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InterPACIFIC project: Comparison of invasive and non-invasive methods for seismic site characterization. Part II: Inter-comparison between surface-wave and borehole methods

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ABSTRACT

The InterPACIFIC project was aimed at assessing the reliability, resolution, and variability of geophysical methods in estimating the shear-wave velocity profile for seismic ground response analyses. Three different subsoil conditions, which can be broadly defined as soft-soil, stiff-soil, and hard-rock, were investigated. At each site, several participants performed and interpreted invasive measurements of shear wave velocity (*Vs*) and compression wave velocity (*Vp*) in the same boreholes. Additionally, participants in the project analysed a common surface-wave dataset using their preferred strategies for processing and inversion to obtain *Vs* profiles. The most significant difference between the invasive borehole methods and non-invasive surface wave methods is related to resolution of thin layers and abrupt contrasts, which is inherently better for invasive methods. However, similar variability is observed in the estimated invasive and non-invasive *Vs* profiles, underscoring the need to account for such uncertainty in site response studies. $V_{S,30}$ estimates are comparable between invasive and non-invasive methods, confirming that the higher resolution provided by invasive methods is quite irrelevant for computing this parameter.

1. Introduction

The assessment of reliability of experimental techniques typically requires an investigation of their accuracy (ability to obtain the true target value) and precision (repeatability). Most often the number of repetitions of a measurement at a site are not sufficient for an estimation of precision. With regards to accuracy, the "true" value of the measured quantity is unknown for natural systems.

The shear-wave velocity (V_S) profile is typically obtained using either in-hole seismic measurements (referred to herein as invasive methods) or ground surface measurements such as surface-wave methods (referred to herein as non-invasive methods). Because of budget restrictions in typical site-characterization projects, only a single technique and a single realization of the test are generally available. It is therefore quite difficult in practice to estimate the "true" uncertainty in a parameter which has a significant influence on seismic site response analyses.

For invasive methods, the measurement is performed inside the medium. This strategy poses the issue of placing the source and/or the receiver into the ground. This is usually achieved by drilling a hole in which the instruments are placed. Nevertheless, other strategies can be used to place instruments into the ground, avoiding the necessity of drilling a hole. This is the case for the Seismic Cone Test and the Seismic Dilatometer Test, in which the receivers are driven into the ground by pushing a rod. Among invasive methods, the Cross-Hole Test is widely considered the most reliable as the measurements are performed locally at any specific depth along short travel paths. However, a comparative study by Jung et al. [1] showed that Cross-Hole results are very

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close to those of other invasive methods. Because they are based on local measurements at multiple depths, invasive methods exhibit minimal decreases in resolution with increasing depth (within limits of investigation depth associated to the equipment). For this reason they are commonly considered more reliable than non-invasive methods and their results are often considered as benchmark values.

Non-invasive methods are based on measurements performed along a single boundary of the medium (i.e., the ground surface). Their main advantage is that the sources and receivers do not need to penetrate the medium. On the other hand, measuring along a single boundary leads to a decreasing resolution with increasing distance from the ground surface (i.e., with depth). Surface-wave methods have become quite popular to evaluate the V_S model not only because they are time and cost effective, but also because they can be applied to a variety of ground conditions [2]. A major criticism of surface wave methods is that the surface-wave inverse problem is strongly non-linear and affected by solution non-uniqueness [3]. This leads to interpretation ambiguities since several possible V_S profiles are solutions to the inverse problem [4].

Since early 2000's, when surface-wave methods became popular in near-surface geophysics and geotechnical engineering, several researchers have compared surface-wave analysis results with borehole measurements to validate the technique (e.g. [5–10]). In recent years systematic comparative studies between invasive and surface-wave methods have been produced. The Institute of Geological and Nuclear Sciences (New Zealand) sponsored a blind trial of ambient noise versus cone penetrometer and seismic refraction data in glacial sediments near Wellington harbor [11]. Boore and Asten [12] reported a similar study for two sites in California with constantly increasing velocity with depth. However, all six sites in this blind test, which are in the Santa Clara Valley, California, are quite similar to each other and lack strong gradients in subsoil stiffness. Brown et al. [7] compared V_S profiles inferred from surface-wave methods and in-hole measurements at 10 sites, but only a single determination was available for each technique. A study with multiple realizations of surface-wave and borehole methods was proposed by Kim et al. [13], however, only a single site was investigated and hence the study was related only to a specific subsoil condition (shallow bedrock at 15-m depth).

