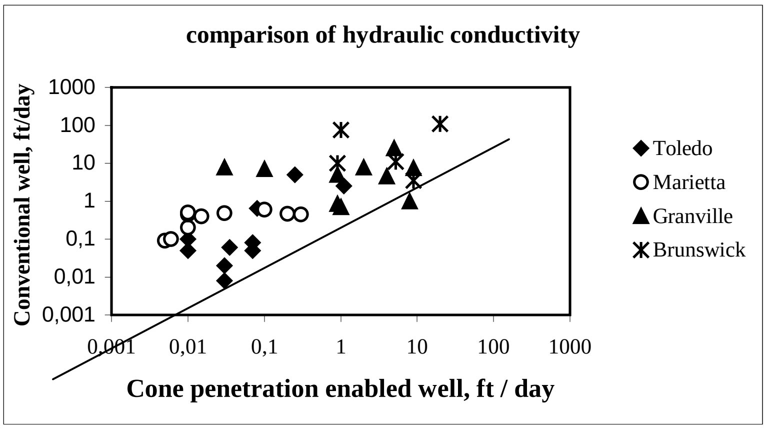

***Figure 4**. Hydraulic Conductivity Determined by Hvsorlev and Bower-Rice Methods.*

***Figure 4.** Conductivité hydraulique déterminée par les méthodes de Hvsorlev et de Bower-Rice.*

5.Cost comparison

A cost comparison was done by the Technology Innovation Office of the NorthEast Hazardous Research Center, USA. The study showed that the for an installation of 50m well by drilling installed monitoring well versus CPT well, a direct savings of more than US$ 4,000 was realized (OnSite-InSight, 1999). If a site with numerous monitoring well needs to be installed, a net saving can be of very high order.

6.Conclusions

For any technology, new technology to be viable and acceptable over the existing technology, it has to be efficient and economical compare to the existing technology. With the predicted change in climate the stresses associated with these changes as well as rapid growth in the urbanization of coastal areas pose a serious problem for geotechnical / geoenvironmental engineers to design, develop, and implement a system of monitoring which is economical, less damaging to the environment, and which results in real-time observation. In the preceeding paragraphs case studies with cone penetrometer based applications are discussed in terms of permeability which is a very commonly sought parameters among many specialists and a special addition to the existing cone penetrometer based LIF system. It has been shown that CPT based technology has made a great progress in last decade and can be effectively used in place of existing technology. CPT has proven to be faster, more cost effective, and more environmental friendly than drilling. Furthermore, CPT generate minimal or no waste, while drilling generate significant quantities of waste materials, which must be treated as hazardous. Like any technology CPT-based technology does have its own limitations, in the case of CPT enabled monitoring well, if the well is not properly prepared it may underestimate the permeability results. Similarly, in the case of CPT-LIF, it can be expensive for a limited number of sampling, also natural fluorescent material can lead to false positives. It is recommended that the town planners, engineers and political decision makers are made aware of these developments and their efficiency so that these new technologies can be incorporated in new planning while keeping these limitations in mind.

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