Science of the Total Environment 578 (2017) 186–202

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Insights into bedrock surface morphology using low-cost passive seismic surveys and integrated geostatistical analysis

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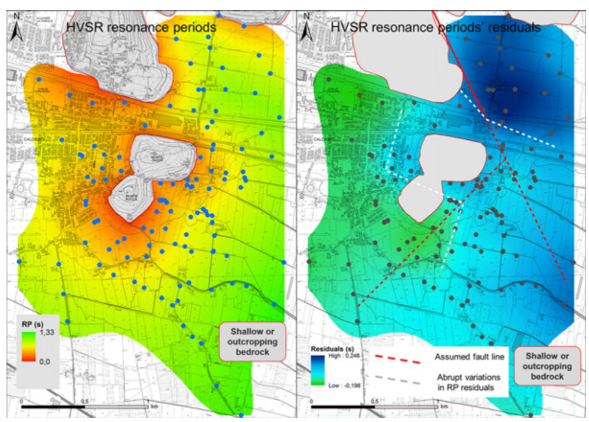
HIGHLIGHTS

- The increase in available geo-environmental data requires ad-hoc data analysis techniques.
- We perform a geostatistical analysis of 116 HVSR single station measurements.
- The trend/residual decomposition permits to gain insight into the bedrock morphology.
- The interpolation approach uses auxiliary information for improved mapping.
- The potential heteroscedasticity of HVSR resonance frequencies should be considered.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 17 August 2016
Received in revised form 6 November 2016
Accepted 6 November 2016
Available online 15 November 2016

Keywords:
Data integration
Bedrock morphology
HVSR
Kriging
Mapping
Seismic microzonation

ABSTRACT

The HVSR (Horizontal to Vertical Spectral Ratio) technique is very popular in the context of seismic microzonation and for the mapping of shallow seismic reflectors, such as the sediment/bedrock transition surface. This easy-to-deploy single station passive seismic technique permits the collection of a considerable amount of HVSR data in a cost-effective way. It is not surprising that some recent studies have adopted single station micro-tremor analyses in order to retrieve information on geological structures in 1D, 2D or even 3D reconstructions. However, the interpolation approaches followed in these studies for extending the punctual HVSR data spatially are not supported by a detailed spatial statistical analysis. Conversely, in order to exploit the informative content and quantify the related uncertainty of HVSR data it is necessary to utilize a deep spatial statistical analysis and objective interpolation approaches. Moreover, the interpolation approach should make it possible to use expert knowledge and auxiliary information. Accordingly, we present an integrated geostatistical approach applied to HVSR data, collected for retrieving information on the morphology of a buried bedrock surface. The geostatistical study is conducted on an experimental dataset of 116 HVSR data collected in a small thermal basin located in the Venetian Plain (Caldiero Basin, N-E Italy). The explorative geostatistical analysis of the data coupled with the use of interpolation kriging techniques permit the extraction of relevant information on the resonance properties of the subsoil. The utilized approach, based on kriging with external drift (or its extension, i.e. regression kriging), permits the researcher to take into account auxiliary information, evaluate the related

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http://dx.doi.org/10.1016/j.scitotenv.2016.11.041

prediction uncertainty, and highlight abrupt variations in subsoil resonance frequencies. The results of the analysis are discussed, also with reflections pertaining to the geo-engineering and geo-environmental context.

1. Introduction

Constant urban sprawl is an almost global process inducing an increase in the interactions between geo-environmental and anthropic processes. At the same time, the extensive characterization of the geo-environmental factors and processes that typify urbanized areas is of utmost importance. Consequently, the flourishing of new methodologies and technologies for the geo-environmental and geo-engineering characterization of territories is not surprising (e.g., van der Meer et al., 2012; Hansen and Stone, 2015; Avila et al. 2016; Benjumea, B. et al., 2016; Jayawickreme et al., 2014). This, however, corresponds to an exponential increase in available geo-environmental data, which, in turn, require the adoption of ad-hoc technologies (e.g., geographical information systems, GIS) and data analysis techniques (e.g., Goovaerts, 1997; Kanevsky and Maignan, 2004; Fabbri and Trevisani, 2005a; Trevisani and Fabbri, 2010; Dell'Aversana, 2013; Holden et al., 2016; Kashani et al., 2016).

