Session report: Geophysics,1

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ABSTRACT: A large number of papers has been presented in the session devoted to geophysical methods, confirming their consolidated role in site characterization. Different applications and a wide variety of techniques are covered in the contributions with several case histories and some developments on new tools. Crucial issues are also discussed in the present report. For one the reliability, which can be improved with advanced interpretation strategies based on joint inversion of multiple geophysical datasets. The role of guidelines for the execution and interpretation in improving the standard of practice is finally commented.

1 INTRODUCTION

The role of geophysical surveys in site characterization has been growing in the past decades thanks to the relevant improvements in the interpretation processes and to the availability of increasingly powerful hardware at cheaper and cheaper prices. Nevertheless great attention has to be posed as diffusion of geophysical surveys is not always taking place with sufficient quality in the professional practice. A deeper insight on geophysical methods is required not only to service providers but also to the end users, e.g. the professionals making use of the results of geophysical tests for the conception of the geological and the geotechnical model.

The relevance of geophysical methods for site characterization is associated to two different objectives of the investigation:

- Reconstruction of subsurface geometries (layering, inclusions, lateral variability);
- Direct or indirect estimate of physical and mechanical parameters of interest for the geotechnical model.

As the first point is concerned a very wide variety of geophysical methods can provide useful information for the construction of 2D-3D subsurface models. A recent overview is provided by Malehmir et al. (2016). Crucial points are the sensitivity of the specific geophysical parameter to the expected variation in the subsoil and the resolution with depth, considering that most geophysical tests are run from the ground surface.

As for the second objective, seismic methods traditionally play a major role as the geophysical parameters (i.e. the seismic velocities) are directly related to elastic parameters, which are of direct use in geotechnical models as they represent the mechanical response of the medium in the low strain region. Other geophysical parameters can be related to parameters of interest for the geotechnical model (e.g. the soil porosity), but only with the adoption of empirical rock physic relations.

The growing interest in geophysical prospecting for near-surface geotechnical and geoenvironmental applications is testified by the number of papers presented in the different editions of this series of International conferences on Site Characterization (ISC), which has been initiated in 1998 in Atlanta (USA) and has now reached its 5th edition in Gold Coast (Australia).

The large number of papers submitted for the ISC'5 conference has led to the decision of splitting the theme of Geophysical Methods in two different sessions, one of which is reviewed and commented in the present contribution. Most papers in this session are related to non-seismic methods, nevertheless to account for the importance of seismic methods in geotechnical site characterization, part of the paper will be devoted to the latter.

The paper is organized as follows, after a general overview of the topics covered by the papers presented in the session, some issue related to reliability of geophysical methods and a review of existing guidelines are reported.

2 GENERAL OVERVIEW

Most papers in the session are devoted to the identification of stratigraphic features, which is attempted with a variety of techniques. In some situations different techniques are used at the same site (e.g. Pfaffhuber et al. 2016, Bazin et al. 2016), but the level of coupling between different methods is usually weak: the final results are compared in order to assess from a qualitative/quantitative point of view the reliability of the results. Joint inversion schemes could provide a much significant synergy between different methods, as discussed in the next section. Similarly, stratigraphic information from boreholes and direct push methods could be used as additional constraints in the inversion process in order to get robust estimates and reliable soil models. In fact, in most projects the stratigraphic information is just used a posteriori for double-checking the results obtained with geophysical test or for calibration (e.g. to identify the stratigraphic features associated to the estimated geophysical model).

When dealing with the identification of the stratigraphic sequence, it is important to recognize the inherent nature of the data that are presented. 2D models are most often reconstructed with tomographic techniques (Reynolds 1997), in which a single inversion problem is solved using all the available experimental data. A notable exception is constituted by MASW profiling (e.g. Cox 2016) in which the 2D distribution of the geophysical parameter (V_S) is obtained from a collection of 1D profiles that are interpolated to provide a pseudo-2D section. The main implication is that with this approach the inverse problem is typically solved as a collection of individual 1D inversions. Considering the ill-posedness of inverse problems (see next section), such an approach may lead to instabilities of the results. A possible countermeasure is to impose a lateral constraint on each 1D profile (Figure 1) in order to solve a single better-posed inverse problem (Auken and Christiansen 2004, Wisen and Christiansen 2005, Socco et al. 2009).

