SEISMIC RADAR AND ELECTRICAL TECHNIQUES FOR WASTE DISPOSAL ASSESSMENT

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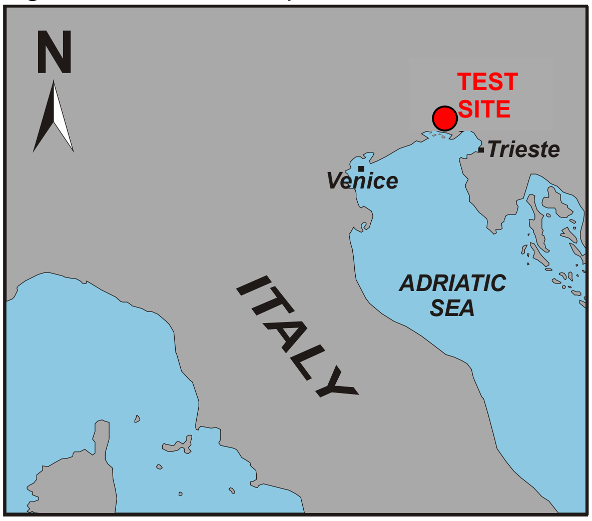
Abstract
Waste disposal site assessment and characterization through non-invasive geophysical data integration can ensure investigation depth and resolution necessary to properly image subsurface conditions. Localized and extended anomalies of subsurface physical parameters in heterogeneous media are successfully identified by means of surface and borehole radar investigation, geoelectrical surveys and Rayleigh wave analysis. We exploited surface GPR (Ground Penetrating Radar) data for shallow high-resolution imaging, while borehole VRP (Vertical Radar Profiling) data were acquired to assist site characterization and velocity estimation. Waste materials are often characterized by electrical properties significantly different from those of the surrounding filling and bedrock. Results from geoelectrical surveys were used in conjunction with seismic sounding to delineate lateral variations at depths where radar waves fail to penetrate due to scattering and attenuation. We used Multi-channel Analysis of Surface Waves (MASW) to determine vertical shear-wave profile and aid electrical data interpretation thus establishing a robust and cross-validated technology. We tested different computational approaches to optimise performances and implement fast and efficient data acquisition and processing procedures. Phase shift method proved to be the most effective solution both in terms of noise content and acquisition parameters. Data modelling was constrained and validated by borehole stratigraphy.

Introduction
Non-invasive characterization of waste disposal and contaminated sites provides large amounts of subsurface information at low cost and is a highly desirable approach for site management. High-resolution non-invasive methods can be further exploited to monitor contamination processes, such as leakage from waste disposal or contaminants diffusion into the ground from pipes, tanks, surface accidents, and to plan rehabilitation procedures. We integrate results of surface and borehole GPR surveys, geoelectrical tomography and Rayleigh-wave phase velocity analysis to reconstruct near-surface stratigraphy down to bedrock (approximately 18 m deep). A Test Site was chosen to validate the methods. The Test Site was a waste disposal with mixed industrial and solid urban waste piled on mixed alluvial and marine sequences in NE-Italy (Fig.-1). The stratigraphic column includes sandy loams with variable fractions of silt and clay, a gravel and coarse sand aquifer and a limestone bedrock. Two shallow layers, an allochtonous soil up to 1.5 m thick lying on coke ashes mixed with industrial debris (approximately 1 m thick), attenuate the radar wave due to strong scattering and low resistivity thus reducing radar penetration to approximately 2.5-3.0 m. We performed GPR borehole measurements to reconstruct the velocity field. Results were then validated by some laboratory measurements of EM properties performed on borehole samples and by finite-difference time domain (FDTD) modelling. We computed vertical shear-wave velocity profiles via multi-channel analysis of surface wave (MASW) to study deeper layers. Performances of three different phase velocity estimators (F-K, tau-p and phase shift) were evaluated. Inversion/modelling of the observed dispersion curve

indicates a sequence coherent with radar and geoelectrical results and borehole stratigraphy.

