Combining active and passive methods to understand the seismic velocity distribution in a thick Quaternary succession of the Po Plain. (Terre del Reno, Ferrara, Italy)

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Introduction

To properly evaluate the local effects of earthquakes and improves the seismic profiles inversion, a good knowledge of the seismic velocity depth distribution is needed. Acquiring such a distribution is however a challenging issue in fast-subsiding alluvial sedimentary basins, with thick unlithified, low-velocity successions, and reduced seismic impedance contrasts, as in the Po Plain (Mascandola *et al*., 2021). Passive acquisition techniques, based on stand-alone stations and focused on the estimation of resonance frequency, can provide only raw information on the local velocity profile and are not particularly effective, by themselves, in areas as the lower Po Plain. Their proper interpretation needs independent stratigraphic data on the subsurface. Other passive techniques, based on array configurations of seismic stations, with varying geometries and apertures, increase the frequency band of analysis. Recent technology improvements and the advances in the array processing of three-component ambient-vibration recording further constrains the inversion process, generating a reliable shear-wave velocity profile, and supporting the extraction of the Rayleigh-wave ellipticity (Whatelet *et al*., 2018). HVSR and array methods however produce the most reliable results only in presence of sharp seismic contrasts, developed at a relatively shallow depth (approximately < 200 m), which is not the case of the study area. An effective approach to the reconstruction of deep velocity profiles, in similar sedimentary basins, consists in the combination of passive and active methods. Downhole and seismic reflection prospecting can provide reliable S and P velocity profiles. Petronio *et al*. (2023) shows an example of a successful application of such active methods in a case study from the Po Plain area, about 25 km west to our investigation site. The authors derived shear-wave (Vs) and compressional (Vp) velocity tomography models down to a depth of about 300 and 700 m respectively; Vs never exceed 600 m/s. Our study combines multiple geophysical techniques to define the seismic wave propagation model in a site at the south-west of Ferrara, near San Carlo (Fig. 1A), affected by the 2012 earthquakes. We acquired one of the deepest down-hole measurements so far available in the Po Plain, providing a rare opportunity to calibrate the velocity models produced by surface geophysical investigations. The Quaternary succession was drilled to the depth of almost 400 m, cuttings were analysed, and a continuous spontaneous emission gamma log was measured. Accurate down-hole velocity measurements of both V_P and V_S were acquired, from the surface to the depth of 370 m, providing results in good match with a previous investigation, which was limited in depth (Minarelli *et al*. 2016). The down-hole recordings were compared with the results of the vertical seismic profile and of surface investigation we performed on site, consisting of a seismic reflection profile, passive seismic arrays, and single-station vibration measurements. The various sources of information were combined to generate a reliable Vs profile and an interdisciplinary image of the subsurface properties.

Geology and Stratigraphy Framework

The research region belongs to the external buried portion of the Apennines, dominated by active thrust-fold structures (Martelli *et al.*, 2017), developed through Plio-Pleistocene times (Ghielmi *et al*., 2013). The investigated site is placed on a broad syncline (Fig. 1A), part of the tectonic Ferrara Arc. The active faults generate a significant seismic activity, including that of May 2012. The strong synsedimentary deformation largely influenced the Plio-Quaternary stratigraphic architecture. The older unit involved in the research consists of Pliocene deep-marine terrigenous turbidites (P2, Fig. 3A). The interruption of the turbidite sedimentation in the study area (Porto Garibaldi Fm top) corresponds to the tectonic rising of submarine anticline bulges in western areas (e.g. Mirandola), preventing the currents from reaching eastern regions (Ghielmi *et al.* 2010, 2013). The following Marine Quaternary unit records the evolution from deep-water argillaceous deposits (QM2) to delta sediments (QM1). The combination of tectonics, eustasy, and climate fluctuations induced the unconformity surfaces supporting the subdivision of the following Quaternary successions into allostratigraphic units (Regione Emilia-Romagna *et al.*, 1998). A phase of deformation induced the unconformity base of the Emilia-Romagna Supersynthem, which is bipartite into the Lower (AEI) and Upper (AES) Emilia-Romagna Synthems by a surface associated with a gentler phase of structural reorganization and marine lowstand (Martelli, 2021). At the study site, the lowermost portion of AEI still records marine influences, associated with interglacial highstand phases. The upper part of AEI and in AES record purely continental conditions. The synthems in turn frame several subsynthems, each corresponding to an individual glacio-eustasy fluctuation, in the 100,000-year frequency band, as in the upper three Subsynthems (AES 6, 7, 8). The research well crossed the whole of the Emilia-Romagna Supersynthem and penetrated a large portion of QM1. The properties of the underlying units, down to the Pliocene turbidites (P2), were indirectly interpreted from the seismic investigation we performed.

