Geophysical and Geotechnical Data Fusion for Levee Assessment – Interface Detection with Biased Geophysical Data

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Theo Dezert
Institut Français des Sciences et Technologies des Transports, de l'Aménagement …

Sergio Palma Lopes
Institut Français des Sciences et Technologies des Transports, de l'Aménagement …

Philippe COTE
Institut Français des Sciences et Technologies des Transports, de l'Aménagement …

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Geophysical and Geotechnical Data Fusion for Levee Assessment - Interface Detection with Biased Geophysical Data

T. Dezert[1]*, S. Palma Lopes[2], Y. Fargier[1], P. Cóte[2]

[1] Ifsttar - Cerema, [2] Ifsttar

Summary

To prevent disastrous consequences imputed to levee breakage, assessment methodologies have to be improved. Geophysical and geotechnical investigation methods are usually used to make such assessments. However, the effective combination of these two specific types of data remains a challenge. We propose the fusion of geophysical and geotechnical data by means of Belief Functions. Here we demonstrate our approach on a synthetic case study including geophysical (electrical resistivity) and geotechnical (cone-bearing) data and by implementing Smets and PCR5 normalization rules. This new data combination approach allows the characterization of horizontal interfaces and of a geological structure initially hidden by the effects of a highly conductive body.

Introduction

Fluvial levees are elevated partitions between channels and floodplains (Brierley et al, 1997), built for flood protection. These structures are considered as hazardous and may fail, leading to disastrous consequences such as human or material loss and economic disasters. Levee assessment acknowledged methodologies usually include geotechnical and geophysical investigation methods (Fauchard and Mériaux, 2007). While geotechnical investigation methods are intrusive, they provide quite accurate and punctual information. Instead, geophysical methods are non-intrusive and provide physical information on large quantity of subsoil with high output and potentially significant related uncertainties. These associated uncertainties can particularly be attributed to the indirect and integrating aspects of the methods as well as to the resolution of inverse problems. One of the important issues of assessment of levees is the combination of geotechnical and geophysical data taking into consideration their respective associated imprecisions, uncertainties and spatial distributions. In this work, we suggest the use of Belief Functions (BFs) and combination rules to merge artificial geotechnical (cone bearing) and geophysical (electrical resistivities) data. The objective is to display their ability to discriminate three sets of geological materials with the presence of a conductive anomaly, affecting the quality of the geophysical data. We assume that the reader is familiar with the BFs introduced by Shafer (1976). The use of BFs needs : (1) to select a common frame of discernment (FoD) of the considered problem, (2) to determine the masses of belief or Basic Belief Assignments (BBAs) from available data (geotechnical and geophysical) and (3) to choose a rule of combination.

FoD and BBAs construction

For the addressed levee problematic, we consider three classes of distinct materials θ_1, θ_2 and θ_3. Since the FoD, Θ, must consist of a set of exclusive and exhaustive hypotheses, we will be using a fourth class θ_4 to cover the physical characteristics not included in the three first sets. We use $\Theta = \{\theta_1, \theta_2, \theta_3, \theta_4\}$. The construction of the BBAs for each data source consists in assigning each data type (geophysical and geotechnical) to Θ.

Construction from geophysical data – electrical resistivity values

Since the electrical resistivity (ER) tomography method is one of the most employed for levee investigation, we propose the use of ER as geophysical data. We put ourselves in a fluvial levee problematic and consider two soil layers: an upper resistive layer (10^3 Ω.m) standing for sands (Palacky and West, 1987) and a subjacent and more conductive one (10 Ω.m) standing for a clayey core starting at 6 m depth. An anomaly (10^2 Ω.m) standing for a silty lens of about 1.3 m high and 40.5 m wide is positioned at 7 m depth (Figure 1.a). We then associate ER classes of specific soils (split into ranges of ER) to Θ so that: $\theta_1 = [\,5, 20\,]$, $\theta_2 = [\,50, 2 \cdot 10^2\,]$, $\theta_3 = [\,5 \cdot 10^2, 2 \cdot 10^3\,]$ and $\theta_4 = [\,0.2, 5\,[\,\cup\,]\,20, 50\,[\,\cup\,]\,2 \cdot 10^2, 5 \cdot 10^2\,[\,\cup\,]\,2 \cdot 10^3, 5 \cdot 10^3\,]$. We finally deliberately place a very small (0.5×0.5 m) conductive anomaly (10^{-6} Ω.m) centered at 1.35 m depth (represented in green Figure 1.a), that could be considered as a manmade metallic pipe. We use Res2Dmod free software (Loke, 2002) to simulate non-noised data acquisition from a chosen resistivity model (Figure 1.a) and then use the Res2Dinv software (Loke and Barker, 1996) to get the inverted ER section as one would obtain from the processing of survey data (Figure 1.b). The discrimination between sands and clays is manifest while the distinction of the anomaly is not obvious. Indeed, the conductive punctual anomaly generates resistive artefacts close to it and a very large and conductive anomaly deeper in the subsoil, hiding the presence of the silty lens. The image given by the inverted ER (Figure 1.b) is not that close to the true model (Figure 1.a). We finally use the Res2dinv discretization grid for the BBA $m_1(\cdot)$ corresponding to each event of 2^Θ. The values of the masses are set using the Wasserstein distances between an inverted ER value ± its uncertainty issued from Res2dinv and the interval corresponding to each event, so as each cell of the grid gets a normalized BBA.