In this context, the use of single station ambient noise recordings (Bonnefoy-Claudet et al. 2006; Bonnefoy-Claudet et al. 2008) at the base of the horizontal to vertical Fourier amplitude spectral ratio (HVSR, Nogoshi and Igarashi, 1970) technique, is emblematic. HVSR technique is very popular in the context of seismic microzonation (Nakamura, 1989) and for the mapping of evident seismic reflectors, such as the sediment/bedrock transition (Ibs Von Seht and Wohlenberg, 1999). In fact, HVSR measurements, permitting the evaluation of soil resonance frequencies, can be correlated with the depth of the bedrock-sediment transition surface (Field and Jacob, 1993). This low cost and easy-to-deploy technique makes it feasible to collect a considerable amount of HVSR data. Consequently, the spatial analysis of a set of HSVR measurements can provide information on the morphology of bedrock-sediment transition, which can be very useful for geo-structural interpretation and in the context of geo-engineering and geo-environmental issues. Some recent works derive HVSR frequency related maps for geological reconstruction purposes or seismic microzonation by means of interpolation of punctual HVSR measurements (Gosar, 2007; D'Amico et al., 2008; Pilz et al., 2010; Nardone et al., 2011; Agostini et al., 2015; Benjumea et al., 2016) or of derived parameters (e.g., shear waves velocity and bedrock depth). However, in these works the discussion on the spatial statistical characteristics of data is missing or very concise and few details on the interpolation approaches adopted are reported (e.g., Gosar, 2007; D'Amico et al., 2008; Pilz et al., 2010). Moreover, deterministic interpolation approaches such as inverse distance methods (Isaaks and Srivastava, 1989) and natural neighbor method (NN, Watson, 1999) are often used. For example, NN method is used by Agostini et al. (2015) for interpolating HVSR frequencies and by Benjumea et al. (2016), for interpolating sediment cover thickness derived by HVSR frequencies. NN is a good interpolation approach for preliminary analysis, given that it is free from user-defined parameters and it can take into account data clustering and the distance of data from the interpolation point. Nevertheless, NN is a completely deterministic approach, and the interpolation weighting scheme relies exclusively on the spatial sampling geometry of the data, without any connection with the data spatial-statistical structure. A very different perspective is considered within the geostatistical methodology (Isaaks and Srivastava, 1989), where the interpolation is conducted objectively, taking explicitly into account the spatial statistical structure of the data. It is emblematic, from this viewpoint, that Gandin's interpolation approach (Gandin, 1965), with many analogies to kriging geostatistical algorithm (Herzfeld, 1996), is named "objective analysis".

Geostatistical approaches based on spatial continuity analysis and kriging interpolators (e.g., Goovaerts, 1997) provide an effective and well-known spatial statistical framework. The geostatistical tools promote and require an integrated analysis of the available data, by means of a reciprocal interaction between statistical analysis and expert knowledge. Moreover, geostatistical tools permit the integrated use of auxiliary/secondary information (e.g., Hudson and Wackernagel, 1994; Hengl et al., 2007), related to the primary variable of interest, by means of appropriate interpolation algorithms. Finally, geostatistical algorithms permit the production of maps of the interpolated spatial property together with an evaluation of their uncertainty (variance) and cross-validation statistics.

In this study, we perform a geostatistical analysis of 116 HVSR single station measurements related to a geothermal basin located in the Caldiero thermal basin, NE Italy (Agostini et al., 2015). The main aim is to gain insight into the bedrock morphology, in order to potentially exploit this information for the identification of priority zones where further geological and geophysical studies may be conducted, with the final objective of developing the local low enthalpy geothermal reservoir.

The case study presented is particularly well suited to highlight the benefits of a careful geostatistical analysis of HVSR data for geo-structural interpretation. First of all, various deep boreholes have been conducted in the area for groundwater geothermal exploitation together with various geophysical surveys, furnishing a good general knowledge of the studied area. Then, the sharp impedance contrast between the loose sedimentary cover and the bedrock facilitates the interpretation of HVSR measurements (Castellaro and Mulargia, 2009), given the presence of well-defined HVSR peaks (for more details in the studied area see Agostini et al., 2015). Moreover, the geo-structural conformation of the area, with bedrock outcropping in correspondence to the hills and deepening with the increase in distance from the foothills, is well suited for highlighting interesting aspects of the spatial statistical structure of HVSR data. In fact, in this setting, the peculiar spatial statistical properties of HVSR data are evident and it is possible to show how the interpolation of HVSR data can benefit from the use of secondary information.

2. Study site and geological framework

The studied thermal district of Caldiero covers an area of about 10 km^2, located in the North-Eastern part of Italy, between the Adige River to the south and the Lessinean Hills to the north (Fig. 1). The site was known in ancient Roman times as 'Calidarium', stemming from the thermal baths located there starting from the 4th century B.C. The hot springs are still active nowadays and have an important economic value related to the use of the thermal waters for therapeutic purposes and bathing.

The lithostratigraphic succession of the Caldiero district (Fig. 1) includes sedimentary formations ranging from Upper Cretaceous marly limestones to Eocene nummulitic limestone interspersed with Paleogene basalts (see Agostini et al., 2015 for more details). The structural setting of the site is the result of crustal events that took place in the context of the Alpine orogeny compressive phase, and has a tabular structure slightly arched, with strata dipping toward S-SW (Sighinolfi et al., 1982; Sorbini et al., 1984; Cantelli and Castellarin, 1994). The geological and geophysical surveys conducted in the area have allowed the identification of some fault lines in correspondence to the hilly relief