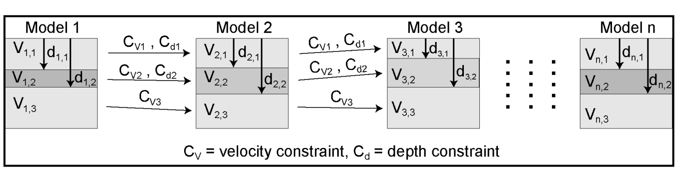

Figure 1. Laterally Constrained Inversion (LCI) scheme: adjacent 1D model are linked by constraints on the model parameters to be resolved (velocity of each layer and interface depths in this example) (modified after Wisen and Christiansen, 2004)

Several papers in the session deal with the identification of underground voids, which is a typical application of geophysical tests in engineering projects. In particular, ERT (Abduljauwad et al. 2016, Porres-Benito et al. 2016), GPR (Hughes et al. 2016) or a combination of the two (Jafarzadeh et al. 2016) are adopted.

GPR is also proposed as a tool for the evaluation of lateral variability in the context of foundation engineering (Hebsur et al. 2016) and of slope stability (Bednarczyk 2016). Although some features are identified, the interpretation is not always straightforward and the association of the observed discontinuities in radargrams to specific stratigraphic conditions requires an expert interpretation procedure.

A few papers are dealing with penetrating probes equipped for geophysical measurements, either of electrical resistivity (Bazin et al. 2016, Fuiji et al. 2016) or seismic velocities (Amoroso et al. 2016). These approaches are very promising as they provide improved capabilities for the identifications of layers with respect to conventional penetration testing. Apart for being used as standalone tools, such probes could provide very useful information for the calibration and verification of ground surface geophysical measurements. A significant advancement would be gained by including these data in joint inversion algorithms to constrain the solution of tomographic 2D reconstructions.

Two papers in the session are focused on the comparison of laboratory and field data (Bazin et al. 2016, Campbell 2016). This aspect is very relevant and more and more studies should be devoted to it in the future. Indeed the investigation of geophysical properties of soils and rocks under controlled conditions in the lab may help in the definition of general and site-specific correlations with geotechnical parameters. These are the prerequisite for a quantitative use of geophysical parameters for the conception of the geotechnical model.

Campbell (2016) presented a statistical analysis of shear wave velocities measured in soils and rocks to assess the influence of different material parameters. Several other authors have dealt in the past with the relationship between in situ and laboratory measurements of seismic wave velocity. Indeed two counteracting main factors have to be taken into account: namely sampling disturbance and scale effects. The effect of the former is typically a reduction of the measured shear wave velocity on laboratory sample as the original fabric and the structure of the material are damaged by sampling operation, even in virtually undisturbed sampling. This effect is typically prevalent in soils. Stokoe and Santamarina (2000) showed that the effect of sample disturbance is more important for stiffer soils. The comparison of laboratory and in situ shear wave velocity can hence be used as a proxy for the evaluation of sample quality (Jamiolkowski, 2012). In rocks, the scale effect is usually prevalent as laboratory measurements are conducted on intact cores and not affected by the fractures of the rock mass. Therefore typically a higher velocity is obtained on laboratory samples than on site. Musso et al. (2015) exploited this property to develop a procedure aimed at quantitatively define the representativeness of rock samples for the construction of the geomechanical model.

Bazin et al. (2016) deal with the comparison of in situ and laboratory values of both seismic velocities and electrical resistivity in soils. In particular they have used the combination of the different parameters in order to identify quick clay layers. Combination of seismic and electrical measurements could indeed be pursued at higher levels of integration by using seismo-electrical models (e.g. Mota and Monteiro Santos, 2010). Cosentini and Foti (2014) reported an example of the combined use of measured seismic wave velocities and electrical resistivity in unsaturated soils to infer soil porosity and degree of saturation.

3 RELIABILITY OF GEOPHYSICAL SURVEYS

A crucial issue in geophysical methods is related to the reliability of the reconstruction of the ground model. Indeed most geophysical tests are based on the solution of inverse problems which are inherently ill-posed and ill-conditioned, according to the Hadamard (1902) definition. The main consequence is solution non-uniqueness, i.e. several different geophysical models may honour equally well the available experimental data that are used to constrain the solution. Possible countermeasures to mitigate solution non-uniqueness are:

1) the inclusion of a-priori information on the ground model to better constrain the solution (Tarantola, 1987);
2) the adoption of joint inversion schemes in which different experimental datasets are simultaneously inverted (Vozoff and Jupp 1975).

Several examples are reported in the literature where different geophysical dataset are jointly inverted with a significant improvement in the reliability when compared to individual inversion of each dataset (Dobroka et al. 1991, Comina et al. 2002, Dal Moro 2008, Doetsch et al. 2010, Gao et al. 2010, Piatti et al. 2013). Typically the combination of the datasets is obtained with a structural merging of the different geophysical model, i.e. by assuming the same geometry for the subsoil models (Haber and Oldenburg 1997, Hu et al. 2009). A stronger link can be devised by adding a link between geophysical parameters (Eberhart-Phillips et al. 1989, Dell'Aversana et al. 2011, Gao et al. 2011). For example, Garofalo (2014) proposed a joint inversion scheme in which the soil porosity links the geoelectrical model to the seismic model. In particular Archie's relation (Archie 1942) is used to express the soil resistivity as a function of porosity, whereas the formula proposed by Foti et al. (2002) on the basis of Biot's theory (Biot, 1956a-b) for wave propagation in saturated porous media is used to express soil porosity as a function of wave velocities. Considering that the two models (seismic and electrical) are expected to share the same porosities, a further constraint is introduced in the inversion process (Figure 2).