Construction from geotechnical data – cone bearing values

We use artificial cone bearing values (expressed in MPa) as geotechnical data. These physical values could have been obtained from a cone penetrometer test investigation campaign. We simulate a data acquisition from four boreholes with an interspacing of 20 m, drilled to 17 m depth with an acquisition every 50 cm (dashed lines in Figure 1.a). Two of the boreholes are positioned so that they go through the silty lens. We assign intervals of cone bearing values to Θ so that: $\theta_1 = [\,2, 8\,]$, $\theta_2 = [\,20, 80\,]$, $\theta_3 = [\,2 \cdot 10^2, 8 \cdot 10^2\,]$ and $\theta_4 = [\,0.1, 2\,[\,\cup\,]\,8, 20\,[\,\cup\,]\,80, 2 \cdot 10^2\,[\,\cup\,]\,8 \cdot 10^2, 10^3\,]$. These intervals can be associated to specific soils (Robertson, 1990) such as clays for low values, silty soils for intermediate values and sands for higher ones. We assume a mass of belief equal to 1 in the borehole and impose an exponential lateral decrease of the trust in the data (following the mean horizontal scale of fluctuation of about 50 m proposed by Phoon and Kulhawy (1999)). The geotechnical grid depends on the distance between the boreholes and the acquisition rate. Thus, for each cell, a second BBA $m_2(\cdot)$ is fixed, entering in the fusion process.

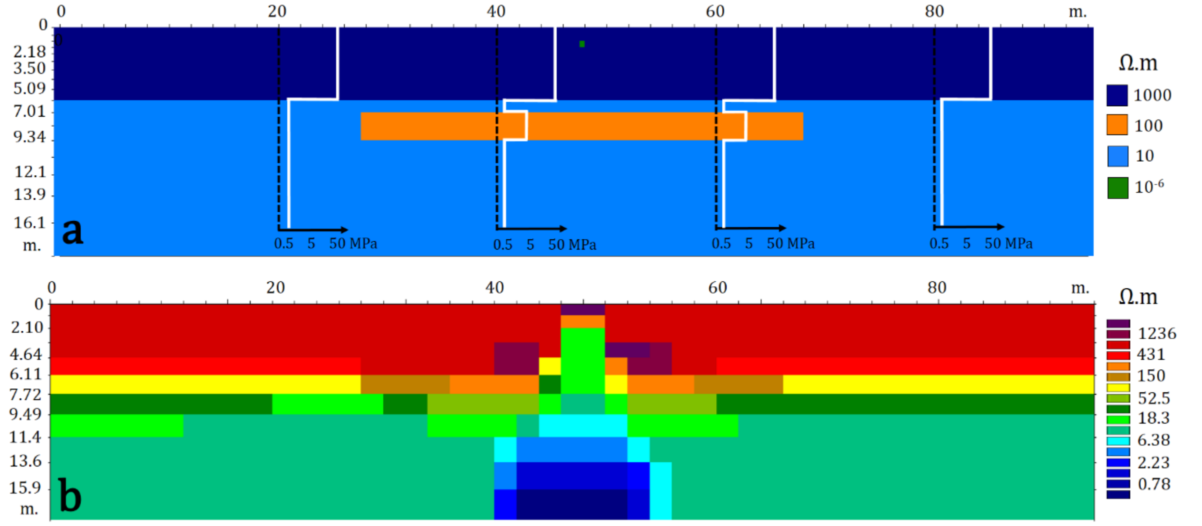

Figure 1 *2D section of subsoil displaying a) true ER with boreholes position in dashed line and associated cone bearing values in white and b) inverted ER with model data block.*

