INTEGRATING GEOPHYSICAL MEASUREMENTS WITH SOIL SAMPLING FOR SITE CHARACTERIZATION USING KERNEL ESTIMATION

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Abstract

Reconstructing the variation of contaminant concentration with punctual soil samples is more or less the norm, even though it fails more often than not for problems of even moderate complexity. To overcome the limits of punctual soil sampling, we propose to integrate soil sampling with continuous surface geophysical measurements in a geostatistical framework. We present this integrated analysis for a PAH contaminated site in France. For the study site, two 3D surveys were acquired: an electrical resistivity tomography survey and a seismic travel time tomography survey. Those two surveys permitted to infer two spatially continuous physical properties on the whole volume, namely the resistivity and P-wave velocity. The probability density function relating the velocity-resistivity pairs with each of the 75 punctual lab measurements of PAH concentration was modeled using a Gaussian kernel. This probability density function combined with the two 3D volumes of resistivity and Vp velocity permits to translate the later in 3D map of PAH concentration. This 3D map of concentration was then used as a secondary variable in a cokriging of the 75 punctual lab samples, thus reintroducing the spatial correlation of the initial dataset. Comparing this final 3D HAP concentration model with the simple kriging of the PAH samples, the geophysical integrated model reproduce much better the distribution of measured concentration, shows a much more realistic spatial pattern of the contamination and lowers the estimated contaminated volume.

Introduction

Geophysical data are more and more viewed as useful methods to bridge the gap between punctual measurements and 3D subsurface (Ruggeri, et al., 2013). Indeed, geophysical surveys bring information on spatial connectivity that cannot be inferred from direct measurements. Applied to soil characterization, geophysical properties can be affected directly by the presence of contaminants (Ajo-Franklin, et al., 2006), or indirectly by preferential migration pathways (Coscia, et al., 2012). In this paper, we show how 3D geophysical surveys and direct soil sampling can be integrated to obtain a more precise estimation of contaminated soil volumes in a complex, heterogeneous geology.

Study Site

The study site is located in an industrial environment. The main contaminating activity is the creosote treatment of wood, which began in the 1950s. Creosote contamination of soil and groundwater is of concern in the area, as local inhabitants rely on groundwater for drinking water. This contamination takes mainly the form of polycyclic aromatic hydrocarbons (PAH). Our study focuses on a small area of the property, measuring 30 meters per 200 meters. In this area, two sources of PAH contamination have been identified: a tailing pond and a sump, which were used to treat wastewater on site. The goal is to characterize the extent of those sources, particularly in the unsaturated sediments. The natural sediments in place are comprised of a rather homogeneous coarse alluvial sands deposit. However, due to the industrial nature of the site, backfill materials of different sources and nature have been put in place at different periods. Hence, the first several meters of soils are rather heterogeneous. For this reason, mapping the extent of the contaminated zone is challenging.

Field Measurements

We base our characterization effort on a recent soil and water sampling campaign carried out by Envisol, an environmental french consulting firm. The following analysis is based on the total PAH concentrations in soil measured on 75 of those samples. Many measurements exceeded 70 mg/kg, the limit after which contaminants may migrate and contaminate water. The highest measured concentration reached 7000 mg/kg. Hence, soil contamination is known to be present, but contaminated volumes are difficult to predict due to the backfill heterogeneity.