Research methods and results

In the research site, multiple geophysical techniques were combined to achieve a reliable seismic wave propagation model. The site was selected because placed in the epicentral area of the 2012 seismic sequence, and because of the availability of an accessible deep well, where a previous down-hole investigation (Minarelli *et al.*, 2016) already measured both Vp and Vs velocities, to the depth of 265 m. We performed new accurate downhole measurements (Fig. 1B), to the depth of 370 m, together with passive and active seismic surveys at the surface. Active methods, performed by OGS authors, involved the data-acquisition, in the S-waves mode, by geophones and hydrophones in the deep borehole, using a Mini-Vibratory (MiniVib) as source. First-break arrivals and reflected waves were analysed to generate a 1D shear-wave velocity profile, analysed together with the reflection signals recorded by a linear pattern of horizontal geophones, placed at the surface. Passive methods were also applied, through a high-resolution frequency-wavenumber beamforming (f-k) and spatial autocorrelation (SPAC) analysis (Hailemikael *et al.*, 2023), using a 2D array of seismic stations, with a maximum aperture of about 880 m (Fig. 1B). We computed the Rayleigh (R) and Love (L) dispersion curves (DC) from both (*i*) the linear array of geophones, using the f-k method, and the MiniVib as active source, and (*ii*) from the 2D array of seismic stations, using ambient vibration three-component data, though f-k and SPAC methods. The observed dispersion and H/V curves were jointly inverted with the Geopsy tool (Wathelet et al. 2020) to obtain the 1D shear-wave velocity (Vs) profiles (Fig. 2).

The main result of the work is a consistent mono-dimensional Vs profile, generated by the synthesis the active and passive methodologies, supporting the seismic stratigraphy interpretation of the subsurface to a depth of about 700 m (Fig. 3). The regional unconformity surfaces, supporting the stratigraphic subdivision of the Quaternary successions, are associated with discrete layers of sharp increase of the seismic velocity. The strongest velocity increase is associated with the top of the P2 turbidites, at about 680 m, in perfect match with the base of the Marine Quaternary (QM) illustrated by the Emilia-Romagna Region study, as visible in Fig. 3. The 1D seismic velocity model, developed at the study site, can be extrapolated to similar syncline areas in a wider Po basin area in the finality of seismic response analysis and microzonation analyses.

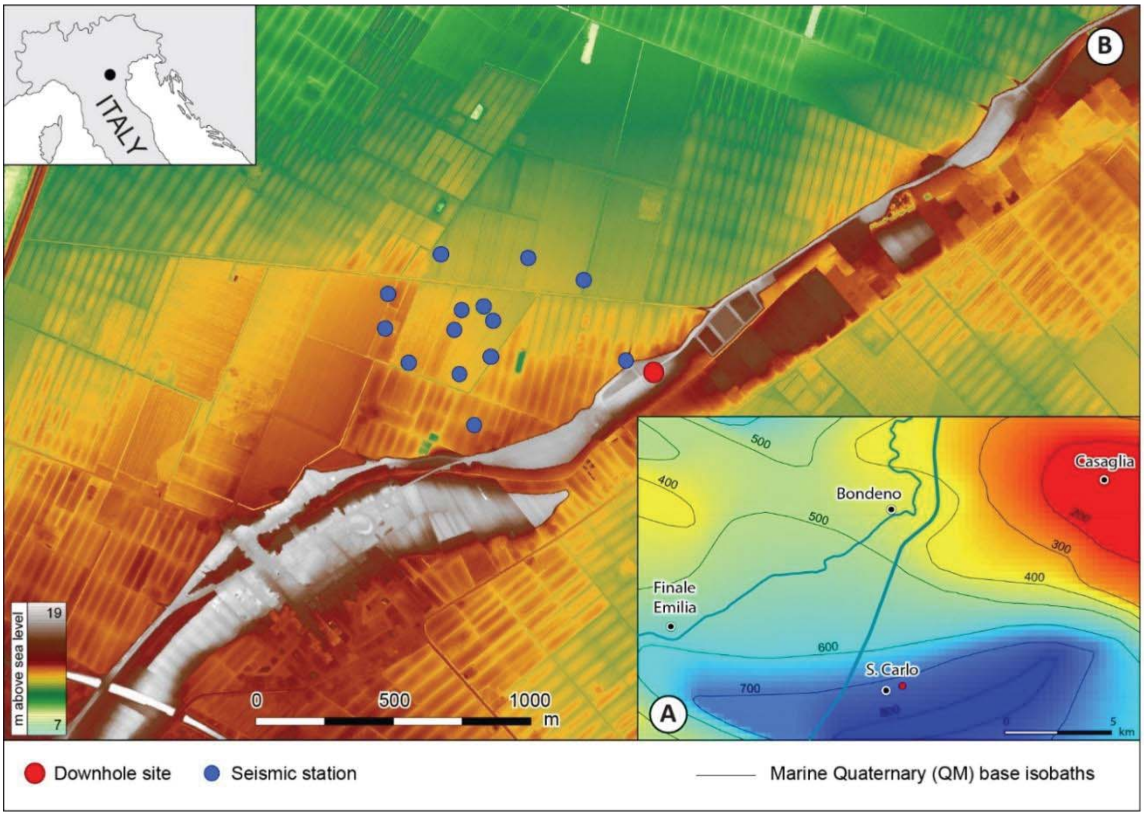

Fig. 1. (A) Depth of the Marine Quaternary top, which has been largely deformed by the ongoing compressional deformation (map produced by the Emilia-Romagna Region Geology Survey). The investigations site is placed on the syncline, at the south of the Casaglia High. (B) Location of the down-hole and of the array of seismic stations. A MiniVib as source was applied for the down-hole acquisition, whereas the seismic stations recorded ambient vibration data. The image background shows the Lidar generated elevation model, depicting the depositional fluvial ridge of the river Reno.