Figure 1: Location map of the test site used for geophysical acquisitions.



Methods

We used an ultra-wide band (UWB) Ground Penetrating Radar (Malå Geoscience) equipped with shielded (250 MHz) and unshielded antennas (100 MHz). Single-fold profiles were first obtained on a regular grid (12 m x 80 m, 1 m crossline spacing) in the Test Site area. We then performed a multiple common-offset-data acquisition to obtain multi-fold sections with average 1200 % fold. VRP was accomplished in a 20 m borehole located at the border of the rectangular grid utilized for the surface GPR acquisition. A 100 MHz surface transmitter was positioned at offset ranging from 0.6 to 3.6 m from the well. The offset increment was 10 cm. The 100 MHz borehole receiver was lowered to the bottom of the borehole and pulled up while triggering data acquisition every 5 cm.

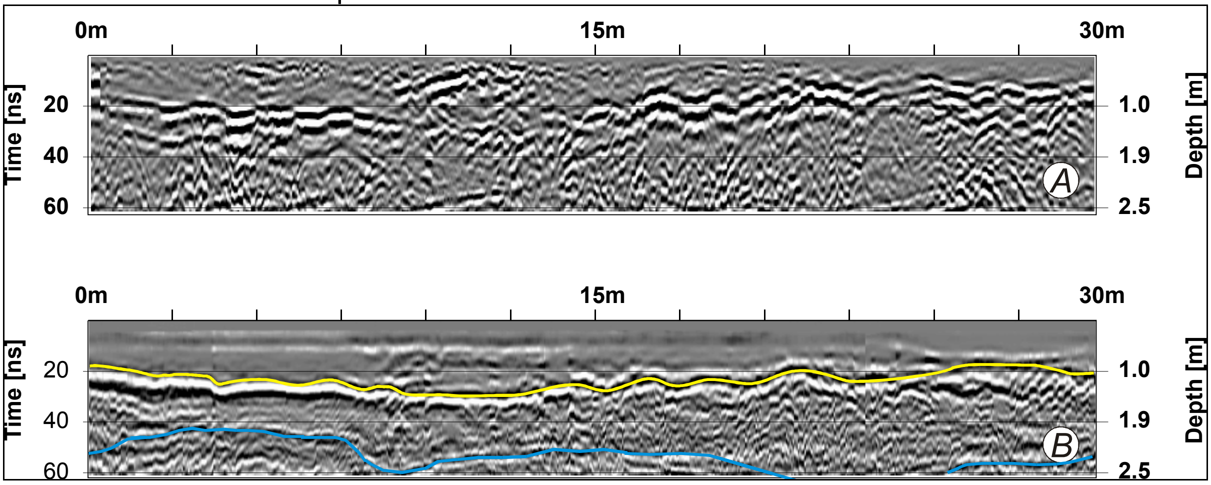
We exploited Multi-channel Analysis of Surface Wave (MASW) [2,5,6] to determine an average vertical shear-wave velocity profile correlated to the stratigraphic sequence at depths exceeding the maximum penetration of radar waves (around 2.5-3 m on the average). The seismic instrument was a 24-channel GEODE – Geometrics. We used the seismic data to define the dispersion curve and proceed in geological interpretation.

The GPR and seismic studies were integrated by a resistivity survey. 12 parallel Wenner pseudosections, spaced 1 m apart, were obtained with a PASI 16G multi-electrode instrument, on the same grid used for GPR acquisition. A 32 equivalent electrodes array with a spacing of 2 m was used in order to get information from a maximum depth of about 15m.