Soil sampling was complemented by surface geophysical measurements. Two methods were chosen on site because of their ability to infer physical properties correlated with the lithology: electrical resistivity tomography (ERT) and seismic refraction tomography. In total, 9 parallel ERT lines were acquired along the East/West direction and 10 parallel lines were acquired along the North-West/South-East direction. Each line consisted of 48 electrodes with a spacing of 1.5 m, in a dipole-dipole configuration. A total of 5 seismic lines were acquired, parallel to the East/West direction. Geophones were planted at a 2 m interval, and sources at every 6 m. ERT and seismic lines were inverted in 2D separately, and interpolated with an inverse distance weighting to obtain 3D continuous models. The resulting electrical resistivity model is shown in Figure 1a. Resistivity values vary strongly laterally and vertically. Surface backfills are usually resistive, but can vary between 100 and 1000 Ω·m. This high level of heterogeneity is manifest of the complexity of contaminant characterization on this site. The resulting velocity 3D model is shown in Figure 1b. Lateral variations are much more subtle than for ERT. Three layers are visible: the first loose dry soil layer with a velocity around 300 m/s, the saturated sediment around 1400 m/s, and the bedrock, around 2500 m/s. Small velocity variations are, however, present inside each layer.

Data Integration

The difficulty of using direct correlations between geophysical measurements and soil contaminant concentrations is well illustrated in this study. Inlets of Figures 1a and 1b show crossplots between the measured total HAP concentration in soil samples and electrical resistivity and P-wave velocity respectively. A very poor correlation coefficient of -0.28 is obtained for ERT, and a better correlation of 0.6 for seismic velocities. This is to be expected as organic contaminants are far from being the only factor influencing the electrical resistivity or P-wave velocity of soils. On their own, very little quantitative information can be obtained from these correlations.

Based on the observation that some factors may influence both electrical resistivity and P-wave velocity, we seek to build a multi-parameter relationship that suppresses common variance due to unknown factors, but amplify the influence of HAP concentrations. To do so, we use the kernel density estimation approach of (Silverman, 1981): a density function taking as input the electrical resistivity and the P-wave velocity and outputs the PAH concentration is obtained by interpolating known sample triplets with a Gaussian kernel. The density function obtained in this fashion is shown in Figure 1c. It allows to recover the mean of the PAH conditional distribution given any value of measured resistivity and P-wave velocities. In the resistivity-velocity plane, PAH samples are gathered in families of high and low levels of concentration. This shows that contaminated zones take specific pairs of P-wave and electrical resistivity. These families cannot be obtained from one to one linear correlations.

Using this density function, we can convert the resistivity and velocity 3D models into a 3D PAH pseudo-concentration map, shown in Figure 1d. This model does not reproduce exactly the measured values of PAH concentration at the samples location, as shown in the inlet of Figure 1d. This is to be expected, as the kernel averages the PAH values around each velocity-resistivity pairs. However, the correlation between measured and predicted concentration is very good, at 0.95. In order to honour exactly the measured PAH values we use collocated cokriging with the PAH model built with the kernel as a secondary variable (Figure 1f). As shown in the crossplot, the final cokriged model reproduces exactly the measured concentrations. Comparing this model with the result of simple kriging that does not include information from geophysical measurements (Figure 1e), we see that simple kriging produces overestimated values of concentration. Geophysical information allowed the kriging to be performed locally in zones of similar resistivity-velocity values.

Conclusion

In summary, we propose the following workflow to integrate geophysical measurements to soil contamination characterization. First, acquire soil samples with precise contaminant analysis with an adequate spatial sampling of the zone to characterize. Second, acquire 3D geophysical surveys covering the whole area, with at least 2 measured physical parameters (in this case, electrical resistivity and P-wave velocity). With appropriate geophysical measurements, a multiparameter function with geophysical properties as input and concentration value as output can be built with a kernel estimation. Using this function, build an intermediate concentration model that can finally be used as a secondary variable to the cokriging of the soil samples value. We do not claim that this workflow is applicable to all contamination types or all geological settings, but in many cases, as shown in this case study, it can be used successfully integrate geophysical information at low cost.