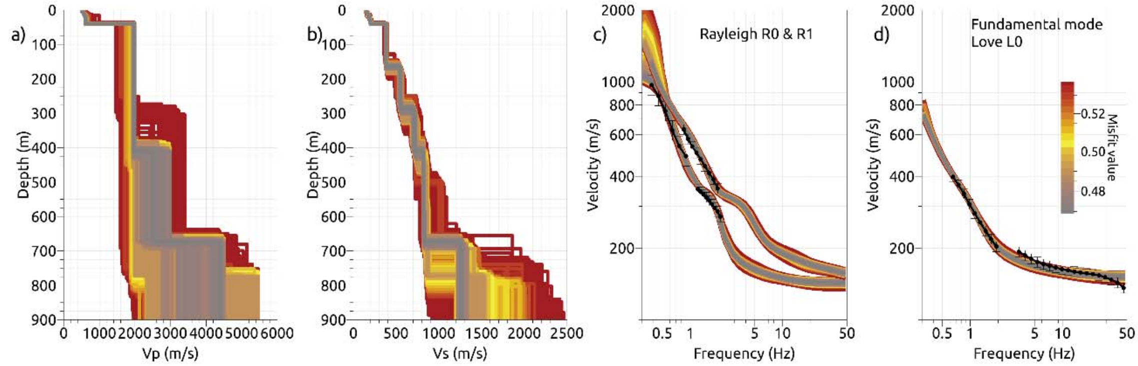

Fig. 2. Inversion results with the rainbow scale proportional to the misfit value. a) Vp models; b) Vs models; c) DCs of the fundamental Rayleigh (R0) and the first higher (R1) mode; d) DCs of the fundamental Love (L0) mode. The field DCs are overlaid in black.

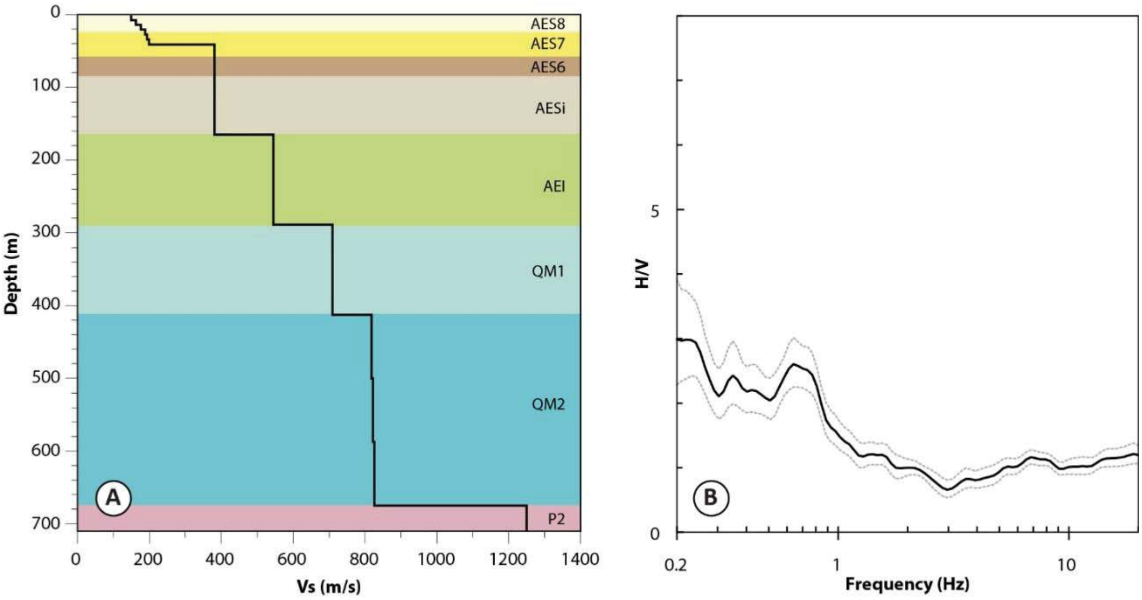

Fig. 3. (A) Average distribution of the S waves velocity with depth, generated by the synthesis of the active and passive methods data, correlated with the stratigraphic units described in the text. Sharp increases in velocity, of the best fitting model extracted from Fig. 2, are normally matched with the main discordance surfaces and stratigraphic boundaries. (B) H/V noise spectral ratios in proximity of the downhole site, derived from many hours of ambient vibration data acquired in November 2018.

Acknowledgements

This work is dedicated to and in memory of Lorenzo Petronio.

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