Results and discussion

Multi-fold GPR dataset was first processed with a basic sequence including de-wow, background removal, amplitude analysis and corrections, spectral analysis and high-pass filter. Wavelet Transform Techniques were adopted for the de-wow procedure while maximum entropy deconvolution was applied to pre-stack dip-moveout-corrected gathers in order to enhance vertical and lateral resolution. Pre-stack time and depth imaging was also performed. Instantaneous phase was calculated through Wavelet Transform, which proved to be less sensitive to noise and allowed a better reconstruction of stratigraphy. Post-stack time migration provided satisfactory results in areas characterized by homogeneous shallow materials and limited dip (waste-sediments contact). Migration velocity determination and VRP arrival time analysis allowed velocity field reconstruction and the kinematic characterization of waste materials. Stack GPR profiles are considerably more detailed in comparison with Single Fold ones (Fig. 2). Stack sections allow a clear identification of weathering-waste disposal and waste disposal-silt contacts.

Figure.2: (A) Example of Single Fold 250 MHz processed surface GPR section; (B) Stack section of the same profile shown in (A). In yellow the “weathering-waste disposal” contact and in blue the “waste disposal-silt” one.

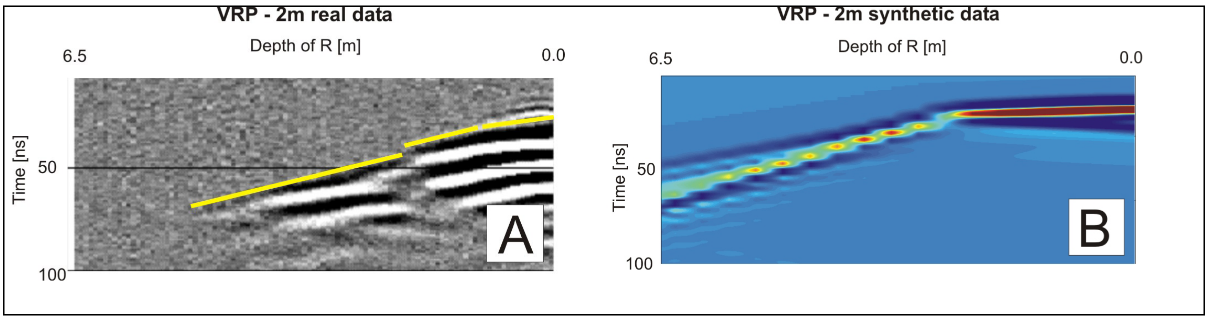


We used laboratory analysis of EM properties, obtained by a network analyser in the range 200-3000 MHz on borehole samples, borehole stratigraphy and surface radar results to build a subsurface model to assist VPR data interpretation. The relevant EM properties (dielectric constant and conductivity) are listed in Tab.1 (we assume that the relative magnetic permeability is constant and equal to 1 for all the materials) together with the parameters of the seismic model (shear-wave velocity, density and layer thickness; Poisson’s ratio equal to 0.4 for unconsolidated sediments and 0.25 for limestone bedrock). A Finite-Difference Time Domain (FDTD) modelling algorithm, (3) was used to calculate the radar wavefield for the VRP experiment. Results (Fig.3) were exploited to interpret the VRP records and to update the subsurface model (4).

Table1: Electromagnetic, elastic and geometric properties for the proposed model.