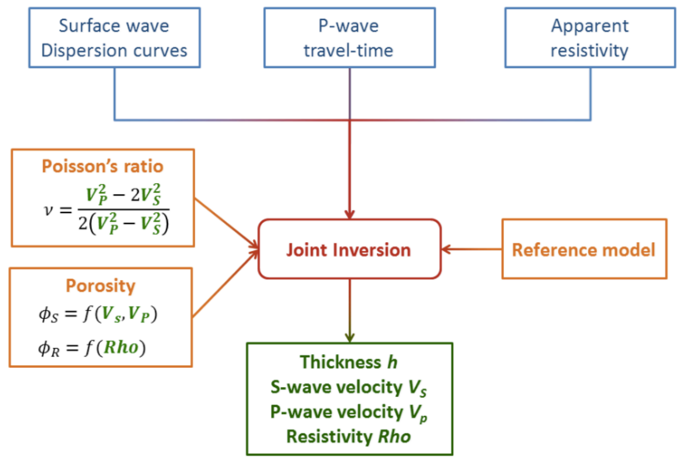

Figure 2. Example of joint inversion scheme in which the experimental data from different geophysical datasets (surface wave analysis, P-wave refraction and vertical electrical soundings) are simultaneous inverted with the addition of physical constraint between model parameter to retrieve a robust seismo-electrical model of the site (Garofalo, 2014)

However it is observed that in the case histories presented at the ISC'5 conference little attention has been posed to this aspect. Indeed most of the interpretations are based on the use of available commercial software, which are typically specialized on the processing and interpretation of a single technique dataset. The use of multiple methods is confined to a low level of integration in which the final results are visually compared to check the consistency of observed features in geophysical models from different techniques.

In this respect, the state of the practice of geophysical applications, as demonstrate by the contributions presented in the geophysical session at ISC'5, is a step behind the state of the art of the research in geophysics.

For the future it is desirable that this gap is filled. The technical community should adopt joint inversion schemes more frequently as they offer the possibility to improve significantly the reliability of the ground models retrieved by geophysical methods. In this respect, it is necessary that commercial codes are expanded and improved to allow the analysis of multiple datasets from a variety of methods.

Another relevant issue for the reliability of geophysical tests is related to the repeatability and reproducibility of the results. Indeed the reliability can be described as the combination of accuracy (i.e. the ability to get the true value of the parameter) and precision (i.e. the ability to get the same result when repeating the measurement).

Attempt to study accuracy of the solution typically faces the difficulty of dealing with unknown targets, as the focus of the characterization is indeed on natural materials (soils and rocks). For this reason, quite often synthetic datasets obtained from numerical simulations are used to check the accuracy of inversion algorithms. Such approach is obviously limited in scope as it is not able to account for the inherent uncertainties associated to the measurement process. Other possible approaches are based on small scale experiments on physical models. For example the paper by Porres-Benito et al. (2016) at ISC'5 reports an experiment on scaled model aimed at representing the presence of voids. In this case the potential of ERT are clearly shown. Nevertheless, as in several similar applications, the performance are not explicitly quantified and the accuracy is only estimated from visual inspection. A typical limitation in terms of the capability of reconstructing sharp boundaries is observed. This is common to most tomographic inversion process as regularization criteria are imposed to improve the stability of the solution (e.g Tikhonov and Arsenin, 1977). Borsic et al. (2005) and Comina et al. (2008) report experiments at laboratory scale, showing that under controlled boundary conditions it is possible to reach a good accuracy. As for seismic techniques, experiments on scaled model are reported by Bodet et al. (2005) and Bergamo et al. (2014), showing the possibility to obtain not only geometrical features of the deposit, but also quantitative information of the 2D shear wave velocity model.

As mentioned above the other side of reliability is represented by the precision. An assessment of the repeatability requires repeated of measurements in the same configuration. Examples for cross-hole tests are reported in Callerio et al. (2013), whose results have been subsequently used by Passeri and Foti (2016) to assess the reliability of porosity estimate from seismic wave velocities. The observed uncertainty on the field data can be projected into an estimate of uncertainties on the estimated model parameters, by using error propagation techniques (Tarantola 1987, Taylor 1997). Examples for shear wave velocity obtained from surface wave inversion are reported by Lai et al., 2005.