Combination of BBAs and exploratory results

We suggest the use of a fusion mesh containing all the meshes from the geophysical and geotechnical grids so that we avoid the unnecessary data alteration attributed to interpolations. The data merging consists in combining $m_1(\cdot)$ and $m_2(\cdot)$ assigned to each cell of the grid. While many rules of BBA combination have been proposed, in this work we present only two of them: Smets' rule (Smets, 1990) and the Proportional Conflict Redistribution rule no. 5 (PCR5) (Smarandache and Dezert, 2009). Smets' rule (conjunctive rule under an open-world assumption) allows the quantification of the conflict level of our two information sources (geotechnical and geophysical sources) represented by (Eq. 1):

$$m_{12}(\emptyset) = \sum_{X_1, X_2 \subseteq \Theta \mid X_1 \cap X_2 = \emptyset} m_1(X_1) m_2(X_2) \quad (1)$$

Thanks to it, we are able to point out the conflictual zones around: the horizontal interfaces, the silty lens, the punctual conductive anomaly and the resistive and conductive artefacts (in red, Figure 2.a).

$$m_{12}^{DS}(A) = \frac{1}{1 - m_{12}(\emptyset)} \sum_{X_1, X_2 \subseteq \Theta \mid X_1 \cap X_2 = A} m_1(X_1) m_2(X_2) \quad (2)$$

The fusion, following Dempster-Shafer's rule (Eq. 2) (closed world assumption) (Shafer, 1976) with the PCR5 normalization (Smarandache and Dezert, 2009) (Figure 3.a) is fairly close to the true model we imposed (Figure 1.a). It proposes a quite clear view of the interface between sands and clays and allows the visualization of the silty lens despite the grey zone generated by the conductive anomaly (Figure 1.b). As a decision-making support, we decide to display the events having the highest belief masses (Figure 2.a and 3.a) and their associated degrees of belief (Figure 2.b and 3.b).

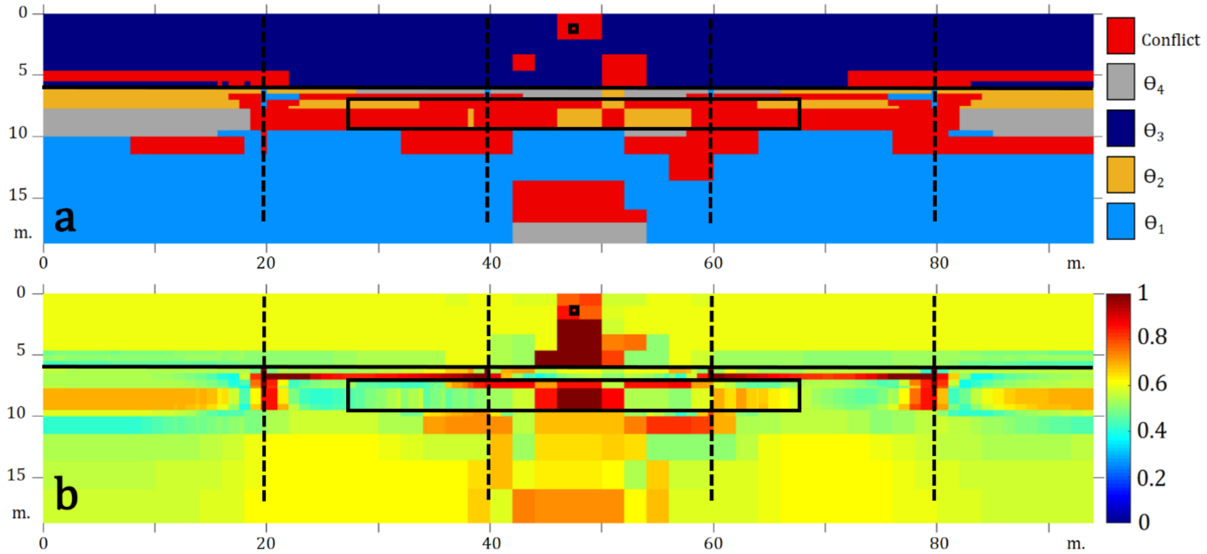

Figure 2 *Data merging with Smets' combination rule: b) represents the BBAs associated to the most plausible events presented in a). The black lines stand for the interfaces and the conductive anomaly fixed in the ER model (Figure 1.a) while the dashed lines stand for the boreholes position.*