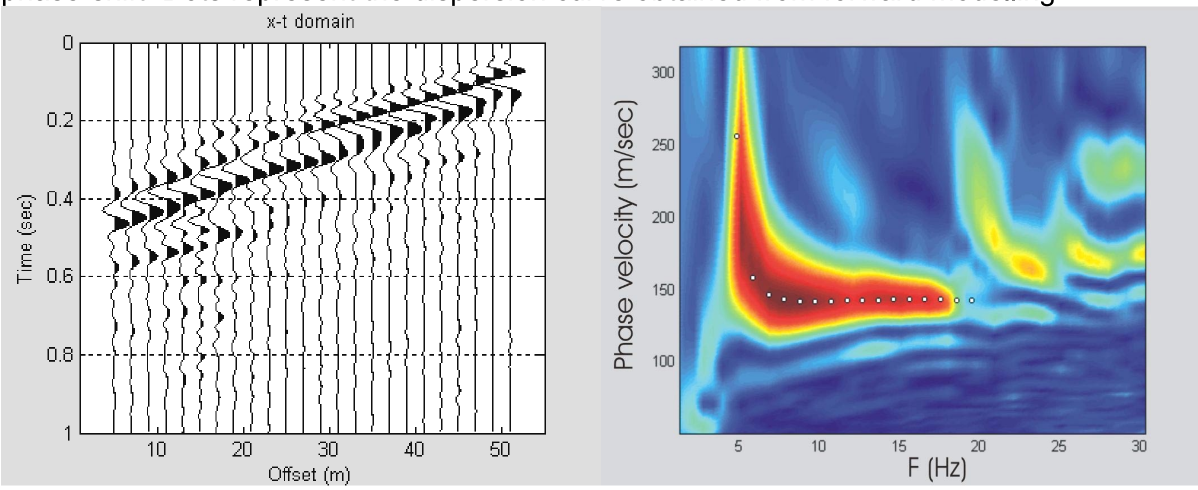
Medium type	ε_r	σ(S/m)	V_s (m/sec)	ρ	h(m)
	GPR		***Seismic Surface waves***		
WATER	81.0	0.8	-	-	
AIR	1.0	0.0	-	-	
WASTE	4.0	0.08	104		1.5
SILT (dry)	6.0	0.05	170	1.7	5.0
SILT/SAND (wet)	25.0	0.5	135		6.5
GRAVEL	30.0	0.2	320	1.8	4.0
LIMESTONE	6.0	0.04	2000	2.4	∞

Figure 3: A) VRP record (100 MHz, maximum offset=2 m); B) synthetic VRP record obtained from FDTD numerical simulation.



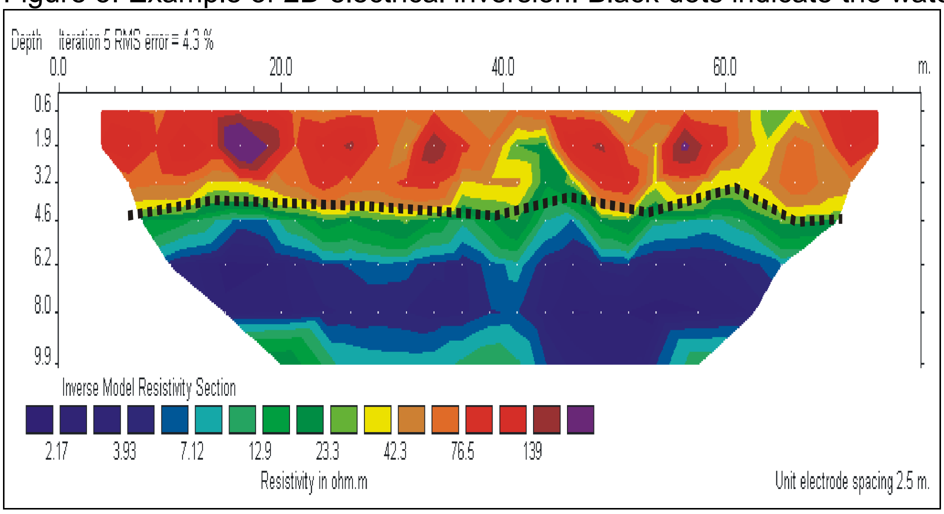
As for the seismic dataset, three phase velocity estimation methods (F-K, Tau-p and phase shift) were tested to evaluate their performances for the considered geological structure and for various data acquisition parameters. Phase shift (5) proved to be the most robust flexible and computationally effective method. Fig.3 shows a Common-Shot Gather and dispersion curve calculated via phase shift. The observed dispersion curve was considered both for inversion and forward modelling. The small “hillock” (local phase velocity maximum) centred around 17 Hz and typical of a velocity inversion in depth, was predictably not well reproduced by inversion algorithms (6) that tend to smooth the curve and loose information content. Forward modelling was thus considered to better fit the observed curve. Fundamental mode phase velocities for the considered model are represented by dots overlapping the observed velocity spectrum in Fig.4. Geological interpretation/correlation (Tab.1) is accomplished by taking into account the stratigraphy of nearby boreholes.