The main scope of the InterPACIFIC InterPACIFIC (Intercomparison of methods for site parameter and velocity profile characterization) project is to assess the reliability/variability of seismic site characterization methods (in-hole and surface-wave methods) for estimating the shear-wave velocity profile. A series of blind tests has been organized in which several participants performed both invasive and non-invasive techniques at each sites without any a-priori information about the site. In contrast to aforementioned comparative studies, three different subsoil conditions were selected as test sites: a soft-soil, a stiff-soil and a hard-rock sites. In this paper the results from the invasive methods are first compared in order to assess the intra-method variability (i.e., the variability among the results obtained by different participants using a single in-hole method, or the repeatability of the test) as well as the inter-method variability (i.e., the variability among the results obtained for various in-hole tests). Next, the results of the surface-wave methods (discussed in the companion paper [14]) are compared with the in-hole results. When comparing invasive and non-invasive methods, it is important to note that the results from invasive methods refer only to the soil column immediately around the borehole(s), while the results from surface-wave methods are representative of the whole volume underling the array(s). Thus, differences in Vs are expected between the two classes of methods simply based on the "sampling" of different volumes of a vertical and lateral heterogeneous material.

The test sites considered in this study are: Mirandola (MIR) in Italy ("soft soil" class); Grenoble (GRE) in France ("stiff-soil" class); and Cadarache (CAD) in France ("hard-rock" class). At each site, at least two boreholes were available to perform the in-hole measurements. Both active and passive surface-wave data were collected with arrays in the vicinity of the boreholes to achieve a meaningful comparison between the results from invasive and non-invasive methods. Different teams of engineers, geophysicists and seismologists, were invited to take part in the project. In order to ensure that each participant performed a blind test, the same experimental non-invasive datasets were provided to all of the teams with very little information about the sites [14]. For the invasive methods, different companies repeated the measurements in order to assess the repeatability with different acquisition strategies and equipment.

2. Test-sites

Mirandola is located in the Po river plain, Italy. The Secchia river, a stream of the Po river, flows north-south on the west side of the site. The area was affected by a couple of strong earthquakes in May 2012 [15]. The station of the Italian Accelerometric Network placed in Mirandola provided strong-motion records in the vicinity of the epicenter for both shocks. For this reason, Emilia-Romagna authority planned a specific site investigation. Specifically, two boreholes placed 6.8 m from each other were drilled to a depth of 125 m. A simplified stratigraphic log is reported in Fig. 1. The site is characterized mainly by alluvial deposits with alternating sequences of silty-clayey layers of alluvial plain and sandy horizons. The geological substratum (i.e., "bedrock") consists of marine and transitional deposits of lower-middle Pleistocene age and it was found at a depth of 118 m in the borehole. The water table was detected at a depth of approximately 4-m.

The Grenoble site is located in the French Alps (the southeast region of France) in the vicinity of the "Institut Laue Langevin" nuclear research facility. The site is flat and is characterized by recent alluvial deposits (mainly sands and gravels) on a Quaternary lacustrine clayey/marly deposit, overlaying a Mesozoic bedrock. The expected depth of the contact between the alluvial

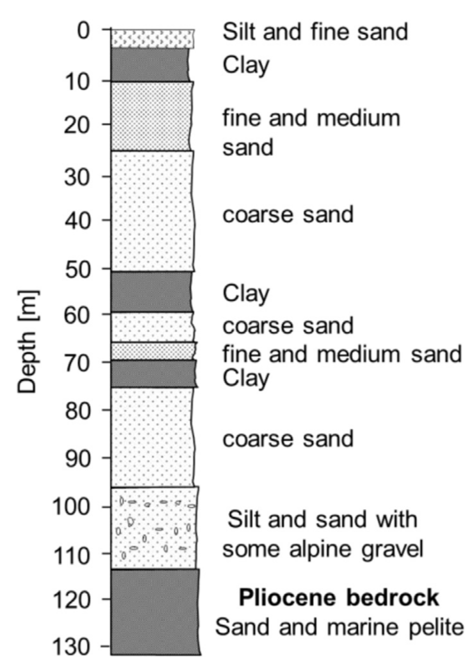

Fig. 1. Soil stratigraphy at Mirandola site (MIR).