In more general terms, the whole chain of experimental data collection and interpretation affects precision and accuracy. In this respect the results obtained in round robin tests in which different operators are asked to perform measurements at the same test site may provide valuable information on reliability. Several blind tests have been performed in the past, especially with respect to seismic methods (e.g. Brown et al. 2002, Xia et al. 2002, Jung et al. 2012). Kim et al. (2013) report a comparison at a shallow bedrock site where several in-hole and surface measurements where adopted for the characterization of the shallow sediments. More recently, during the Interpacific Project the performance of different seismic techniques have been compared at three test sites in France and Italy (Garofalo et al., 2016a,b). The sites cover a variety of geological conditions ranging from rock outcrop to soft alluvial sediments. In particular, the focus was on the evaluation of the shear wave velocity profile under the assumption of horizontally layered media. Results from surface wave methods (with active and passive measurements) have been compared to different invasive methods (Cross-Hole Test, Down Hole Test, P-S suspension logging, Seismic dilatometer SDMT). The main findings can be summarized as follows:

- invasive methods provide an higher vertical resolution, with the possibility to identify stratigraphical details also at large depth;
- although invasive methods are often considered more reliable than surface methods, the observed variability in the results is comparable. This uncertainty should therefore be taken into account when the results are used for modeling;
- for average parameters, such as the $V_{S,30}$ often adopted for site classification in seismic codes, very similar results are obtained from surface wave analysis and invasive methods, both in terms of mean values and of associated variability;
- observed variability in surface wave test results is mainly due to non-uniqueness of the solution of the problem, whereas the estimated experimental dispersion curves show very limited variability. This variability could be reduced with the inclusion of a-priori information, often available from other surveys (e.g. stratigraphic information from boreholes).

4 TESTING STANDARDS AND GUIDELINES

The fast and wide diffusion of geophysical tests has lead to the necessity of technical references that can help in homogenizing the quality and the significance of these surveys. Testing standards (e.g. by ASTM, American Society of Testing Materials) are available for several geophysical methods. They can be imposed for quality assurance. However, for some geophysical methods the interpretation process is hard to standardize as it can be successfully performed with different strategies. This is for example the case for surface wave analysis, which can be implemented with a large variety of tools (see Socco et al. 2010 and Foti et al 2011 for literature reviews).

Moreover, testing standards are of little help for a full understanding of potentiality and limitations of each technique.

For a correct planning of a geophysical survey, the first essential step is the choice of the right technique according to the target of the project. Multidisciplinary cooperation is therefore necessary since the first stages of the project.

Recently the technical community has developed some guidelines for geophysical testing (e.g. Butcher et al., 2005 for down-hole tests). These may fill the gap between textbooks and testing standards or replace the latter, when they are not available for a given method.

The Geological Survey of Canada, issued a guideline for site characterization in terms of shear wave velocity, covering most invasive and non-invasive seismic tests (Hunter and Crow 2012). The Canadian guidelines also include brief coverage of other geophysical techniques that provide complementary information to improve the characterization and the interpretation of seismic tests (Electromagnetic methods, Resistivity methods, Ground penetrating radar, Microgravimetric surveys).

Guidelines for the execution and interpretation of single-station passive measurements with the Horizontal-to-Vertical Spectral Ratio (HVSR) technique, also known as Nakamura method, are provided by SESAME (2004).

Guidelines for 1D V_S profiling with surface wave analysis have been developed within the previously mentioned Interpacific project (Foti et al., 2016). These guidelines cover both active (MASW – Multistation Analysis of Surface Waves) and passive (AVA – Ambient Vibration Analysis) methods providing the key elements for the planning and interpretation. The guidelines are addressed specifically to non-expert users, but may constitute a reference for professionals and researchers involved in the field at different levels. The theoretical background is reported in textbooks (Okada 2003, Foti et al. 2014).

Recently COSMOS (Consortium of Organizations for Strong-Motion Observation Systems) has launched an international effort for the development of thorough guidelines covering a variety of seismic methods for site characterization (Yong et al., 2016), focusing on methods from the ground surface.

5 CONCLUSIONS

The role of geophysical tests in site characterization is progressively increasing in the years, as reflected in the proceedings of the series of International Conferences on Geotechnical and Geophysical Site Characterization. Several issues deserve further efforts in research and development:

- Reliability, with the quantification of expected accuracy and precision. Model tests and blind tests are desirable to collect more data on these two issues respectively;
- interaction with lab tests can provide significant synergies that are worth to be exploited more systematically;
- development of joint interpretation at the highest possible level to improve the reliability of the geophysical model that is then reflected on the geotechnical model of the site;
- formulation of shared guidelines that can help in improving the quality of geophysical services.

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