Figure 4: Example of 24-channel Common-Shot Gather and dispersion curve calculated via phase-shift. Dots represent the dispersion curve obtained from forward modelling.



The analysis of resistivity dataset was performed using an inversion technique based on the smoothness-constrained least square method (1). The convergence criterion was the change in RMS error, for which a threshold of 5% was selected. The resulting resistivity models were then examined in 2-D and 3-D for the electrical characterization of the main stratigraphic units and the correlation with the radar datasets. Fig.5 shows an example of 2D electrical inversion. The final model shows vertical and lateral variations of resistivity distribution: a strong decrease of resistivity indicated with dots in fig. 5 represents the water table and high shallow resistivity values (up to 150 Ωm) are related with lateral variations in the waste disposal layer. These features are coherent with GPR and seismic results and were validated by a trench dug in the area.

Figure 5: Example of 2D electrical inversion. Black dots indicate the water table.



Conclusions

In waste disposal areas, where surface GPR single-fold data provided poor results, the multi-fold GPR technique was able to successfully image the uneven weathering-waste (approximately 1.2 m deep in Fig. 2) and waste-silt (around 2-2.5 m deep) contacts validated by borehole samples. Maximum radar wave penetration is around 3 m. Fig. 3 shows real and FDTD modeled VRP data whose parameters are reported in Tab.1 (see [4] for more details). Waste lays on an alluvial sequence composed by silt/sand (dry/wet) and gravel (during GPR acquisitions water table was at 4.0 m from the surface as indicated by resistivity inversion results). Deeper features (top of limestone basement and gravel layer thickness/depth) inferred from Rayleigh wave dispersion analysis were corroborated by borehole stratigraphy. Integrated surface and borehole GPR with seismic and electrical techniques allow a complete stratigraphic reconstruction of soil layers, waste disposal, and deeper geological units.

The geophysical results were first validated by numerical simulation and successively by ground truth, obtained at a trench dug in the area.

Acknowledgments

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References

(1) M.H. Loke and R.D. Barker, Rapid least-square inversion of apparent resistivity pseudosections by a quasi-Newton method, Geophysical Prospecting, **44**, 131-152, (1996)

(2) C. B. Park, R. D Miller and J. Xia, Multi-channel Analysis of Surface Waves, Geophysics, **64**, 800-808, (1999)

(3) Taflove Computational Electrodynamics: the Finite-Difference Time-Domain method, Artech House, (1995).

(4) M. Pipan, E. Forte, G. Dal Moro, M. Sugan & I. Finetti, Integrated Vertical Radar Profiles (VRP) and Multi-Fold GPR for Site Characterization, 2nd International Workshop on Advanced Ground Penetrating Radar (IWAGPR), Delft, The Netherlands, (14-16 May 2003)

(5) C. B. Park, J. Xia and R. D. Miller, Imaging Dispersion Curves of Surface Waves on Multichannel Record, 68th Ann. Internat. Mtg., Soc. Explor. Geophys., New Orleans, USA, Expanded Abstracts, 1377-1380, (1998)

(6) G.J. Rix & C.G. Lai, Elastic, Uncoupled, Fundamental-Mode Surface Wave Inversion Program, matlab code, (2001)

(7) M. Pipan, E. Forte, F. Guangyou, and I. Finetti, Waste Disposal Sites Evaluation by Means of GPR, Session: M-06, 63rd Mtg. of Eur. Assn. of Expl. Geophys., (2001)

(8) R. D Woods (Editor), Geophysical Characterization of Sites, Ashgate Publishing, ISBN 9054102608, (1994)