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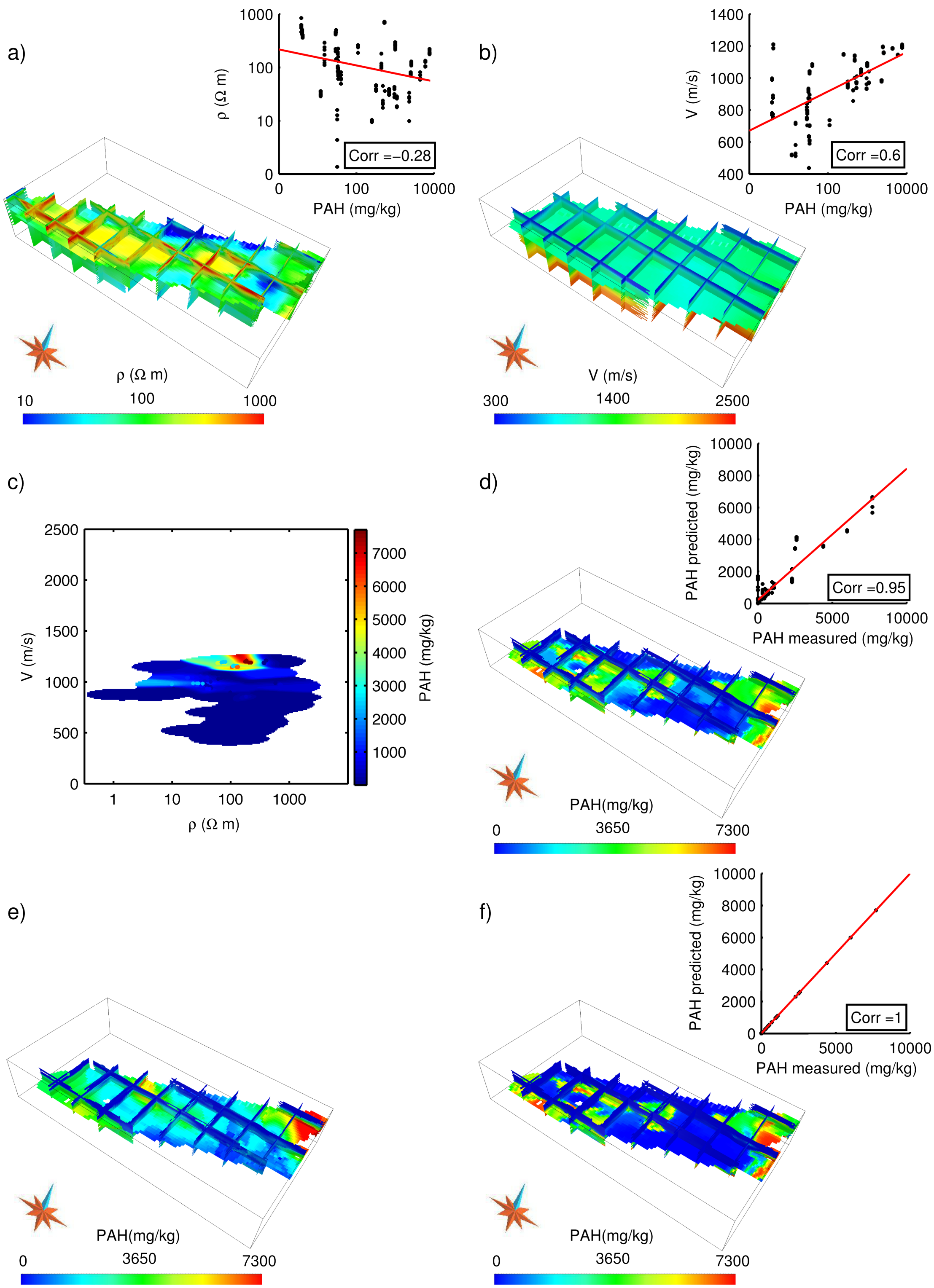

Figure 1: Resistivity and P-wave velocity in a) and b), density function in c), PAH concentration given by the density function in d), PAH concentration obtained by simple kriging in e) and PAH concentration obtained by cokriging in f). The inlets show the correlation with laboratory measurements.