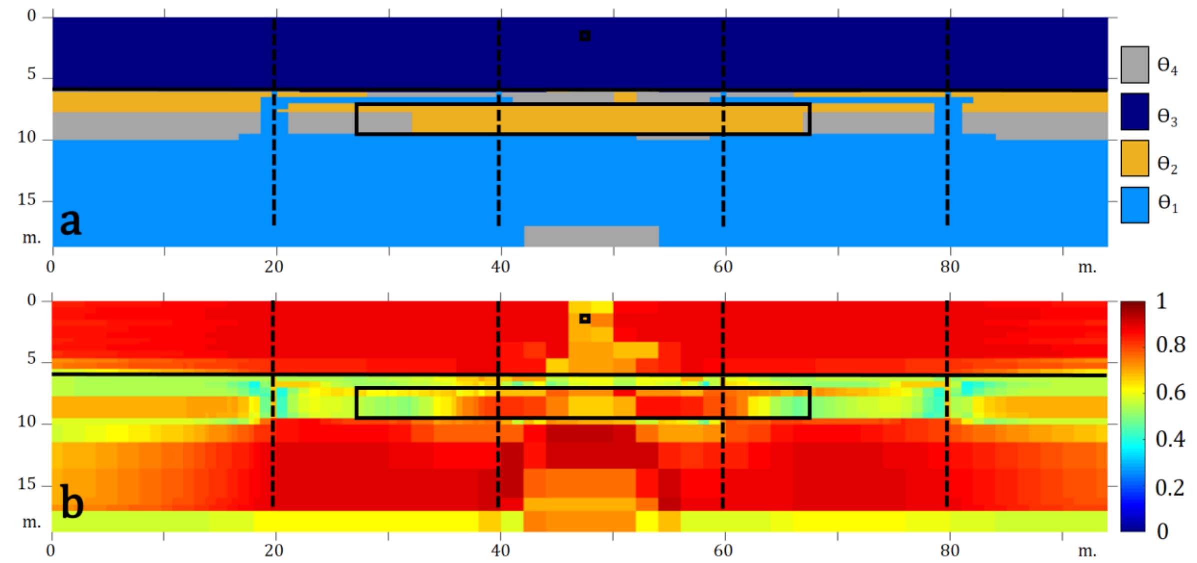

Figure 3 *Data merging with PCR5 normalization rule: b) represents the BBAs associated to the most plausible events presented in a). The black lines stand for the interfaces and the conductive anomaly fixed in the ER model (Figure 1.a) while the dashed lines stand for the boreholes position.*

Via our procedure, even though the conductive anomaly (that can be associated to a manmade metallic pipe) is not clearly detected and characterized, Figure 2.a still points out a conflictual zone around the position of that anomaly. Unfortunately, we still have incorrect values on the 19 first meters and 15 last meters around the sand/clays interface because of the wrong ER values proposed by the geophysical model (Figure 1.b). In the future, this kind of effect should be minimized by reconsidering the way to decrease the lateral trust of the geotechnical data.

Conclusions

The use of BFs for investigation of fluvial levees is promising. Indeed, it enables to highlight the presence of an interface between two geological media much more precisely than the geophysical method alone. Furthermore, it enables the reliable estimation of the complete extension of an anomaly with intermediate ER and cone bearing values, even though the effects of a punctual conductive anomaly (that could be associated to a transversal metallic pipe) hid the anomaly. Such merging procedures could be used to clarify perturbed geophysical data thanks to punctual geotechnical information. Without normalization, Smets' combination rule easily spotlights the conflicting zones. Such information could also be precious during an investigation campaign, indicating zones where survey has to be reinforced. This kind of problematics will be in the heart of our further studies in order to be able to propose the most pertinent positions for geotechnical boreholes thanks to belief functions and combination rules, therewith to improve fluvial levee assessment. In future work, we will also focus on parametric studies to choose the best decreasing functions for the lateral propagation of the geotechnical information. Finally, we will test our algorithm using real data acquired on a scale model as well as on a levee in order to propose a 3D modelling.

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